The atmosphere of our Earth, of planets of our solar system and of exoplanets

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7. Breathing of Men and Animals
7.0 Classification of Animals

Mammals, Reptilians, Fishes, Birds and Amphibians belong to the Vertebrates (about 3% of all animals). The remaining 97% are Invertebrates; an example of invertebrates are Insects (Arthropods).

7.0.1 Aerobic and Anaerobic Respiration

Aerobic respiration (cellular respiration, internal respiration) are processes in cells of living organisms in which hydrogen atoms (H) are oxidized; these H-atoms arise through different oxidative metabolic processes and are bound to special carriers. Elemental molecular oxygen (O₂) serves as an oxidizing agent and is thereby reduced to water. The purpose of aerobic respiration is the supply of energy in the form of ATP (s. pp 259 and p. 6-A-2-2). The term aerobic respiration is particularly used for biological processes of the respiratory chain in the inner membrane of the mitochondria (p. 259), at the end of which ATP is synthesized.

The cellular respiration is therefore a process in which energy-rich substances are decomposed. In cellular respiration, the glucose molecule C₆H₁₂O₆ is most often oxidized in a series of steps to so-called C₁-units (one-carbon units such as CH₃-, CH₂OH-, CHO-…), CO₂ and H₂O. The over-all balance of cellular respiration is discussed at p. 258.

In contrast to aerobic breathers, anaerobic breathers are creatures, which do not need oxygen for their metabolism but are rather exhibited by oxygen. For the oxidation in their metabolism, not oxygen but rather alternative electron acceptors such as nitrates, trivalent iron ions (Fe³⁺), quadrivalent manganese ions (Mn⁴⁺), sulfates and CO₂.

Under oxygen-free conditions, as for example in sediments of lakes, etc., one often finds prokaryotes (organisms without cell nuclei (bacteria, blue-green algae)); their metabolic energy is delivered from anaerobic respiration. These respiration processes are known as nitrate respiration, sulfate respiration etc. Anaerobic respiration is a very old form of energy source, which goes back to the ancient time when oxygen was present in the atmosphere only as a tracer element.
Vertebrates are animals having a backbone. These notably include fishes, reptiles, birds, mammals, amphibians, as well as agnathans (ancient vertebrates). The Table below shows the classes of vertebrates and the percent values of each class. With 55%, the fishes are by far the largest class.

The animal body is subdivided into head, barrel and tail. The skeleton consists of a backbone, the rips, the cranium (located at the frontside of the backbone), the shoulder- and the pelvic gurdle (Beckengürtel) as well as the extremities.

The respiration system of fishes consists of gills while the respiratory system of the other four vertebrate classes is the lung.

<table>
<thead>
<tr>
<th>Vertebrate classes</th>
<th>Biological diversity in %</th>
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<tbody>
<tr>
<td>55% Fishes</td>
<td>12% Reptiles</td>
</tr>
<tr>
<td>8% Mammals</td>
<td>16% Birds</td>
</tr>
<tr>
<td>5% Amphibians</td>
<td>4% Agnathans (ancient vertebrates)</td>
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</tbody>
</table>

Vertebrates are spread worldwide. They are living on all continents, including the Antarctica, in the oceans down to the deep-sea, in freshwaters and in the inland in all biotopes including the high-mountain region. Birds and bats have the ability of active flying.

In biological systematics, vertebrates have the taxonomic rank of a subphylum (Unterstamm).

Only about 3% of all animals are Vertebrates; the remaining 97% are Invertebrates (s. p. 276 and p. 321)
All animals without backbone are referred to as invertebrates. The majority of all living beings (about 97%!) belong to this animal species. Invertebrates are opposed to and form an affinity group to vertebrates.

Well known examples of invertebrates are insects, worms, mussels, crustaceans (crabs), octopus, snails and starfishes.

List of Invertebrates

<table>
<thead>
<tr>
<th>Insects</th>
<th>Crustaceans</th>
<th>Mollusces</th>
<th>and others</th>
</tr>
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<tbody>
<tr>
<td><img src="image1" alt="Insects" /></td>
<td><img src="image2" alt="Crustaceans" /></td>
<td><img src="image3" alt="Mollusces" /></td>
<td><img src="image4" alt="Others" /></td>
</tr>
</tbody>
</table>
7.1 Respiration of Mammals

Mammals: Lung – Heart – Blood circulation – Blood vessels

Veins: Blood vessels which transport blood to the heart. Venous blood is deoxygenated blood (CO₂) which travels from the peripheral vessels, through the venous system into the right atrium of the heart. Venous blood is dark red (here in blue). (However, the pulmonary vein carries oxygen rich blood (s. Figure and Ref. R.7.1.1).

Artery: Blood vessels which transport blood away from the heart. Arterial blood is the oxygenated (O₂) blood in the circulatory system found in the lungs, the left chamber of the heart, and the arteries. Arterial blood is red in colour. (However, pulmonary artery carries deoxygenated blood (s. Figure and Ref. R.7.1.1)).
Pulmonary Respiration of Humans - 1

Respiration is defined as the gas exchange in the body: Oxygen (O₂) is inhaled and carbon dioxide (CO₂) is exhaled. Respiration belongs to the vital functions of the body [there are three vital functions for life, namely the brain activity, the respiration and the blood circulation]. By far the greatest part of the external respiration occurs over the lungs. The contribution of cutaneous respiration to pulmonary respiration is only about 1%.

During inspiration, the air flows through the mouth and the nose and then passes through the pharynx to the larynx; it then passes the vocal cords across the trachea into the bronchia. This air way is also referred to as the respiratory passage. At the end of the bronchia the air enters the pulmonary alveoli from which oxygen enters the capillary vessels of the blood circulation and CO₂ is deposited. Oxygen is distributed over the body by means of the red blood cells.

In the case of normal shallow breathing, the chest is expanded by contraction of the pectoral muscles resulting in a reduced pressure in the lung.

In the case of deep breathing, also called abdominal breathing, the diaphragm contracts, the belly expands forward and the volume in the chest extends downwards.

[Remark: Breathing through the skin of humans is less than 1%]

Pulmonary Respiration of Humans - 2

The lung is connected to the ribs, the breathbone and the diaphragm by the plural (a gliding displacement layer) which avoids collapsing.

The respiration is regulated by the respiration center in the extended spiral coral. Here, the CO₂ content in the blood is monitored. If it exceeds a certain limiting value, a respiratory stimulation triggers inhalation. After a brief pause for breath, the pectorial muscles and the diaphragm relax again. The lung extracts by its own elasticity and the air is expelled. The normal breathing frequency at rest is about 12 breaths per minute for adults, about 20 for adolescents, about 30 for young children and about 40 for babies. An adult male at rest inhales about 500 mL air per breath volume. For a frequency of 12 breaths per minute, this corresponds to a volume of 6 L.

From the alveoli, oxygen diffuses into the blood; this is referred to as external respiration. At the same time, CO₂ leaves the blood and diffuses into the alveoli (s. pp 281, 282).

Besides the external respiration, there is also an internal respiration: Each human cell needs O₂ for live. During metabolism, O₂ is consumed, whereby CO₂ is created (s. pp 281, 282).
- **Alveoli**: connects with the bronchiolies, is where oxygen \( O_2 \) diffuses into the blood and carbon dioxide \( CO_2 \) diffuses out of the blood.
- **Alveolar wall**: a thin layer of cell, usually about 0.7 mm, which is so thin that \( O_2 \) and \( CO_2 \) can easily go through.
- **Microvascular**: the smallest blood vascular in the lungs, like capillaries.
- **Erythrocyte**: the red blood cells, contain hemoglobin, slowly go through the Microvascular, release \( CO_2 \) and absorb \( O_2 \).
- **Cells**: about 10 – 20 \( \mu \)m; cell nucleus of mammals: 5 - 10 \( \mu \)m.
- **Blood pressure**: (blue arrow): pressure that pushes from the blood against the wall of micro-vascular and the tissue.
- **Osmotic pressure**: (the green arrow): pressure that pushes from the tissue against the wall of micro-vascular and the tissue.

**Pulmonary Alveoli and Capillaries**

The alveoli are the structural elements of the lungs. During respiration, the gas exchange between the blood and the alveolar air takes place.

Alveoli have the shape of tiny bubbles. They are wound around the alveolar ducts like grapes and form alveolar sacks which are attached to the end of the bronchia. A single alveole has a rounded to polygonal basic form. Its diameter ranges between 50 and 250 \( \mu \)m.

Hairpins are microscopally small blood vessels (capillaries). They are connecting the arteria and veins in the blood circulation system. In these capillaries (alveoli), the energy exchange with the body cells takes place.

In the lung, the Alveoli, are enveloped by a network of capillaries (Haargefässe).

After leaving the heart, the blood vessels are getting narrow and narrower. Arteries are narrowing to metarterides (precapillaries) and to arterides before they are linking up to capillaries. The latter recombine to increasingly larger venules and veins.
A yawn is a reflex of simultaneous inhalation of air and stretching of the eardrums, followed by exhalation of breath. Yawning is commonly associated with tiredness, stress, overwork, lack of stimulation and boredom, though recent studies show it may be linked to the cooling of the brain. In humans, yawning is often triggered by others yawning. This «infectious» yawning has also been observed by chimpanzees and dogs. The process of yawning starts with a deep breath where the mouth is widely openend and ends by closing the mouth with a simultaneous exhalation of air. It is highly probable that most mammals and even vertebrates are yawning.

Snoring: During the day, the muscles are tense and the upper air passages are straightened: The breathing air can flow freely through the nose and the mouth to the lungs (left-hand picture).

At night, however, the body relaxes and the lower jaw sags down and backwards resulting in an obstruction of the respiratory tract. The breathing air must be sucked in with a considerable additional strain. Due to the impeded respiratory passage, large «wind velocities» are generated, putting the uvula (located in the middle of the soft palate) into vibrations. In this way, the snoring noise arises (right-hand picture).

**Sleep Apnoea Syndrom (SAS)** is caused by a respiratory arrest (Apnoe) during sleep. The Apnoea leads to a reduced oxygen supply and to repeated wake up reactions. The so-called Obstructive SAS (OSAS) is by far the most frequent form. The direct origin of OSAS is a strong relaxation of the ring-like musculature around the upper air passages during sleep: The upper part of the airways collapses, resulting in a disability (obstruction) of this airway (s. also right-hand picture on p. 283). The most common treatment is the use of a mask which generates a continuous air-overpressure of about 5 to 20 mbar.

**Apnoe-diving**: Before free-diving, the diver inhales air and in contrast to the scuba diver he uses only a single breath of air. The time period of holding the breath is referred to as Apnoe. The increase of pressure is one bar per 10 m → pains in the ears → the eardrum would rupture after a few meters → Diver must frequently adapt air pressure in its body parts against the external pressure → he presses air out of his lungs into the sensitive cavities. Because of his lungs this works only down to 25 - 35 m → The diver must adapt his body by using complicated equalization techniques e.g. by increasing the elasticity of its chest, midriff, etc.

By using all these adaptations, diving depths of more than 200 meters have been achieved ! The pressure of the water column above the diver is than more than 20 bar ! The dive time is about 20 minutes !
The most important pulmonary diseases


Obstructive lung diseases: or Chronic Obstructive Pulmonary Diseases (COPD): It is due to a narrowing of the airways which impedes the air flow. The most important risk factor is smoking, but in addition, air pollution and other factors are contributing. Examples of COPD's are chronic bronchitis and pulmonary emphysema (irreversible hyperinflation of the pulmonary alveoli).

Restrictive lung disorder: Here, the flexibility of the lung is restricted. As a consequence, the volume of the lung and the flexibility to pressure changes are limited. Examples are sarcoidosis (disease of the connecting tissue and granuloma formation), pneumoconiosis (black lung) and other diseases which are associated with a fibrosis of the lung tissue.

Pulmonary oedemata: Collection of fluid in the lung tissue. It should be distinguished between two types of oedemata: 1) «Permeability oedema» in which the permeability of the capillaries is increased, and 2) «hydrostatic oedema» (cardiogenic pulmonary oedema, oedema of altitude); in the latter, the pressure in the capillary strongly exceeds the pressure in the alveoli and the liquid from the capillaries is squeezed out.

Atelektase: Here, part of the lung is collapsed, and the alveoli contain no alveolar air or only very little air (see p. 282).

Inflammations of the lung: Such inflammations are pneumonia, in which the lung tissue is affected, as well as bronchitis, an inflammation of the bronchial tubes. In the case of acute bronchitis, the small bronchia are affected.

Neoplasms: Cancer diseases of the lung: they are known as bronchial carcinoma because they are due to the malignant growth of degenerate cells of the bronchial tubes or the small bronchia. Lung cancer is one of the most common malignant diseases of humans. Subtypes are: Squamous Cell Carcinomas (SAS), Adenocarcinoma, small and large cell carcinomas. Due to the filter function of the lung, the lung contains often metastases from other tumors.

The Lungs of a Dog

The lungs of a dog occupy the largest part of the thorax. They are protected by the ribs and consist of 7 pulmonary lobes, three on the left-hand side and 4 on the right-hand side. The fourth lobe on the right-hand side is small and not visible in the picture below. [Note that humans have 3 lobes on the right lung and 2 lobes on the left lung]. The lungs and the bronchia belong to the lower airways.

For many animals, the respiration acts also as a temperature regulator, this is the case for the rapid shallow breathing of dogs. For quiet inhalation and exhalation, the inhaled air volume for one breath is known as the tidal air; for dogs it varies between 0.1 and 0.4 liter.
7.2 Respiration of Amphibians

The Amphibians (Toads, Frogs, Salamanders) are the phylogenetically oldest class of terrestrial vertebrates. Many species first spend a larval stage with gill breathing in water and only after a metamorphosis they start to spend a terrestrial live. Amphibians are cold-blooded animals, i.e. their body temperature adapts itself to the ambient temperature. Due to these properties, their scientific name is «Amphibia» (from the Old Greek adjective «amphibios» (dual live): In the course of a year, they often live in both, aquatic as well as in terestrial habitats. Many Amphibians are nocturnal in order to keep water losses over the skin as small as possible. In the following we show some amphibian species:

- Common toad
- Common tree frog
- Fire salamander
- Crested newt
Respiration types of Amphibian

Depending on the environment and season, adult amphibians have three different respiration systems: skin or cutaneous, oral or buccopharyngeal, and lung or pulmonary respiration.

The following, slightly adapted Table from BLAUSCHECK (1985, p. 24 (our Reference. R.7.2.3)), contains the percentage contributions of the respiration systems of the adult amphibians shown at p. 288.

<table>
<thead>
<tr>
<th>Examples / Resp. organ</th>
<th>Skin</th>
<th>Oral respiration</th>
<th>Lungs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common toad</td>
<td>27.6 %</td>
<td>0.9 %</td>
<td>71.5 %</td>
</tr>
<tr>
<td>Common free frog</td>
<td>24.2 %</td>
<td>1.1 %</td>
<td>74.7 %</td>
</tr>
<tr>
<td>Fire salamander</td>
<td>41.4 %</td>
<td>1.3 %</td>
<td>57.3 %</td>
</tr>
<tr>
<td>Great crested newt</td>
<td>73.7 %</td>
<td>3.0 %</td>
<td>23.3 %</td>
</tr>
</tbody>
</table>

1. In Skin or cutaneous respiration, gases are exchanged through the skin, which many types of the amphibians use including toads, frogs, salamanders and newts. In cutaneous respiration, gases pass through the skin and directly into blood vessels. This type of respiration is controlled by capillarity density, amount of blood flow and blood vessel radius. Cutaneous respiration also allows amphibians to breath underwater, as oxygen dissolved in the water is captured by the amphibian’s skin.

2. In Oral or buccopharyngeal respiration, gas is exchanged between the buccal and the pharynx through rapid pulses in the throat. Air is first sucked in through the nostrils to fill the buccopharyngeal cavity, then the throat is contracted. This forces the air from the buccopharyngeal cavity into the lungs, which expel the air through the throat. This type of respiration is less common than cutaneous but is present in most species of frogs.

3. Pulmonary respiration is the use of simple paired lungs like most land-dwelling animals. In amphibians, pulmonary systems are most often found in some species of salamanders and caecilians, the worm-like amphibians. In caecilians, especially those with thin bodies, the left lung is usually larger than the right. [common caecilians = Erdwühlen].

Cutaneous respiration of Amphibians: Cross-section through skin

The thin moist skin of Amphibians is excellently suited for the process of respiration. Subdermal, a dense capillary network is present which enables an exchange of substances by diffusion. This means that O₂ can be absorbed through the skin while CO₂ is desorbed. The absorption of O₂ through the skin is a passive process.

Many amphibians, in particular frogs, are moistening their skin with a slippery mucous layer, which is produced by the mucous gland. This is an effective means to escaping predators and sustains the skin respiration. The poison glands are emitting a skin poison which is a protection against animal grub.

For very small amphibians, cutaneous respiration is particularly important because in this case, the ratio of surface F to volume V, F/V, is large (for a sphere with radius R we have F/V = 3/R while for a cylinder with radius R and length L >> R, F/V ≈ 2/R); the smaller R, the larger is F/V.

The skin of amphibians may exhibit a wide variety of colors and patterns. In many species, these characteristics help them blend into their natural environments in order to avoid predation. However, certain amphibians display bright warning colorations and patterns that may include hues of red, yellow, orange, and black, which serve as bright signal to predators that they may be poisonous. Indeed, several species, such as the cane toads and poison arrow frogs, are equipped with skin glands that secrete powerful toxins.

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7 – 10
7.3 Respiration of Reptiles

7.3.1 Reptiles – Some Examples

Reptiles or crawlers form a class of vertebrates between the lower (anamnia) and higher (amnions) vertebrates. Examples are Lizards, e.g. true Lizards, Varanides and the Chameleon. Other examples are Crocodiles, Turtles and Snakes.

- True lizard
- Veranus giganteous (with a length of up to 3 m and a mass of 70 kg)
- Chameleon
- Crocodile (largest and most dangerous lizard!)
- Turtle
- Snake: Cobe cobra
As amphibians, reptiles are cold-blooded animals which regulate their body temperature as far as possible according to their behaviour and environment. Among others, animals such as lizards, chameleons, crocodiles, turtles and snakes belong to the class of reptiles (s. p. 292).

What reptiles all have in common is the scaling of their skin. Concerning their external shape, they have, however, little in common: Their external forms are, indeed, very different, starting from the wormlike blindworms and snakes to the four-footed lizards (to which also the crocodiles belong) and to the turtles. With the exception of the latter, the bodies of all reptiles are elongated; in addition, they are completely footless (snakes) or they have two or four extremities which often serve only as a support of the body gliding over the floor. In addition, however, there are also numerous walking or running species, as well as climbing and digging reptiles; many reptiles are also able to swim and to dive skillfully. In the primeval world also flying reptiles existed.

Their skeleton is almost completely bony, implying that reptiles belong to a higher stage than amphibians; they contain many cartilagenous parts. Ribs are present over nearly the whole length of the torso.

Even at the young age, the lungs are providing the respiration; as a rule the lungs have the form of long, capacious sacks which extend well to the back of the animals (s. pp 302, 303).

### Characteristics of Reptiles

1) **The extremities are armed with claws; these claws are a characteristic of lizards and other reptiles.**

2) **The skin is covered with scales of horn → effective protection against evaporation.**

3) **The formation of a set of teeth is a further characteristic of reptiles → for hunting the prey.**

4) **Venomous snakes have a sophisticated system of smell organs for the detection of their prey.**

5) **Reptiles have lungs with large indentations; each of which is folded ones more. This folding considerably increases the surface of the lungs.**

6) **Mammals have a substantially greater demand of oxygen and the lungs are strongly branched out. → Immense large number of pulmonary alveoli.**
The lungs of reptiles are large, and they are often divided internally into several chambers. The lining of the lungs may be folded into numerous small sacs called alveoli. Alveoli greatly increase the internal surface area of the lungs, thus increasing the amount of oxygen that can be absorbed. In most snakes, only the right lung actively functions (s. p. 303). It is elongated and may be half as long as the body. The left lung is either reduced to a small nonfunctional sac or absent entirely.

A reptile fills its lungs by expanding its rib cage. This expansion reduces the pressure within the thorax and draws air into the lungs. When the ribs return to their resting position, pressure within the thorax increases, and air is forced out of the lungs. Similar movements help humans to breath.

7.3.2 Respiration of Lizards

All crawlers, including lizards, have simple and structured lungs. However, their lung is already more developed than the lung of amphibians. The lung of crawlers is divided into a few chambers and their internal surface is increased by folds.

If crocodiles are breathing, they are supported by a refractor muscle which is comparable to our midriff. During inhalation, the muscle retrieves the organ and the air is sucked into the lungs. During exhalation, the liver is moving forward similar to a pump plunger. If crocodiles are walking, the swinging hips support the pumping function. In this way, running animals can even support their breath. Their breathing frequency increases and the air is inhaled more deeply.
7.3.3 Tortoises and Turtles - General

Turtoises and turtles are both reptiles from the order of Testudines, but in different classification families. They are one of the oldest animals of the world and exist about 150 Million years on Earth.

The major difference between the two is that tortoises dwell on land, while turtles live in the water some or nearly all the time.

The most obvious feature of any turtoise or turtle is its shell; the dome-shaped shell is the animals primary defense mechanism against «would-be predators» (potential enemies). These reptiles are generally reclusive and shy in nature.

With a few exceptions, tortoises and turtles are lung breathers. They are cold-blooded and diurnal animals.

Tortoises: Properties and Examples

True tortoises are the testudes which are best adapted to a terrestrial way of life. Already the ancient tortoises were terrestrial animals; this has been demonstrated by findings from the late Triassic. Today, 16 genera containing 48 species are known which are mainly living in the Tropics and Subtropics. The Egyptian tortoise (left-hand picture) belongs to the smallest tortoises. On the other hand, the largest tortoise is the giant Galápagos tortoise (right-hand picture); the latter animals can have a mass of up to 250 kg. [The largest tortoise of all times is said to be the now extinct Testudo atlas with a carapace length of 2.5 meters].

Tortoises have most often a high domed shell and are both, plant eaters as well as scavengers. For this reason they can walk at slow pace from one plant to the next one. As vegetarians there is no need to rush. Their legs are wide and their hind legs are columnar.
Respiration of Tortoises (and Tortles)

Mouth and Pharynx: Cavities inside the skull where food, water and air enters.

Glotis: Slit-like opening behind the tongue. It connects the pharynx (Rachen) and larynx (Kehlkopf). It closes when the turtle is underwater or eating.

Larynx: The upper end of the respiratory duct. It is connected to the glottis and leads into the trachea.

Trachea and Bronchii: The trachea is a long hollow tube between the lungs and the larynx. Halfway down, it divides into two tubes, called bronchii. One bronchus enters the left lung, the other the right lung.

Right and Left Lungs: Air passes from the bronchii into smaller tubes in the lungs called bronchioles. The bronchioles get progressively smaller and they end into a small cluster of air sacs. These air sacs, known as alveoli (see p. 282 for humans), located at the end of the bronchioles are where gases are exchanged. Oxygen (O₂) from air dissolves into the blood, while carbon dioxide (CO₂) diffuses out of the blood into the air.

Freshwater Turtles and Seawater Turtles

Among the Turtles there are freshwater turtles and seawater turtles. Turtles are hunters because in the aquatic element, they can reach considerable speeds. Their shells are shallower and more streamlined as those of the tortoises and their feet are fin-shaped, i.e. they have webs between the claws.

Their eyes are adapted to the life element of water: the lens of their eyes adjusts the angle of refraction of water and therefore, turtles are able to see clearly also underwater.

Marine turtles are laying their eggs ashore, most often at the place of their birth. For this purpose, they are often swimming several thousands of kilometers. The most well-known marine turtles are the «Hawksbill turtles», and the «Green sea turtles» (s. p. 301). The «Leatherback sea turtle» is also a remarkable species. It is the largest still living turtle reaching a mass of up to 750 kg!
**Respiration of Turtles**

"Common musk turtles" are freshwater turtles and are able to stay underwater up to half a year without breathing. Their size is only about 7.5 - 10 cm and they are one of the smallest species of turtles. They are characterised by a lobed surface (papillae) of the oral cavity and pharynx space which is infused by small blood vessels. These papillae are thoroughly rinsed since the turtles supply their pharynx regularly with fresh water. Due to the large surface of these papillae, an exchange between O$_2$ and CO$_2$ is possible, i.e. the animals have developed something similar to gill breathing.

Many marine turtles are able to dive several hundred meters and do not require oxygen for several hours; the green sea turtle can stay under water up to 5 hours. This is possible by the slowdown of their heartbeat. During such extreme dives, the heartbeat is drastically reduced (9 heartbeats per minute). By taking breath, the lung deflates in a single breath and refills immediately.

**7.3.4 Snakes**

Snakes are a suborder of scaled reptiles. They are descending from lizard-like ancestors. In contrast to lizards, their body is greatly enlarged and their extremities are nearly rudimentary. Today, about 3’000 species are known. Depending on the species, the size of snakes ranges between 10 cm for the slender blind snake and nearly 7 m for the reticulated phyton.

Due to their body shape, most of the internal organs are elongated. The left lung is underdeveloped. For respiration, only the right lung is essentially used. It extends up to two third of the body length.

In the back, the trachea ends in an Air sack from which the snake can cover its oxygen demand in specific cases. (This may be the case during swallowing a large prey where the trachea is sometimes compressed; it also is a source of air for sea snakes in the case of long immersion times in the water). For sea snakes, the Air sack serves in addition as a hydrostatic organ.

As most of the reptiles, snakes are also cold-blooded animals.
**Snake Respiratory System Anatomy**

Snakes have a small opening just behind the tongue called glottis, which opens into the trachea (p. 302), or windpipe. Unlike what mammals have, the reptile glottis is always closed, forming a vertical slit, unless the snake takes a breath. A small piece of cartilage just inside the glottis vibrates when the snake forcefully expells air from its lungs. This produces a snake's characteristic hiss. Snakes are able to extend their glottis out of the side of their mouth while they eat, which allows for respiration while they consume large prey items.

The trachea is a long, strawlike structure supported by cartilaginous rings. This configuration is also seen in lizards. The trachea usually terminates just in front of the heart, and at this point it splits into the two primary bronchi, airways that direct air into either the left or right lung.

In most snakes, the short left bronchus terminates in a vestigial, or rudimentary, left lung. The size and functional capacity of this lung varies depending on the species. It can be complete in some of the water snakes where it is used for hydrostatic purposes. The right bronchus terminates in the functional right lung. Water snakes can dive up to 180 meters and for breathing, they must return to the water surface only after 30 minutes to two hours (see picture).

Snakes breathe principally by contracting muscles between their ribs. Unlike mammals, they lack a diaphragm, the large smooth muscle responsible for inspiration and expiration between the chest and abdomen. Inspiration is an active process (muscles contract), whereas expiration is passive (muscles relax).

The portion of a snake’s lung nearest its head has a respiratory function; this is where oxygen exchange occurs. The long portion nearest the tail, regardless of the lung’s size, is more of an air sac (p. 302). The inside of these sac portions look more like the inside of a balloon than a lung. There is no exchange of respiratory gases.

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**Venomous Snakes**

Worldwide, about 3'000 species of snakes are known. About 1'300 of them are venomous snakes. The latter occur in the following families:

Venomous viper snakes with 2 subgroups:
- Poisonous vipers (e.g. Mamba, Cobra, Coral snake)
- Sea snakes (e.g. Late Taale snake, Flate-tailed Sea Snake, Taipan, Brown Hous Snake, Tiger snake)

Vipers with 3 subgroups:
- Fea vipers (e.g. crossed viper, aspis viper, field viper, puff otter, saw-scaled viper)
- Pit vipers (e.g. Rattle snake, Moccasins, ance-head viper, bamboo viper)
- Original vipers: (mole viper; only one species)

One of the most venomous snake is the Inland Taipan of Australia and certain Sea snakes. The poison of the Inland Taipan emitted by one bite of a completely charged gland is theoretically sufficient to kill about 250 humans, 250'000 mice or 150'000 rats! The Faint-Banded Sea Snake is even said to be about 100 times more toxic than the Inland Taipan and makes it the most poisonous snake of the world. But this snake seldom bites unless severely provoked and even then seldomly releases its entire store of venom.
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<thead>
<tr>
<th>Snakes in Mythology and Snake poison in Medicine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adam und Eve (Michelangelo)</td>
</tr>
<tr>
<td>Adam und Eve first live in the «Garden of Eden». Contrary to God’s ban, the snake convinced them to eat from the «Tree of Knowledge». As a punishment, God expels Adam and Eve from the paradise.</td>
</tr>
<tr>
<td>Medusa’s head (Rubens)</td>
</tr>
<tr>
<td>In the late classical Greek mythology, Medusa was first an incredible beauty. But when Pallas Athene surprised Poseidon during forcible rate of Medusa, she was extremely furious and turned Medusa into a monster: each wavy lock of her hair was changed into a venomous snake.</td>
</tr>
</tbody>
</table>

Left: Aesclepius with its staff of Aesclepius. In the Greek mythology, Aesclepius was the God of medicine. He was represented as a bearded man supporting himself on a staff around which a nonvenous snake was curled.

Right: Aesculapian snake with a drinking bowl as a symbol for a pharmacist. The distinguished physician Paracelsus (1493-1541) coined the words: «Poison is in everything and no thing is without poison. The dosage makes it either a poison or a remedy».

Ambivalence: The poison of snakes is a further example of ambivalency: In small doses, snake poison can be be used as a medicine.
7.4 Respiration of Birds

In contrast to mammals, the lungs of birds are incorporated rigidly in the thorax. Although the pleura is present in the embryonic stage, it then regresses. The avian lung is not lobed and during respiration, its volume does not change.

At the furcation of the trachea, the air-conducting system branches into the two main bronchi. This is also the location of the vocal organ. From the main bronchi, four groups of secondary bronchi are branching out. The secondary bronchi are followed by parabronchi; the thickness of the latter ranges between 0.5 to 2 mm.

In the wall of the parabronchi there are small funnel-shaped bellmouths which are leading into the air capillaries. Normally, the air capillaries form a network of communicating pipes and function as the essential exchange tissue. Around this tissue, a dense network of blood capillaries is present.

In contrast to mammals, the respiration system of birds is not blind ending but it is rather an open tubular system. After perfusion of the lung, the air enters air sacs which function as air blowers for ventilation.
The air sacs of birds are thin-walled attachments of the lungs which conduct the air through the lungs similar to bellows. But in the air sacs no gas exchange takes place. These sacks are very thin with transparent walls. Beside their function as a «motor for respiration», they are also involved in the formation of the voice: high frequency expirations are modulated in the syrinx to produce the bird song. The third important function of the air sacs lies in their involvement as thermoregulators by rejection of heat via evaporation (evaporation based cooling).

The anterior air sacs are located between two membranes of connecting tissue inside the thorax and embrace the heart and the true stomach. In the case of singing birds they are merging with the air sac of the collar bone.

The positions of the posterior breast air sacs are directly near the body wall and they are located behind the anterior air sacs.

The abdominal air sacs are thin balloons which are located between the intestinal loops and are pneumatizing the pelvic-girdle.

Respiratory cycles of Birds:
First inhalation: Oxygen-rich air flows into the posterior air sacs. This is associated by an expansion of the air sacs.

First exhalation: Air is pressed into the lung capillaries. → Blood is supplied with O₂ and the air sacs are contracting.

Second inhalation: CO₂ enriched air is flowing into the anterior air sacs which expand again. At the same time, new oxygen-rich air (red arrow) is flowing into the posterior air sacs.

Second exhalation: From the anterior air sacs, O₂ depleted and CO₂ enriched air is pressed out and the air sacs are contracting again.

For more detailed explanations s. p. 310.
Synchronization and Air Current in the Respiratory System

The air which a bird inhales with the first breath of air (process A in the diagram of p. 309, shown in blue), is flowing unidirectionally through the air sac - lung system. The individual steps [(A,B) and (C,D)] are the following: From the trachea, the air is first flowing into the posterior air sacs, which then extend together with the anterior air sacs. This corresponds to the first inhalation. In process B, the air flows into the lung (first exhalation) and thereby the air sacs are contracting. In process C, the air flows into the anterior air sacs whereby the air sacs are expanding again. In a second inhalation, fresh air is simultaneously entering again through the trachea (red arrow). Therefore, the first and the second inhalations are synchronized. Finally, the air is leaving the anterior air sacs and escapes into the atmosphere as illustrated in process D.

In processes A and [(A,B) and (C,D)], oxygen-rich air is inhaled while in the final process D, oxygen depleted and carbon dioxide enriched air is leaving.

These processes have been experimentally confirmed: Oxygen sensors have been placed at different positions in the bird’s respiratory system. In this experiment, the bird is inhaling pure oxygen in one breath which is followed by one breath of normal air. The oxygen sensors located at different sites are recording the times at which the pure oxygen reaches the sensors.

To sum up, it can be concluded that the air is flowing unidirectionally from the posterior air sacs through the rigid lung to the anterior air sacs. The total air flow contains two cycles (A,B) and (C,D); in each cycle there is an inhalation and an exhalation.

The combination of the small weight of the air sacs, the small weight of the hollow bones and their wings (Chapter 4, pp 148, 149) makes birds to be masters of flight.
7.5 Respiration of Fish

Systematics of Fish

Fish are aquatic living vertebrates which are breathing with gills (pp 316, 317). Lungfishes are also primary gill breathers in water but in addition they are also air breathing if the tip of their snout barely touches the water surface (s. p. 319). Two species of fish are distinguished, namely cartilaginous fish and bony fish (Osteichthyes); s. p. 315.

- Cartilagenous Fish
  - Living almost exclusively in the Sea:
    - Sharks
    - Rays
    - Chimaeras

- Osteichthyes or bony Fish
  - Lobe-finned Fish
    - Marine coelacanths
      - Lungfish
  - Ray-finned Fish
    - All other fish groups, including all European freshwater fish
**Physiology of Fish**

- **External appearance**
  - Dorsal fin
  - Caudal fin
  - Nasal opening
  - Gill cover
  - Pelvic fins
  - Kidneys
  - Scales
  - Brain and spinal cord
  - Organ of smell
  - Stomach
  - Heart
  - Liver
  - Swim bladder
  - Intestine
  - Urinal bladder
  - Backbone
  - Ribs

- **Internal organs**
  - Gastrointestinal tract
  - Respiratory system
  - Circulatory system

- **Skeleton**
  - Vertebrae
  - Fish bone

---

**Oxygen concentration in Freshwater and Seawater**

The oxygen content in air is about 21%. If air is in contact with pure water, oxygen ($O_2$) diffuses from air into water: The solubility of $O_2$ depends on temperature $\theta$ (in °C), on the atmospheric pressure $P$ in Torr (760 Torr = 1 atm = 1013 hPa), and from the vapour pressure $p$ of water (in Torr). There exist empirical approximate formulas for the «Dissolved Oxygen» $DO$ in mg/l:

For $0°C < \theta < 30°C$ we have: $DO = [0.678 \times (P – p) / (35 + \theta)]$

For $30°C < \theta < 50°C$ we have: $DO = [0.827 \times (P – p) / (49 + \theta)]$  (s. Graphs)

In the Word’s oceans, the oxygen concentration is smaller than in freshwater (s. right-hand Graph). With increasing depth below sea level, the $O_2$-concentration decreases and at about 1000 m below sea level it reaches a minimum; With increasing depth, however, the $O_2$-concentration increases again (s. Appendix 7.A.5.1).
Differences between bony fish and cartilaginous fish

With a few exceptions, bony fish have air bladders, gill covers, scales and movable pectoral fins. The morphology of cartilaginous fish is different.

Because of the gas-filled air bladder, most bony fish are able to swim in different water depths without problems. For most bony fishes the function of the air bladder is the regulation of their density in such a way that they can easily float in water or sink slowly to the floor. However, not all bony fish dispose of an air bladder: fish species living on the ground or fish which are able to swim particularly well can renounce on an air bladder.

For the cartilaginous fish, the situation is even simpler: They do not require at all an air bladder because they have a low-weight skeleton of cartilage. In addition, their large and fatty liver generates a stronger buoyancy. As external characteristics, the immovable and often deck-like profile of the pectoral fins as well as the asymmetric caudal fins are an additional advantage. Sharks belong to the species of cartilagenous fish.

Their is also a disadvantage associated with the immovable pectoral fins: many cartilaginous fish are unable to swim backwards. But on the other hand, they are most often very flexible and fast swimmers.

Cartilagenous fish have a gill cover which covers the gill arches; between the gill arches there are slits, the so-called gill slits. Their skin is also different: while bony fish have scales, cartilagenous fish have a very leathery skin which consists on tooth-like scales. As an example, sharks are covered with such tooth-like scales.

Gill breathing of Fish

For many aquatic animals, gill breathing refers to the exchange of the gases O₂ and CO₂ between the blood and the ambient water. If water flows into the gills, O₂-rich water gets into contact with de-oxygenated blood. This difference in partial pressure gives rise to a diffusion of O₂ dissolved in water into the blood. As a result of the counterflow, the blood leaving the gills contains more O₂ than the water streaming out.

As shown in the pictures, fish have 4 bony gill arches at each side which are located behind the gill covers. At the gill arches, the gill filaments are located (s. Figure at p. 317). The latter are filtering the water passing by, similar to the prongs of a comb. By this filtration, the sensible gill filaments are protected from dirt particles contained in the water (Figur p. 317).

Upon opening of the mouth, water is streaming into the mouth cavity. Upon closing the mouth, water passing the gills is pressed through the gill cavities into the exterior air. Thereby, the gill covers are slightly lifted and a (skin) lapped is fold back. During the respiration process the pharynx remains closed.
The O$_2$ uptake and the CO$_2$ release takes place during the time in which the water is flowing around the gill filaments. In the gill filaments, there is a large number of blood vessels. In the illustration on the left, they are shown in red and blue. If during the respiration process, water is flowing around the gill filaments, oxygen diffuses from water into the blood vessels (shown in red). At the same time, CO$_2$, which has been produced as a waste product during the metabolism is released from the blood vessels back into the water.

The gill filaments are the lungs of the fish. They can work only in water. On land they would quickly stick together and the fish would inevitably suffocate. If the O$_2$ concentration in water is too small (< 4 mg/L, s. Graph, p. 314), the fishes will also suffocate in this water, particularly in view of the fact that the expenditure of energy for breathing in water is significantly larger than in air.

Due to particular accommodations, some fish species are able to leave the water for longer periods of time. One possibility to achieve this is to supply their breathing water in the gill caves a second time with oxygen.

**Sharks and Whales**

Breathing of sharks: Roughly, it can be distinguished between Whitetip sharks and Deep-see sharks.

Whitetip sharks have to be always in motion in order not to suffocate; for this reason, the are sleeping also during swimming. They are swimming with open mouth. Therefore, water can penetrate through the pharynx into the gills. Thereby, water is de-oxygenated and oxygen is transferred into the blood.

Deep-sea sharks are closing and opening the mouth alternately. Thereby, a suction is produced. Thus, they take care themselves for the water influx. During this procedure, they use the oxygen dissolved in water. Sharks are cartilaginous fishes (s. p. 312).

Whales are not fish but rather mammals which are living exclusively in water. As all mammals, whales are breathing air and have lungs. Whales are warm-blooded animals. Some species of whales belong to the largest animals of the Earth (Blue whales have body lengths up to 33 m and weights up to 200 tons!)

For breathing, whales have to expose their head above the water surface. They are first breathing out, whereby they are blowing a large water cloud into the air. If whales are taking air, they exchange 80 to 90 % of the air contained in the lung (for humans: only 10 bis 15 %). Sperm whales are able to dive up to 90 minutes and reach depths up to 3'000 m ! Bottlenose whales are able to dive with a single breath up to 2 hours!
Lungfish are a subgenus of osteichthyes. They are «animals dipnoe» (double breathers) because they have both, gills for breathing in water, as well as lungs for breathing air at the surface of water. The lung of these animals is an organ located in the intestine which is homologous to the air bladder (s. p. 315). The Australian lung fish has a single lung. All other species (for example African lung fish) have lung pairs which are located ventrally. For breathing air, lung fish ascend every 30 to 60 minutes to the water surface. Some species depend on pulmonary respiration. If they are kept too long under water, they are drowning – a very particular property for fish.

The two lungs of African lung fish are placed vertically at the forearm. They have internal gills, which are, however, strongly receded and are therefore only partially available for gas exchange. Breathing through the skin is also of importance: by cutaneous respiration, they extract dissolved oxygen from water. The lungs are primarily used during rapid hunting, if they are scared up and during the dry season (aestivation).
7.6 Respiration of Invertebrates

7.6.1 Invertebrates - General and Examples

The prevailing part of all animal species are the invertebrates. Today, about 95% of all known animal species belong to the invertebrates. Beside the absence of a backbone, these animals have in general not much in common. The largest invertebrate is the «Giant Squid» which can have a length of more than 16 meters, but it should be noted that this is a great exception. Most of the invertebrates are, however, very small. One of the smallest insects is the fairy wasp or fairyfly with a length of only 0.14 mm.
Invertebrates: Examples

- Mollusces (for example: scallops, snails)
- Arthropods
  - Insects (for example: ants, butterflies)
- Ringed worms (for example: leech)
- Cnidarians (for example: jellyfish)
- Protezoa (for example: amoebae)

Respiration of two mollusces: Giant Squids and Snails

Section 4.2 was devoted to flying and gliding of invertebrates. In this Section we discuss the breathing mechanism of some selected invertebrates; firstly we consider two mollusces, and then some insects.

About Respiration of a Giant Squid
The Giant Squid is a cephalopod („Kopffüssler“). Their gills are the primary respiratory organs. A large gill surface and a thin tissue of the gills allows an effective gas exchange both for O₂ as well as for CO₂. Since the gills are located in the mantle cavity, breathing is coupled to the movement: Thus, ventilation is not possible without moving. Therefore, they are obliged to swim continuously.

About Respiration of a vineyard Snail
For breathing in, the snail is lowering its mantle cavity at open spiracle, thereby creating a low pressure whereby oxygen-rich air flows in (s. Figure). The gas exchange takes place at the top of the mantle cavity where oxygen diffuses from the respiratory air into the blood. In the opposite direction, CO₂ diffuses from the blood into the air. The respiratory organ is known as the internal lung although it is more similar to a single pulmonary alveoli.
7.6.2 Respiration of Insects

In Chapter 4, Sections 4.2, we have discussed the flight of insects. Here, we are interested in the process of respiration. Of course, we have to distinguish between land-living insects and aquatic insects. We first consider the breathing of land-living insects. (Breathing of aquatic insects is discussed at pp 332, 333 and in the Appendix 7-A-6-2, 7-A-6-3).

The following picture shows the internal organs of an air-breathing insect. It consists of three parts: the head, the breast (thorax) and the abdomen. For breathing, the Trachea (Atmungsorgan), the Spiracles (Atemlöcher = tiny holes), and the Air sac (Luftsack) are of special importance. Insects do not have lungs for breathing.

![Internal organs of an air-breathing insect](image)

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7.6.2.1 Insects: Trachea - Tracheole - Spiracles

Insects do not breath through their mouths as we do and they do not have lungs, nor do they transport oxygen through their circulatory system. Instead, insects breath by inhaling the vital oxygen through an array of tiny holes (spiracles or stigmas) at their chitinous exoskeleton. The spiracles are located at both sides of the body and for controlling the gas exchange, they can be closed or opened. The spiracles are followed by a system of air ducts, the trachea, from which more and more branches reach out in ever more tiny capillaries. In this way, oxygen is directly transported to the individual tissues. Most of CO₂ is also exhaled through the tracheas and spiracles but part of it leaves the insect’s body. [For complementary information about «Breathing of Insects»: s. also Appendix at p. 7-A-6-1].

![Insects: Trachea - Tracheole - Spiracles](image)

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7 - 29
**Insects: Trachea and Air sacs**

The trachea of many insects are interconnected with air sacs which support air exchange and serve as oxygen storage. In addition, the air sacs reduce the weight thereby increasing the excellent flight capability. The picture also shows two spiracles for the inhalation of oxygen-rich air.

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**Insects: Trachea, Tracheole and Spiracles**

a): The tracheal system is ever finer branched. The most tender branches (Tracheole) are extending deeply into the tissue, for example in a muscle, where oxygen is needed. The walls of the trachea are strengthened by spirals. For this reason, they can not be pressed together during respiration; they are, however, still elastic similar to the tube of a vacuum cleaner. The trachea consist of the same substance as the exoskeleton of insects: they actually consist on Chitin.

b): The spiracles (or stigmas) are closable. In this way, the gas transport can be regulated (see also pp 326, 7-A-6-1).
7.6.2.2 Respiration of Butterflies

Butterflies constitute an insect family of more than 180,000 described species with 127 families and 46 subfamilies. After the bugs, butterflies are the second rich insect family of the World.

In a simple circular flow, the tubular heart pumps the blood (hemolymph) flowing around the organs through the body. The blood transforms nutrients through the body, but neither oxygen nor CO₂. The gas exchange takes place in the trachea (pp 325–327). The branched tube system of the trachea supplies all organs with oxygen. The oxygen is pumped by means of side-openings (spiracles or stigmas, pp 326, 327) into the body. The maximum transport path of this respiratory system is limited. The reason for this limitation lies in the fact that the grow potential and the size of butterflies and insects are generally small.

![Orange-tip Butterfly](image1)
![Peacock Butterfly](image2)

Butterflies in Art

A Butterfly in Love

*She was a flower, cute and fine,*  
Blooming in the bright sunshine.  
*He was a proud, young butterfly,*  
Devoted hanging on the flower, high.

*Oft a bee came round to visit*  
And zoomed around the flower a bit.  
*Oft a beetle crawled up and down*  
On the flower's blooming crown.

*Oh God, how this pained the butterfly*  
His hurt then almost made him cry.

*But what really horrified him most,*  
And was the worst, and then came last.  
*An old ass ate the whole plant*  
He loved the most in all the land.

*Wilhelm Busch (1832 – 1908)*  
*(Poem and Drawing from 1895)*

*The Butterfly Hunter*  
*Carl Spitzweg (1808 – 1885)*  
*(Drawing from 1840)*
### 7.6.2.3 Ants: Breathing – Anthill and its Ventilation – Wedding flight

Ants are a family within the order of hymenopterous insects. The number of ant species is about 12,000, where about 200 species are living in Europe. The Figure shows the three parts of the insect: the head, the breast (thorax) and the abdomen (s. p. 324).

All known ants are organized into colonies. Ant colonies contain up to several millions individuals. In an anthill, always three castes are living: Workers (females), female ants (including the queen) and male ants. The worker ants are wingless. Only the mature females and the males have wings and are able to fly.

If air is flowing over the hill, the (CO₂-rich) stale (used) air produced by the millions of ants is blown out by convection through the «chimeneys»; at the same time, oxygen-rich air is flowing into the hill by convection (see Figure). In this way, the ants are able to survive in their hills.

At a particular time, all sexual animals belonging to a species swarme out of their colonies for the wedding flight. In this way, inbreading can be avoided. By emission of pheromones, the two opposite sexes attract each other.

The young queen is mated by 2 to 40 males and receives several millions of spermatozoa with which she fertilizes the eggs. Some hours after the wedding flight, the males are dying. They are then transported by the workers into the hill where they serve as nutrient.

### 7.6.2.4 Termites: Properties and Respiration

Termites are mixing sand grains, soil and pieces of wood with a secretion to forme clumps from which they construct huge hills! These hills can be higher than 8 meters.

The millions of termites living in such a fortress must be able to breathe. They need about 250 L of oxygen or more than 1’000 L fresh air per day. The exterior wall has a rib-like structure with ventilation pipes extending from the «floor» to the «basement». The warm air rising in the hill escapes in the floor and then slowly descends down through the tubes. During this flow, the air in the nest takes up oxygen from the exterior and simultaneously emits CO₂. The regenerated air accumulated in the «basement» starts for a new journey through the nest (circulation by external lungs).
Aquatic insects need oxygen too! They are equipped with a variety of adaptations that allow them to carry a supply of oxygen with them under water (i.e. by cuticular respiration) or to acquire it directly from the environment. In the following some adaptations are discussed and we illustrate how insects use them to obtain oxygen and maintain an aquatic lifestyle.

**Biological gills**

A biological gill is an organ that allows dissolved oxygen from the water to pass into the organism’s body. In mayflies the gills are leaf-like in shape. Fanning movement of the gills keep them in contact with an instant supply of fresh water.

**Breathing tubes**

Although many aquatic insects live underwater, they get air from the surface through hollow breathing tubes. In mosquitoes larvae for example, this ‘siphon’-tube is an extension of the posterior spiracles.

**Dissolved oxygen**

Water contains usually a significant amount of dissolved oxygen (DO). Icy cold water (0°C) can hold as much as 14.60 mg/kg oxygen (s. p. 6-A-3-1). With increasing temperature, the oxygen concentration in water decreases. In fresh and cold water, insects can usually rely on gills. In warm water, however, insects may need air bubbles or breathing tubes.

<table>
<thead>
<tr>
<th>Temperature (Celsius)</th>
<th>Oxygen concentration (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14.60</td>
</tr>
<tr>
<td>10</td>
<td>11.27</td>
</tr>
<tr>
<td>20</td>
<td>9.07</td>
</tr>
<tr>
<td>30</td>
<td>7.54</td>
</tr>
</tbody>
</table>

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**Respiration of Aquatic Insects - 2**

**Air Bubbles**

Some aquatic insects (diving beetles), for example, carry a bubble of air with them whenever they dive beneath the water surface. The bubble usually covers one or more spiracles so the insect can ‘breath’ air from the bubble while submerged in water. The picture shows a predacious diving beetle in water. The blue part at the back is the portion of the air bubble the beetle carries with it underwater that it exposes to the water. This allows the beetle to use the bubble as a physical gill.

**Larvae of midges (Bloodworms)**

Hemoglobin is a respiratory pigment that facilitates the capture of oxygen molecules. It is an essential component of all human red blood cells, but it occurs only rarely in insects – most notably in the larvae of certain midges known as bloodworms. These red ‘worms’ usually live in muddy depths of ponds or streams where dissolved oxygen may be in short supply. Under normal conditions, hemoglobin molecules in the blood bind and hold a reserve supply of oxygen. If conditions become anaerobic, the oxygen is slowly released for respiration.
Appendix: Chapter 7

Systemic and Pulmonary Blood Circulation System

The main structures of the cardiovascular system are the heart, arteries, capillaries and veins. The function of the heart is to pump blood through the arteries to the organs of the body. The arteries branch out into a network of capillaries that carry blood with nutrients to the cells and remove their waste products. The capillaries merge to form the veins that circulate the blood back to the heart.

The pulmonary artery carries blood from the heart to the lungs. The function of the lungs is to exchange gases. The carbon dioxide ($CO_2$) produced from carbohydrates, ($C_m(H_2O)_n$), and fat metabolism is carried out in the bloodstream to the lungs where it is released to the atmosphere, and oxygen from the air is absorbed and stored in the hemoglobin of the red blood cells.

The aorta, which is the largest artery in the body, branches from the heart into the mesenteric (Eingeweide) and renal arteries that carry blood to the intestines (Därme) and the kidneys, respectively. The blood in the capillaries of the intestines absorbs carbohydrates, proteins, and fats from the foods processed by the digestive system. Blood from the intestines goes to the liver via the hepatic portal vein (Leberportader). The liver removes toxins from the blood. In the liver, the ammonia produced from protein metabolisms is combined with $CO_2$ to create urea. The blood from the liver flows back to the heart via the hepatic vein (Lebervene) and the interior vena cava (Hohlvene). The kidneys remove nitrogen waste products from the blood. Uric acid from nucleic acid metabolism and urea from protein metabolism are filtered out by the kidneys and extracted in the urine. Blood from the kidneys goes through the renal vein, then to the inferior vena cava, and finally recirculates back to the heart.

Note:
The coronary arteries are the blood vessels that deliver oxygen-rich blood from the heart to the tissues of the body (see p. 278).

On the other hand, the pulmonary arteries carry oxygen-poor blood from the heart to the lungs under low pressure, making these arteries unique (see p. 278).
Prenatal and postnatal respiration system

During birth, two events are responsible for the functional adaptation to postnatal live:

- Interruption of the placentary circulation
- Unfolding the lungs with the first breath

![Diagram of respiration system before and after birth]

The pulmonary respiration of mammals and humans is discussed on pp 278 - 280.

Perfusing its body by breathing independently instead of utilizing placental oxygen is the first challenge of a newborn. At birth, the baby's lung are filled with lung liquid. When the newborn is expelled from the burth canal, its central nervous system reacts to the sudden change in temperature and environment. This triggers it to take the first breath, within about 10 seconds after delivery.

With the first breaths, there is a fall in pulmonary vascular resistance, and an increase in the surface area available for gas exchange. Over the next 30 seconds, the pulmonary blood flow increases and is oxygenated as it flows through the alveoli of the lungs. Oxygenated blood now reaches the left atrium and ventricle, and through the descending aorta reaches the umbilical arteries. Oxygenated blood now stimulates constriction of the umbilical arteries resulting in a reduction in placental blood flow.

As the pulmonary circulation increases there is an equivalent reduction in the placental blood flow which normally ceases completely after about 3 minutes. These two changes result in a rapid redirection of blood flow into the pulmonary vascular bed, from approximately 4% to 100% of cardiac output. The increase in pulmonary venous return results in left atrial pressure being slightly higher than right atrial pressure, which closes the foramen ovale.

The flow pattern changes results in a drop in blood flow across the «ductus arteriosus» and the higher blood oxygen content of blood within the aorta stimulates the construction and ultimately the closure of this fetal circulatory shunt.

[In the developing fetus, the «ductus arteriosus» is a blood vessel connecting the pulmonary artery to the aorta. The «ductus venosus» is the fetal shunt between the left hepatic portal vein and the inferior caval vein (s. Ref. 7-A-1-3 b)].

From the fetal circulation to the first breath
Breathing in and breathing out of Humans

**The mechanism of breathing:** Air moves in and out of the lungs in response to differences in pressure. When the air pressure within the alveolar spaces falls below atmospheric pressure, air enters the lungs (inspiration), provided the larynx (Kehlkopf) is open; when the air pressure within the alveoli exceeds atmospheric pressure, air is blown from the lungs (expiration). The flow of air is rapid or slow in proportion to the magnitude of the pressure difference. Because atmospheric pressure remains relatively constant, flow is determined by how much above or below atmospheric pressure the internal pressure within the lungs rises or falls.

Breathing in modern airtight homes

We have discussed breathing of humans at pp 279, 280 and 7-A-1-4 (breathing in O₂ and breathing out CO₂). In the following we are concerned with the potential problems and dangers associated with breathing during sleeping, in particular with the problem of sleeping in an airtight room with and without ventilation by fresh air.

Adult time spent in bedrooms can be at least 8 hours per day. Children may additionally use their bedroom as a den in which case they could spend almost all their home time. Breathing in an airtight room decreases the oxygen concentration and increases the CO₂ concentration. It is therefore essential that airtight rooms and bedrooms are properly ventilated by fresh air. Based on European CEN Standards 13779, ventilation for «medium» air quality should be at least 10 L/s per occupant (15 L/s for high indoor quality). This equates to a steady state metabolic CO₂ concentration of no more than 800 ppm (see p. 7-A-1-6). It is now known that poorly ventilated spaces create adverse symptoms. A night in an inadequately ventilated bedroom is likely to result in poor daytime health and, possibly, long term damage health.

Measurements of actual ventilation rates, based on CO₂ concentration, have consistently shown that bedroom ventilation rates are dangerously inadequate. The diagrams of p. 7-A-1-6 shows that a CO₂ concentration of 1'000 ppm is «Low performance» and that 2'000 ppm is «High performance». But it is not an untypical result in which the CO₂ concentration reaches a steady state rate of about 5'000 ppm [see diagrams at p. 7-A-1-6 a)]. This corresponds to an occupant ventilation rate of about 1 L/s.

At very high concentrations, CO₂ is a dangerous poison! Concentrations of 7 to 10% by volume (70'000 ppm to 100'000 ppm) may cause suffocation within a few minutes to an our, even in the presence of sufficient oxygen (see Chapter 5, p. 197).
Sleeping in a Bedroom with different ventilations

Experiment (no ventilation)

CO₂ concentrations can reach a steady state approaching 5000 ppm. This corresponds to an occupant ventilation rate of about 1 L/s. This is woefully inadequate but is typical of a bedroom with closed windows and doors. Such a low ventilation rate is simply not healthy but is probably quite common in the modern airtight home.

Theoretical model based on a simple differential equation.

Initial concentrations (at time t = 0): ≈ 21% oxygen (O₂); ≈ 79% nitrogen (N₂); ≈ 0.04% CO₂ = 400 ppm. The calculations have been performed on the basis of a simple differential equation [Reference 7-A-1-6 b)] with a room volume V of 21 m³ during a time of 8 hours. The CO₂ concentration curves have been evaluated for different outdoor air ventilation rates Q (Q = 10, 5, 1, 0.5 and 0 L/s). A more general model for including CO₂, O₂, and H₂O in breathing air of a sleeping room is discussed in the Reference of Appendix 7-A-1-7).

Sleeping in an absolutely airtight bedroom

The Publication of Markov (Reference 7-A-1-7) investigates the consequences of sleeping in airtight or in nearly airtight bedrooms. The present page contains a summary and an illustration worked out by P. Brüesch. I have confined the discussion to a completely airtight room.

Markov discussed the changes in the composition of air in an airtight bedroom with dimensions of 3.5 x 4.8 x 2.5 m³ = 42 m³ in which 4 persons are sleeping (the two parents with their 2 children) during a sleeping time of 9 hours.

Initial conditions: Atmospheric pressure = 94'000 Pa (corresponding to the atmospheric pressure at an altitude of 625 m), constant room temperature of 20 °C and relative air humidity of 30%.

Based on mass-conservation equations, the consumption rate of oxygen (O₂) and the generation rates of both, carbon dioxide (CO₂) and water vapor (H₂O) due to breathing are evaluated and analytical solutions are presented. For the case of a completely airtight room, the initial volume fractions are X₀(O₂) = 20.7884, X₀(CO₂) = 400, and X₀(H₂O) = 7'458 ppm (1 ppm = 1 part per million). After sleeping 9 hours, the final volume fractions are X₉₉(O₂) = 19.461, X₉₉(CO₂) = 9.922 and X₉₉(H₂O) = 16'927 ppm, respectively. Note that the CO₂ concentration in the bedroom has strongly increased, namely by a factor of almost 25 (l).

From the medical point of view, all the investigated examples are dangerous for the occupants’ health since almost in half the year during the night periods in their own bedrooms they would be exposed to indoor air with a very low quality. The present practical examples reveal the reason for the feeling of lowness and faintness experienced on the morning by the people sleeping in sealed spaces by the combined effects of reduced oxygen and, more importantly, by the drastic increased CO₂ concentration in the room air.

7-A-1-7
The O₂ content of Seawater close to the Sea surface is determined by the transition of O₂ from the air into water (by diffusion) as well as by the biological production of O₂ from CO₂ by means of the marine phytoplankton.

With increasing depth and the associated decrease of sunlight, the saturation of O₂ decreases in Seawater. In addition to respiration of O₂ by the zooplankton and by part of the bacterioplankton, the increased biological depletion of biomass also contributes to the decrease of the O₂ content.

The distribution of O₂ in the deep sea is not uniform: there exist so-called Oxygen Minimum Zones (OMZ's), zones at which oxygen saturation in the ocean is at its lowest level. In these OMZ's, anaerobic (*) ammonium oxidation and denitrification can take place (by means of anaerobic respiration of bacteria, molecular nitrogen (N₂) is generated which escapes into the air). OMZ's are often present in tropical regions. One example is the Arabian Sea where OMZ's are present in depths between 200 metres down to about 1'000 metres.

[(*): In anaerobic regions, life without oxygen is possible].

O₂-Depth profiles in Oceans

Remark: $1 \mu M = 10^{-6} \text{ mol/L}$

1 Mol O₂ = 32 g

$\rightarrow \ 250 \ \mu M \ O₂ = 250 \times 10^{-6} \times 32 \text{ g/L O}_2$

$= 8 \text{ mg/L O}_2$

7-A-5-1

Widespread deaths of Fish in oxygen-poor waters

For living, fish need oxygen. In uncontaminated waters, there is sufficient dissolved oxygen (p. 7-A-5-1); in this case, fish have sufficient oxygen for gill breathing.

But if the discharge of nutrients into the sea is too large, the oxygen content is strongly reduced (< 4 mg/L, s. p. 314, left-hand Figure), and the fish are suffocating; in everyday language, this is referred to as the "dying of waters".

In stagnant waters or in slowly running waters, nutrients are continuously introduced, for example phosphates and silicates. If the growing season sets in, more algae are growing as previously. For energy generation, they use photosynthesis to produce oxygen. During night, however, they partly use up the oxygen and it can happen that so much oxygen is used up that the algae themselves are dying back; this is the case if the waters are completely deoxygenated.

In oxygen-poor waters, fish can try to swim just below the surface of the water, thereby benefiting that in this layer atmospheric oxygen is still dissolved. If, however, the oxygen concentration is reduced too much this does not help either. The fish are dying by suffocation and are floating at the surface of the water.

Dead fish are bordering the cost of Salton Sea in California.

7-A-5-2

7 - 38
Breathing of Insects

Tracheal Systems

Insect respiration is independent of its circulatory system. Therefore, the blood does not play a direct role in oxygen transport. Insects have a highly specialized type of respiratory system called the tracheal system, which consists of a network of small tubes that carries oxygen to the entire body. The tracheid system is the most direct and efficient respiratory system in active animals. The tubes in the tracheal system are made of a polymeric material called chitin.

Insect bodies have openings, called spiracles along the thorax and abdomen. These openings connect to the tubular network, allowing oxygen to pass into the body (Figure) and regulating the diffusion of CO₂ and water vapor. Air enters and leaves the tracheal system through the spiracles. Some insects can ventilate the tracheal system with body movements.

When air reaches the tracheole, oxygen dissolves into the tracheal liquid. Through simple diffusion, oxygen then moves to the living cells and carbon dioxide enters the tracheal tube. Carbon dioxide, a metabolic waste, exits the body through the spiracles.

7.6.2.5 Aquatic Insect: Hyphydrus ovatus - Beetle

For certain water insects, adaptations have been developed, which allow breathing under water. Many water-scavenger beetles have body regions with special surfaces which are covered by an air bubble (physical gills).

The hyphydrus ovalus (Kugelschwimmkäfer) shown below has a length of about 5mm. This aquatic insect is relatively common in stagnant and sometimes also in running water.

The beetle is swimming rather rapidly in open water or if it is not swimming, it is sitting on a water plant.

As many other diving beetles, it gets fresh water from the surface of the air, whereby most often an air bubble at the back of the abdomen is present. The air in the bubble creates a strong buoyancy; only if the beetle is swimming it does not ascend to the water surface. For this reason, it often clings to a water plant or to an algae.

If it is filling his air bubble upside down, it keeps his legs close to its body. Viewed from above the water surface, it than looks indeed as a sphere.

Water-scavenger beetle - Hyphydrus ovatus (Kugelschwimm-Käfer) with an air bubble at the back of the abdomen.
Aquatic Insects: Backswimmers

Backswimmers are a family of aquatic insects in the suborder of bugs. Their name is due to their preference to swim on their backs and view the world upside down. This is due to the fact that below their abdominal hair they have stored an air supply which shifts their centre of gravity towards the back. The middle- and forelegs support the animal by the surface tension of water; note that the animal is lighter than water because of their air supply.

Depending upon the season, backswimmers range from about 8 to 18 mm. The animals are not only good swimmers but they also have wings and take flight which they often do in the late summer and fall to mate and populate new bodies of water.

A clear inspection of the tapered end of a backswimmer reveals tufts (Büschel) of fine body hairs. These hairs are used to penetrate the water surface to breath and gather the bubble of air these insects need to survive. They trap a bubble of air, called plastron along their bodies and under their wings, allowing them to survive beneath the surface. The backswimmer absorbs the air through spiracle pores along their bodies directly into their body tissue. This air bubble can be replenished to a degree by fanning their legs to diffuse oxygen dissolved in the surrounding water. Water temperature and the backswimmer’s activity level dictates the dive times. Eventually, they must return to the surface to replenish their air supplies.

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j) http://www.chemedgeda.de/login/vui/vsc.de/ch;8/bc/vui/stoffwechsel/energiegewinnung/vui/Page/
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  Figure from: http://www.scientificpsychic.com/blogentries/the-circulatory-system.html
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  - Venous blood moves through veins of the circulatory system. Veins take blood into the heart from the body organs. Usually, it is dark maroon in colour because of the deoxygenated blood. However, the pulmonary veins carry oxygen rich blood from the lungs to the heart (s. Figure 278).
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R.7.1.9 p. 286: The lungs of a dog

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(Translated from German to English by P. Brüesch)

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R.7-5

### 7.2 Respiration of Amphibians

R.7.2.1 p. 288: Respiration of Amphibians - General


The young amphibians generally undergo metamorphosis from larva with gills to an adult air-breathing form with lungs. Amphibians use their skin as a secondary respiration surface and some small terrestrial salamanders and frogs lack lungs and rely entirely on skin.


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R.7-6
### 7.3 Reptiles

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**p. 292: Reptiles: some Examples**

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**p. 293: Reptiles: General Properties**

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R.7.13
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R.7.14
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