Yuriy Posudin

PHYSICS WITH FUNDAMENTALS OF BIOPHYSICS

Second Edition

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PHYSICS WITH FUNDAMENTALS OF BIOPHYSICS

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Затверджено
Міністерством освіти і науки України
як підручник для студентів вищих навчальних закладів

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Підручник “Physics with Fundamentals of Biophysics” (“Фізика з основами біофізики”), виданий англійською мовою, призначений саме для підготовки студентів, що слухають лекції англійською мовою в навчальних закладах III-IV рівнів акредитації України; він може бути корисним для іноземних студентів та аспірантів, перекладачів та всіх, хто цікавиться англомовною термінологією в галузі фізики та біофізики

Основна мета підручника - навести основні положення, закони та теорії з курсу загальної фізики; розглянути фізичні процеси та механізми, що складають основу життєдіяльності живих організмів – рослин, тварин, мікроорганізмів; викласти проблеми впливу зовнішніх фізичних факторів на живі організми та їх здатності реагувати на ці фактори; висвітлити принципи дії та можливі застосування сучасних фізичних методів та приладів у сільськогосподарській, біологічній, екологічній та медичній практиці.

Підручник містить приклади розв’язання практичних біофізичних проблем, контрольні завдання для перевірки засвоєння матеріалу студентами та запитання, відповіді на які студенти зможуть дати у разі ознайомлення із відповідними розділами підручника. Для оцінки знань студентів пропонується рейтингова система. Кожний змістовний модуль має словник фізичних та біофізичних термінів. Інформативний матеріал представлений у додатку.

POSUDIN Yuriy. Physics with Fundamentals of Biophysics.- Kyiv, Printline, 2d edition, 2014.- P.209

The text-book “Physics with Fundamentals of Biophysics” published in English is intended for the students who attend the English-speaking lectures in educational institutions of Ukraine; it can be useful for the foreign students and post-graduate students, translators and everybody who is interested in English terminology in the field of physics and biophysics.

The main objectives of the course “Physics with Fundamentals of Biophysics” is to expose principal laws and theses of physics which make it possible to study general regularities of natural phenomena; to apply the principles and methods of the physical sciences to biological problems; to consider the biophysical problems which are concerned with the viability of living objects (plants, animals, microorganisms) and their interaction with the environment; to elucidate possible application of physical instrumentation to agricultural, biological, ecological, and medical practice.

The text-book is supplied with the examples of solutions of practical biophysical problems, control questions pertaining to those problems that require clarification. Rating system of estimation of students´ level of knowledge is offered also. Each text modulus contains the vocabulary of physical and biophysical terms. The informative material is given in appendix.

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"The beauty of physics lies in the simplicity of the fundamental physical theories and in the manner in which just a small number of fundamental concepts, equations, and assumptions can alter and expand our view of the world around us".

R. A. Serway

"Biophysics includes everything that is interesting and excludes everything that is not".

K.S. Cole

ПЕРЕДМОВА

З ініціативи ректора Національного університету біоресурсів і природокористування України академіка Д.О. Мельничука, яка знайшла підтримку в Міністерстві освіти і науки України, з вересня 2003 р. упроваджено читання лекцій англійською мовою для студентів-першокурсників. Ця пропозиція сприятиме подальшому удосконаленню вищої освіти, її інтернаціоналізації та взаємовизнанню у рамках фундаментальних принципів, сформульованих в університетській хартії “Magna Charta Universitatum”, прийнятій в Болоньї у 1988 році. Володіння іноземною мовою та спеціальною термінологією дозволить студентам активно спілкуватися з іноземними колегами, більш глибоко ознайомитися з зарубіжною літературою, брати активну участь у стажуваннях за кордоном, відвідувати міжнародні конференції, симпозіуми та семінари.

Підручник “*Physics with Fundamentals of Biophysics*” (“Фізика з основами біофізики”), виданий англійською мовою, призначений саме для підготовки студентів, що слухають лекції англійською мовою в аграрних навчальних закладах III-IV рівнів акредитації; він може бути корисним для іноземних студентів та аспірантів, перекладачів та всіх, хто цікавиться англомовною термінологією в галузі фізики та біофізики. Автор – професор кафедри фізики Національного університету біоресурсів і природокористування України Ю.І. Посудін читав лекції у 1996 році як фулбрайтівський стипендіат в Університеті Джорджіа, США.

Основна мета підручника – навести основні положення, закони та теорії з курсу загальної фізики; розглянути фізичні процеси та механізми, що складають основу життєдіяльності живих організмів – рослин, тварин, мікроорганізмів; викласти проблеми впливу зовнішніх фізичних факторів на живі організми та їх здатності реагувати на ці фактори; висвітлити принципи дії та можливі застосування сучасних фізичних методів та приладів у сільськогосподарській, біологічній, екологічній та медичній практиці. Підручник містить приклади розв’язання практичних біофізичних проблем. Кожний змістовний модуль має словник фізичних та біофізичних термінів. Інформативний матеріал представлений у додатку. Автор з задоволенням висловлює свою щиру вдячність професору Стенлі Д. Кейзу (Університет штата Джорджіа, США) за редагування, критичні зауваження та обговорення підручника.

PREFACE

An initiative by the Rector of the National University of Life and Environmental Sciences of Ukraine, academician Dmytro Melnichuk, to implement the delivery of lectures for first-year students in English, beginning in September of 2003, was supported by the Ministry of Higher Education of the Ukraine. The initiative facilitates the improvement of higher education and its internationalization and mutual understanding in keeping with the fundamental principles of the "Magna Charta Universitatum", accepted in Bologna in 1988. The ability to know foreign languages and special terminology will make it possible for students to better understand modern literature, take a more active role in scientific missions abroad, and enhance attendance at international conferences, symposiums, seminars, etc.

The textbook "*Physics with Fundamentals of Biophysics*" published in English is intended for students who attend the English-speaking lectures at agricultural educational institutions with a III-IV level of accreditation; it is also valuable to foreign and post-graduate students, translators and anyone interested in English terminology in the field of physics and biophysics. The author of the textbook, Professor Yuriy Posudin, National University of Life and Environmental Sciences of Ukraine, delivered a series of lectures as a Fulbright scholar in the USA in 1996.

The main objectives of the course "Physics with Fundamentals of Biophysics" is to expose readers to the principal laws and theses of physics which make it possible to study general regularities of natural phenomena; to apply the principles and methods of the physical sciences to biological problems; to consider biophysical problems which are concerned with the viability of living objects (plants, animals, microorganisms) and their interaction with the environment; and to elucidate possible applications of physical instruments to agricultural, biological, ecological and medical uses. The textbook contains examples of solutions to practical biophysical problems. Each text modulus contains a Ukrainian/English vocabulary of physical and biophysical terms. Additional informative material is provided in the appendix.

The author would like to express his very grateful thanks to Professor Stanley J. Kays (The University of Georgia, USA) who has reviewed, commented and edited the final draft of this book.

Chapter 1. WHAT THIS BOOK IS ABOUT

1.1. PHYSICS AND BIOPHYSICS

Physics is a fundamental science which deals with the most elementary and common principles governing natural phenomena [22]. Physics consists of the following subdivisions:

1. Mechanics – deals with the motion of material objects and the interaction of these objects;

2. Thermodynamics – deals with the basic properties of macroscopic physical systems at a state of thermodynamic equilibrium and the transfer processes among systems;

3. Electricity – the study of phenomena associated with stationary or moving electric charges;

4. Magnetism – the study of phenomena associated with magnets and with moving electric charges, both of which produce magnetic fields in the space surrounding them;

5. Optics – the study of the nature of optical radiation, its propagation and phenomena that are observed during the interaction of light with matter;

5. Atomic and Nuclear Physics – deals with the structure and properties of atoms, nucleuses, and elementary processes at the atomic and nuclear level.

Biophysics – deals with physical phenomena in biological objects and investigates fundamental processes which form the basis of living nature. Biophysics is concerned with the application of the principles and methods of the physical sciences to biological question [6,10, 15, 19, 25]. Biophysics is closely related to the environmental sciences [4,7,8].

1.2. OBJECTIVES OF THE COURSE

The *main objectives* of the course “Physics and the Fundamentals of Biophysics” are to: expose the students to the principles and laws of physics which make it possible to study general regularities of natural phenomena; apply the principles and methods of the physical sciences to biological phenomena; consider biophysical problems associated with viability in living objects (plants, animals, microorganisms) and their interaction with the environment; and identify instrumentation utilized in physics for possible applications in agricultural, biological, ecological, and medical uses.

The main requirements to the student after studying by him the course “Physics with Fundamentals of Biophysics” are the following:

The student must know

the main physical quantities and units, principal laws and theses of general physics, theory and practice of measurement errors;

general physical processes and phenomena which take place in the living organism;

the effects of external physical factors on plants, animals, microorganisms and their interaction with the environment;

possibility of the application of physical instrumentation to future practice.

The student must be able

to process experimental data and estimate measurement errors;

to explain physical principles and mechanisms of function of living organism;

to use modern physical methods and devices in future practice.

Interdisciplinary Links

The course “Physics with Fundamentals of Biophysics is related with those disciplines that precede this course such as Inorganic Chemistry (atomic and molecular weight, the electronic structure of atoms, water and solutions), Mathematics (scalar and vector analysis, differential equations), Informatics and Computer Engineering (search for information in the Internet).

The disciplines, that use the materials of this course, are Animal (or Plant) Physiology (mechanisms of reception, adaptation of living organisms to extreme temperatures, physiological optics), Radiobiology (biological response to ionizing radiation, dosimetry), Physical and Colloid Chemistry (enthalpy, thermodynamic potentials, chemical potential, Nernst equation), Agricultural Meteorology (weather and climatic environmental factors).

Chapter 2. ANALYSIS OF OBSERVED DATA

2.1. APPROXIMATION OF DATA

2.1.1. Rules for Dealing with Significant Numbers

If a student measures the area (S) of square with a ruler and one edge (*a*) of the square is 205 ± 1 mm, only the first two digits (i.e., 20) are significant. The final digit is doubtful – it can be in between either 6 or 4. The calculation of the area of the square gives:

$$S = a^2 = 205^2 = 42025 \text{ mm}^2.$$

The actual area is between 206^2 = 42436 mm^2 and 204^2 = 41616 mm^2. Here only the first digit (4) is significant and the other digits are doubtful. This example demonstrates that the precision of the final result depends only on the precision of measurements; it is not possible to increase the precision of the answer by increasing the precision of calculations. In such a way, the precision of a result is determined by the number of significant figures used to express the number. The principal rules for dealing with significant numbers are as follows.

1. *The most significant number* is always the left-most nonzero digit, regardless of where the decimal point is found.

e.g., 253 0.0215

2. *The least significant number* is the right-most nonzero digit if there is no decimal point.

e.g., 4537 5300

3. *The least significant number* is the right-most digit, whether zero or not, if there is a decimal point.

e.g., 21.34 1.340

All digits between the least and most significant digits are counted as significant numbers.

e.g., *Three significant numbers*: 245; 24500; 24.5; 2.45; 0.245; 0.0245; 0.00245.

Four significant numbers: 11.35; 5608; 0.05638; 2.590; $8.342 \cdot 10^4$.

2.1.2. The Precision of the Measurement during Multiplication or Division

Rule: *The result of multiplication or division should have as many significant numbers as the least precise of its factors.*

e.g.,

$$\begin{array}{r} 13.56 \\ \times 4.56 \\ 61.8336 \approx 61.8 \end{array} \qquad \begin{array}{r} 2.1315 \\ \times 0.0114 \\ 0.029841 \approx 0.0298 \end{array}$$

2.1.3. The Precision of the Measurement during Addition or Subtraction

Rule: *The result of addition or subtraction should not have significant numbers in the least digit orders which are absent in at least in one of summand*

e.g.,

$$\begin{array}{r} 16.28 \\ +\ 0.514 \\ +\ 42.6 \\ 59.394 \approx 59.4 \end{array} \qquad \begin{array}{r} 5.32 \\ -\ 1.2 \\ 4.12 \approx 4.1 \end{array}$$

2.1.4. The Precision of the Measurement during Raising to a Power or Extracting a Root

Rule: *The result of raising to a power or extracting a root should have as many significant numbers as in the initial digit which is measured.*

e.g., $3.2^3 = 10.24 \approx 10$ $\qquad \sqrt{25} = 5.0$

2.2. THEORY OF ERRORS

2.2.1. Types of Errors

If the measurements are physically derived using measuring tools, they are referred to as *direct*; if derived using a formula, they are *indirect.* For example, determining the length of an object with a metric ruler is a direct measurement, while determining the moment of inertia using the formula $I = mr^2$, is an indirect measurement.

The measured value for a quantity always differs from the true value for the quantity. The reasons for the difference are *instrumental measurement errors* (due to the imperfection of the measuring instrument) and *personal errors* (due to measuring errors by the individual). Another method for classifying errors is based on their properties. An error is *systematic* if it is constant over several measurements or *random* if it changes during the measurements. The following definitions more precisely describe these terms.

Error – the difference between the determined value of a physical quantity and the true value.

The foregoing classification of measurement errors is based on the cause of the errors.

Systematic errors are caused by the imperfection of measuring methods and inaccuracy of instruments. These errors remain constant or change in a regular fashion in repeated measurements of one and the same quantity.

Random errors mean the individual errors that are given rise to the person performing the measurements; they include errors owing to incorrect reading of the tenth graduation of an instrument scale, small changes of the measurement conditions, asymmetric placement of the indicator mark etc. These errors are changing in an irregular fashion in repeated measurements of one and the same quantity.

2.2.2. Errors in Direct Measurements

Let x_1, x_2, x_3,… x_n denote the raw data derived from experimental observations. *The arithmetic mean* ($<x>$) is the sum of observations divided by the number (n) of observations:

$$<x> = \frac{x_1 + x_2 + x_3 + ... + x_n}{n} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (2.1)$$

The difference between a data point and the mean is referred to as a *deviation* (δ_i):

$$\delta_i = x_i - <x> \qquad (2.2)$$

Dispersion or *variance* (σ^2) is defined as the sum of the squared deviations divided by n – 1:

$$\sigma^2 = \frac{\sum_{i=1}^{n} \delta_i^2}{n-1} \qquad (2.3)$$

Sample standard deviation (σ) is defined as the square root of the dispersion by the following formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} \delta_i^2}{n-1}} \qquad (2.4)$$

Confidence interval is the difference between the largest and smallest observations in a sample.

Confidence interval of systematic error (Δ_c) is the smallest division of the measuring instrument.

Confidence interval of random error ($\overset{o}{\Delta}$) is defined by the following formula:

$$\overset{o}{\Delta} = t\sqrt{\frac{\sum_{i=1}^{n} \delta_i^2}{n(n-1)}} \qquad (2.5)$$

The Student's coefficient (t) is a criterion of reliability of results and is determined from Table 2.1 using the number (n) of observations and confidence probability (P) desired.

Confidence interval of total error Δ is:

$$\Delta = \overset{o}{\Delta} + \Delta_c \qquad (2.6)$$

Relative error (ε) is the confidence interval of the total error as a percentage of the mean:

$$\varepsilon = \frac{\Delta}{\langle x \rangle} 100\% \qquad (2.7)$$

2.1. The Student's coefficient

N	***P* = 0.90**	***P* = 0.95**	***P* = 0.98**	***P* = 0.99**	***P* = 0.999**
3	2.92	4.30	6.97	9.93	31.60
4	2.35	3.18	4.54	5.84	12.94
5	2.13	2.78	3.75	4.60	8.61
6	2.02	2.57	3.37	4.03	6.86
7	1.94	2.45	3.14	3.71	5.96
8	1.90	2.37	3.00	3.50	5.41
9	1.86	2.31	2.90	3.36	5.04
10	1.83	2.26	2.82	3.25	4.78
11	1.81	2.23	2.76	3.17	4.59
12	1.80	2.20	2.72	3.11	4.44
13	1.78	2.18	2.68	3.06	4.32
14	1.77	2.16	2.65	3.01	4.22
15	1.76	2.15	2.62	2.98	4.14
20	1.73	2.09	2.54	2.86	3.88
∞	1.64	1.96	2.33	2.58	3.29

2.2.3. Errors in Indirect Measurements

Suppose the volume (V) of cylinder has been determined by the following formula:

$$V = \pi \frac{D^2}{4} h \qquad (2.8)$$

where D is the diameter and h the height of cylinder.

The logarithm of the previous formula (2.8) is:

$$\ln V = \ln \pi + 2\ln D - \ln 4 + \ln h \qquad (2.9)$$

The differentiation of expression (2.9) leads to the following:

$$d\ln V = d\ln \pi + 2d\ln D - d\ln 4 + d\ln h \qquad (2.10)$$

Take into account that $d\ln x = \dfrac{dx}{x}$:

$$\frac{dV}{V} + \frac{d\pi}{\pi} + 2\frac{dD}{D} - \frac{d4}{4} + \frac{dh}{h} \qquad (2.11)$$

The differentials are substituted by the confidence intervals with a "+" sign and the symbols of the values by their means (where $\frac{d4}{4} = 0$):

$$\frac{\Delta V}{V} = \frac{\Delta\pi}{\pi} + 2\frac{\Delta D}{D} + \frac{\Delta h}{h} \qquad (2.12)$$

or

$$\varepsilon_V = \varepsilon_\pi + 2\varepsilon_D + \varepsilon_h \qquad (2.13)$$

The error of a tabular value is determined as one half of the last significant summand. For example, error ($\Delta\pi$) of tabular value $\pi = 3.14$ is $\Delta\pi = 0.005$; while the error of tabular value $\pi = 3.141$ is $\Delta\pi = 0.0005$ etc.

Errors of direct measurements ΔD and Δh are determined according to section 2.2.2.

The confidence interval of the total error (Δ) is:

$$\Delta_V = \varepsilon_V \cdot \langle V \rangle \qquad (2.14)$$

and the arithmetic mean ($\langle V \rangle$) can be determine as follow:

$$\langle V \rangle = \pi\frac{\langle D\rangle^2}{4}\langle h\rangle \qquad (2.15)$$

VOCABULARY

English	Ukrainian		English	Ukrainian
Approximation	Округлення		Raising to a power	Піднесення в ступінь
Confidence	Довіра		Random error	Випадкова похибка
Confidence interval	Довірча границя		Relative error	Відносна похибка
Decimal point	Десяткова кома		Sample standard deviation	Середнє квадратичне відхилення
Deviation	Відхилення		Significant figure	Значуща цифра
Dispersion	Дисперсія		Subtraction	Віднімання
Division	Ділення		Systematic error	Систематична похибка
Error	Похибка		The arithmetic mean	Середнє значення
Extracting a root	Добування кореня		The left-most digit	Крайня ліва цифра
Multiplication	Множення		The right-most digit	Крайня права цифра
Probability	Вірогідність		Total error	Загальна похибка

Control Works
Modulus 1

ANALYSIS OF OBSERVED DATA

Problem. How many significant numbers are there for each of the following?

0.045; 24.25; 6583; 2.0; 0.00087; 9000

Problem. Multiply the following and indicate the significant numbers.

5.3456	254.7	6.43
× 0.0134	× 6.43	× 0.78
?	?	?

Problem. Add the following and indicate the significant numbers.

234.5	17.456	4.234
+ 34.794	+435.7	+ 3.17
+ 65.34	+15.05	?
+ 5.13	?	
?		

Problem. Subtract the following and indicate the significant numbers.

93.173	76.1643	486.3
–5.14	–5.032	–6.2349
?	?	?

Problem. Calculate the following and indicate the significant numbers.

$\pi(3.74)^2 = ?$ $(6.213 \cdot 10^{-4})^2 = ?$ $\sqrt{2.567} = ?$

Home Work 1. *For the Veterinary Medicine students:*
The systolic blood pressure *p* (mm Hg) of three students was measured 10 times giving the following data:

Variant	***p* (mm Hg)**		
1	73	84	91
2	72	66	80
3	87	88	90
4	94	104	117
5	100	99	95
6	78	64	69
7	85	95	112
8	87	92	101
9	101	114	107
10	95	81	84

Determine the: arithmetic mean; deviation; dispersion; sample standard deviation; confidence intervals of random, systematic and total errors; and relative error for the blood pressure measurements (confidence interval of systematic error $\Delta_c = 1$; confidence probability $P = 0.95$).

Utilize the rules of data approximation.

Home Work 2. *For the Plant Protection students*:
A student measured the stem elongation rate (l = mm · day^{-1}) of three plants for 10 days grown under the same conditions and obtained the following data.

Variant	***l* (mm · day^{-1})**		
1	64	81	68
2	69	73	78
3	64	75	70
4	66	71	54
5	56	78	68
6	92	79	74
7	75	68	73
8	74	77	69
9	69	62	79
10	61	68	70

Determine the: arithmetic mean; deviation; dispersion; sample standard deviation; confidence intervals of random, systematic and total errors; and relative error of the stem elongation measurements (confidence interval of systematic error (Δ_c) = 1; confidence probability (P) = 0.95).

Utilize the rules of data approximation.

Control Questions and Problems

1. What is the most significant number?
2. What is the least significant number?
3. What factors affect systematic error? random error?
4. What determines the Student's coefficient?
5. What are the types of errors?
6. Determine the difference between direct and indirect measurements.

Chapter 3. MECHANICS

Mechanics is the branch of physics which deals with the motion of material objects and their interaction.

3.1. KINEMATICS

Kinematics is a subdivision of mechanics which is concerned with the study of motion using the concepts of space and time, without regard to the cause of the motion.

3.1.1. Average Velocity

The *average velocity* ($<\upsilon>$) of a particle during the time interval Δt is defined as the ratio of its displacement ($\Delta \vec{r}$) to the time interval for this displacement:

$$<\vec{\upsilon}> = \frac{\Delta \vec{r}}{\Delta t} \qquad (3.1)$$

The unit of velocity measurement is *m/s*.

Example. A particle moving along the x axis is located at x_i (10 m) at t_i (1 s) and at x_f (6 m) at t_f (3 s). Find its displacement and the average velocity during this time interval.

Solution. The displacement is given by:

$$\Delta x = x_f - x_i = 6 \text{ m} - 10 \text{ m} = -4 \text{ m}$$

3.1.2. Instantaneous Velocity

The *instantaneous velocity* ($\vec{\upsilon}$) equals the limit of the average velocity, $\frac{\Delta\vec{r}}{\Delta t}$, as Δt approaches zero:

$$\vec{\upsilon} = \lim_{\Delta t \to 0} \frac{\Delta\vec{r}}{\Delta t} = \frac{d\vec{r}}{dt} . \qquad (3.2)$$

Example. The position of a particle moving along the x axis varies in time according to the expression $x = 4t^2$, where x is in m, and t is in s. Find the instantaneous velocity at any time.

Solution. We can compute the velocity at any time (t) by using the definition of the instantaneous velocity. If the initial coordinate of the particle at time t is $x_i = 4t^2$, then the coordinate at a later time ($t + \Delta t$) is:

$$x_f = 4(t + \Delta t)^2 = 4[t^2 + 2t\Delta t + (\Delta t)^2] = 4t^2 + 8t\Delta t + 4(\Delta t)^2$$

Therefore, the displacement in the time interval is:

$$\Delta x = x_f - x_i = 4t^2 + 8t\Delta t + 4(\Delta t)^2 - 4t^2 = 8t\Delta t + 4(\Delta t)^2$$

The average velocity in the time interval is:

$$\langle\upsilon\rangle = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i} = 8t + 4\Delta t$$

To find the instantaneous velocity, we take the limit of this expression as Δt approaches zero. In doing so, we see that the term 4Δt goes to zero, therefore:

$$\upsilon = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = 8t \ m/s$$

3.1.3. Average Acceleration

The *average acceleration* of a particle in the time interval $\Delta t = t_f - t_i$ is defined as the ratio $\Delta\vec{\upsilon}/\Delta t$, where $\Delta\upsilon = \upsilon_f - \upsilon_i$ is the *change* in velocity during the time interval:

$$\langle\vec{a}\rangle = \frac{\Delta\vec{\upsilon}}{\Delta t} = \frac{\upsilon_f - \upsilon_i}{t_f - t_i} \qquad (3.4)$$

3.1.4. InstantaneousAcceleration

It is useful therefore to define the *instantaneous acceleration (* $\vec{a}$ *)* as the limit of the average acceleration as *Δt* approaches zero:

$$\vec{a} = \lim_{\Delta t \to 0} \frac{\Delta \vec{\upsilon}}{\Delta t} = \frac{d\vec{\upsilon}}{dt} \qquad (3.5)$$

Animals Extremes!

Fastest land animal – the cheetah (*Acinonyx jubatus*) – 110 km/h;

Fastest birds in the sky – the peregrine falcon (*Falco peregrinus*) – 150 km/h and reaches diving speeds of up to 320 km/h; the spine-tailed swift (*Chaeturinae*) – 160 km/h;

Fastest bird on land – the ostrich (*Struthio camelus*) – 160 km/h;

Fastest fish – sailfish (*Istiophorus platypterus*) – 110 km/h;

Longest migration – the arctic tern (*Sterna paradisea*) – 3200–4000 km.

***Plant Extremes*!**

The tallest tree is the sequoia (*Sequoiadendron giganteum*) – the average height of mature trees is 76-84 m which have diameters of 5-7 m; the record is 95 m in height and 11 m in diameter.

3.2. DYNAMICS

Dynamics is study of the motion of an object in connection with the cause(s) of the motion.

3.2.1. Mechanical Properties of Biological Objects

Mass is a term used to measure inertial and gravitational properties of matter. The SI unit of mass is the *kilogram (kg)*.

Typical values for the mass of a cross-section of farm animals are presented in Table. 3.1.

3.1. Mass of Farm Animals

Farm Animal	Mass, kg
Bull	500-1400
Cow	350-500
Horse Fast horse Heavy-draught horse	 400-600 500-700
Hog	200-350
Sow	240 and more
Ram	100-130
Ewe	50-70
He-goat	90
She-goat	50
Hen For eggs For meat	 1.4-1.5 (22 weeks) 1.9-2.2 (22 weeks)
Turkey	4.5-7.5 (22 weeks)
Duck	2.7-2.9 (7 weeks)
Goose	4.5-5.0 (22 weeks)

Density is defined as mass per unit volume ($\rho = m/V$). The SI unit of density is kg/m^3.

Typical values for the density of a cross-section of different substances are presented in Table 3.2.

3.2. Density of various substances

Substance	Density, kg/m³	Temperature, °C
Air	1.293	0
Air	1.205	20
Air	1.128	40
Water	999.8	0
Water	1000.0	4
Water	999.7	10
Water	998.2	20
Water	995.6	30
Water	992.2	40
Milk	1028.5	20
Honey	1400 – 1450	20
Glycerol	1200	20
Castor Oil	900	20
Alcohol	790	20
Animal Blood	1052 – 1060	20
Lung	260	40
Vitrous Humor	1336	40
Cartilage	1100	40
Bone	1800 – 1900	40
Tooth	1950 – 2380	40
Wood	1500-	20
Balsa (*Ochromona lagopus*)	11 – 14	20
Olive (*Olea capensis*)	1490	20

Force can cause a change in velocity (acceleration) of an object and deform the object to some extent. The SI unit of force is $N = kg \cdot m/s^2$.

3.2.2. Newton's Laws

Newton's First Law: An object at rest will remain at rest and an object in motion will continue in motion with a constant velocity unless it experiences a net external force (or resultant force).

Newton's Second Law: The acceleration of an object is directly proportional to the resultant force acting on it and inversely proportional to its mass:

$$\sum \vec{F} = m\vec{a} \qquad (3.7)$$

where $\vec{F}$ is the resultant force, $\vec{a}$ is the acceleration.

Newton's Third Law: *If two bodies interact, the force exerted on body 1 by body 2 is equal to and opposite the force exerted on body 2 by body 1*

$$\vec{F}_{12} = \vec{F}_{21} \qquad (3.8)$$

3.2.3. Newton's Universal Law of Gravity

Newton's Law of Gravitation: *Every particle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.*

If the particles have masses m_1 and m_2 and are separated by a distance *r*, the magnitude of this gravitational force is:

$$F = G\frac{m_1 m_2}{r^2} \qquad (3.9)$$

where *G* is a universal constant called the *gravitational constant*, which has been measured experimentally. Its value in SI units is:

$$G = 6{,}672 \cdot 10^{-11}\frac{N \cdot m^2}{kg^2} \qquad (3.10)$$

3.2.4. Weight

The force exerted by the earth on a body is called the *weight* of the body ($\vec{P}$). A freely falling body experiences an acceleration ($\vec{g}$) acting toward the center of the earth. Applying Newton's second law to a free falling body, with $\vec{a} = \vec{g}$ and $\vec{F} = \vec{P}$, gives:

$$\vec{P} = m\vec{g} \qquad (3.11)$$

3.2.4. Elasticity – Hooke's Law

Deformation means the change of size, shape and mass distribution of an object under load conditions. Deformation is an important consideration in understanding the mechanics of materials and biomechanics of living organisms. *Elastic* means that when the deforming forces are removed, the object returns to its original shape.

Consider a body on a horizontal, smooth surface which is connected to a helical spring. If the spring is stretched or compressed a small distance from its equilibrium configuration, the spring will exert a force on the body given by *Hooke's Law*: *The force* (F) *required to stretch (compress) body is directly proportional to the extension* (x):

$$F = kx \tag{3.12}$$

where k is the stiffness constant (N/m); it is assumed that the stretching or compressing of the body occurs along the axis OX.

The force F per unit cross-sectional area S on an elastic body fixed at one end is called the *stress* (σ) which is equal to F/S and has units N/m^2.

The term *strain* refers to the relative change in dimensions or shape of a body through the application of external force. The *strain* (ε) is a measure of the degree of deformation; it is defined by the ratio x/l, where l is original length of the body (i.e., $\varepsilon = x/l$).

For sufficiently small stresses, the stress is proportional to the strain; the constant of proportionality depends on the material being deformed and on the nature of the deformation. This proportionality constant is called the *elastic modulus* or *Young's modulus* if it measures the resistance of a solid to change in its length:

$$Y = \frac{F/S}{x/l} = \frac{\sigma}{\varepsilon} \tag{3.13}$$

Hooke's law can be written as:

$$\sigma = E \cdot \varepsilon \tag{3.14}$$

The stress-strain curve is called the tensile diagram (fig. 3.1).

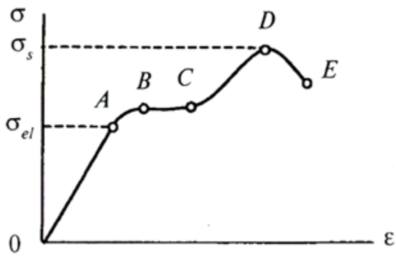


Fig. 3.1. **Tensile diagram: σ — stress; ε — strain;**
***A* — proportionality limit (σ_{el}) stress; *B* — elastic limit;**
***C* — fluidity limit; *D* — strength limit (σ_s); *E* — breaking point**

Typical values for Young’s modulus for a cross-section of biological substances are given in Table 3.3.

3.3. Typical values for Young’s modulus of biological substances

Substance	**Young’s modulus ($N \cdot м^{-2}$)**
Long Bone	$2 \cdot 10^{10}$
Collagen	10^{7}-10^{8}
Tendom	$2 \cdot 10^{7}$
Rib cartilage	$1.2 \cdot 10^{7}$
Resilin	$1.7 \cdot 10^{6}$
Elastin	$6 \cdot 10^{5}$
Bllod vessels	$2 \cdot 10^{5}$
Nonstriated muscle at excitation at rest	 10^{5} 10^{4}
Cell wall of alga *Nitella*	$7 \cdot 10^{8}$
Bamboo	$2 \cdot 10^{10}$
Wood	$(0.35\text{-}1.93) \cdot 10^{10}$

Example. A strip of tissue 6 cm long with a cross-sectional area (*S*) of 0.12 cm^2 has a Young’s modulus (*Y*) of approximately 10^5 $N \cdot m^{-2}$. What mass must be suspended from the strip hung vertically to cause a 0.6 cm elongation?

Solution. Force (*F*), which is applied to the tissue, can be defined as:

$$F = m \cdot g$$

The last equation can be written as:

$$\frac{m \cdot g}{S} = E \cdot \frac{\Delta l}{l}$$

The mass is:

$$m = \frac{E \cdot \Delta l \cdot S}{g \cdot l} = \frac{(10^5 \frac{\text{N}}{\text{m}^2}) \cdot (0.6 \cdot 10^{-2}\,\text{m}) \cdot (0.12 \cdot 10^{-4}\ \text{m}^2)}{(9.8 \frac{\text{m}}{\text{c}^2}) \cdot (6 \cdot 10^{-2}\,\text{m})} = 1.22 \cdot 10^{-2}\,\text{kg}.$$

3.2.5. Work and Energy

The *work* done by a constant force is defined as the product of the component of the force in the direction of the displacement and the magnitude of the displacement:

$$A = \vec{F} \cdot \vec{s} = (F\cos\theta)s \qquad (3.15)$$

where $F\cos\theta$ is the component of $\vec{F}$ in the direction of $\vec{s}$. Work is a scalar quantity and equation 3.15 is the scalar product of the two vectors $\vec{F}$ and $\vec{s}$.

The SI unit of work is the *joule (J = N·m).*

The product of one half the mass (*m*) and the square of the speed (*V*) is defined as the *kinetic energy* of a particle:

$$E_k = \frac{1}{2} mV^2 \qquad (3.16)$$

Potential energy is accumulated in a system as a result of previous work being done.

For instances, the *gravitational potential energy* near the Earth's surface is:

$$E_p = mgh \qquad (3.17)$$

where *m* is the mass of the particle and *h* the displacement.

The *elastic potential energy*, such as that stored in a spring, is:

$$E_p = \frac{1}{2}kx^2 \quad (3.18)$$

where k is the force constant of the spring and x the displacement.

Animal Extremes!

The largest animal is blue wale (*Belaenoptera musculus)* – 190 tons estimated weight.

The smallest bird is the bee hummingbird (*Trochilidae*) – 1.6 g.

3.3. CIRCULAR MOTION

3.3.1. Kinematics of Rotational Motion

If a particle of mass m is traveling in a circular path of radius r with a tangential velocity of υ, the *average angular velocity* ($<\omega>$) is the number of radians swept out by the radius in 1 second:

$$<\vec{\omega}> = \frac{\Delta\vec{\theta}}{\Delta t} \quad (3.19)$$

where $\Delta\theta = \theta_2 - \theta_1$ equals the *angular displacement.*

In analogy to linear velocity, the *instantaneous angular velocity* (ω) is defined as the limit of the ratio in equation 3.19 as Δt approaches zero, or:

$$\vec{\omega} = \lim_{\Delta t \to 0} \frac{\Delta\vec{\theta}}{\Delta t} = \frac{d\vec{\theta}}{dt}, \quad (3.20)$$

Angular velocity has units of *rad/s* or *1/s*, since radians are not dimensional.

The *averaged angular acceleration* ($<\beta>$) of a rotating body is defined as the ratio of the change in the angular velocity to the time interval (Δt):

$$<\vec{\beta}> = \frac{\Delta\vec{\omega}}{\Delta t} \quad (3.21)$$

In analogy to linear acceleration, the *instantaneous angular acceleration* ($\vec{\beta}$) is defined as the limit of the ratio $\frac{\Delta\vec{\omega}}{\Delta t}$ as Δt approaches zero:

$$\vec{\beta} = \lim_{\Delta t \to 0} \frac{\Delta\vec{\omega}}{\Delta t} = \frac{d\vec{\omega}}{dt} \qquad (3.22)$$

Angular acceleration has units of *rad/s*^{2} or *1/s*^{2}.

The tangential velocity (υ) of a point on a rotating rigid body equals the distance of that point from the axis multiplied by the angular velocity, or:

$$\upsilon = r\omega. \qquad (3.23)$$

3.3.2. Dynamics of Rotational Motion

A rigid body is a collection of small particles. If this body rotates about the fixed axis z with an angular velocity of ω, the *total kinetic energy* of the rotating rigid body is the sum of the kinetic energies of the individual particles:

$$E = \sum E_i = \sum \frac{1}{2} m_i V_i^2 = \frac{1}{2} \sum m_i r_i^2 \omega^2 = \frac{1}{2} \left(\sum m_i r_i^2 \right) \omega^2 \qquad (3.24)$$

The quantity in parentheses is called the *moment of inertia* (I):

$$I = \sum m_i r_i^2 \qquad (3.25)$$

Moment of inertia has units of kg·m^2.

The moments of inertia of homogenous rigid bodies with different geometry can be expressed as:

Solid sphere: $I_c = \frac{2}{5} MR^2$

Solid cylinder or disk: $I_c = \frac{1}{2} MR^2$

Long thin rod: $I_c = \frac{1}{12} ML^2$;

Hollow cylinder: $I_c = \frac{1}{2} M(R_1^2 + R_2^2)$

Using this notation, the kinetic energy of the rotating rigid body can be expressed as:

$$E = \frac{1}{2} I\omega^2 \qquad (3.26)$$

3.3.3. Torque

When a force is applied to a rigid body pivoting about an axis, the body will tend to rotate about this axis. The tendency of a force to rotate the body about the axis is measured by a quantity called the *torque (τ)*. Torque ($\vec{\tau}$) resulting from an applied force ($\vec{F}$) can be defined as:

$$\vec{\tau} = \left[\vec{r} \times \vec{F}\right] \qquad (3.27)$$

and the magnitude of the torque as:

$$\tau = rF\sin\theta \qquad (3.28)$$

The direction of $\vec{\tau}$ is that of the advance of a right-handed screw rotated in the direction θ, obtained by rotating $\vec{r}$ toward $\vec{F}$.

The applied force generally acts at an angle (θ) to the horizontal; the quantity $d = r\sin\theta$, called the *lever arm* of the force ($\vec{F}$), represents the perpendicular distance from the rotation axis to the line of action of $\vec{F}$ (fig. 3.2).

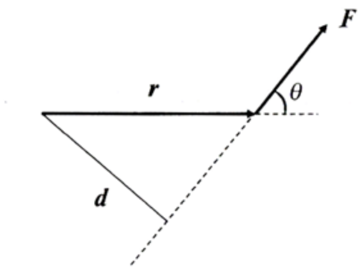


Fig. 3.2. **The torque is a vector $\vec{r} \times \vec{F}$ pointing out of the paper with magnitude** *rFsinq*; **the quantity** $d = r\sin\theta$,, **called the lever arm of the force $\vec{F}$ represents the perpendicular distance from the rotation axis to the line of action of $\vec{F}$**

If several forces act together, the sum of the torques about the same origin must be equal to zero for static equilibrium. The mathematical conditions for a state of static equilibrium are:

The sum of all forces equals zero:

$$\sum_i \vec{F}_i = 0 \qquad (3.29)$$

The sum of all torques equals zero:

$$\sum_i \vec{T}_i = 0 \qquad (3.30)$$

3.3.4. The Lever

A *lever* is the simplest mechanism by which it is possible to balance a larger force by a lesser one. A lever consists of a plank which pivots at a point called the *fulcrum.* There are three forces acting on the plank: the downward force (*F*) used to try to lift the heavy mass (*M*), the reaction force (*R*) at the fulcrum, and the force arising from the gravitational pull on the body (fig. 3.3).

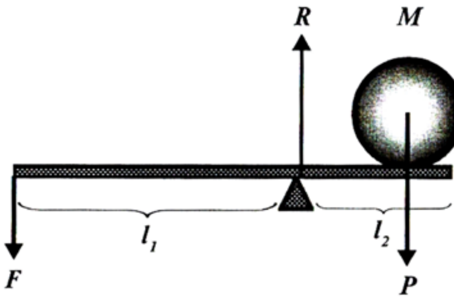


Fig. 3.3. A lever which consists of a plank of mass *M* pivoted near its end can be used to mechanical advantage; l_1 and l_2 are the lever arms; *R* is the reaction force at the fulcrum

Two of these forces, *F* and *P*, tend to rotate the plank about the fulcrum, the extent of which depends on the product of the force and its perpendicular distance from the fulcrum. The product is called the *moment of the force* and the plank will be in equilibrium when the clockwise and counterclockwise moments are equal:

$$Fl_1 = Pl_2 \qquad (3.31)$$

Hence, *F* will be small if l_2 is small, in which case the point of pivot should be as near the body as possible. The ratio Pl_2/F is known as the *mechanical advantage* of the lever.

The biceps muscles and the jaws are examples of a lever mechanism in a living organism.

Example. Consider the diagram of the biceps muscles which lift a weight 6 N held in the hand (fig.3.4). The *biceps*, the flexor muscle of the forearm, is at an angle of $\theta = 12^\circ$ to the elbow. Find the force exerted by the biceps.

Solution. The component of the force exerted by the biceps muscles that is perpendicular to the lever is $F\cos\theta$. The equation of equilibrium of lever moments is:

$$P \cdot l_1 = F \cdot l_2$$
$$6\,N \cdot 5x = Fx\cos 12^\circ$$

$$F = \frac{30}{0.978} = 30.7\ N$$

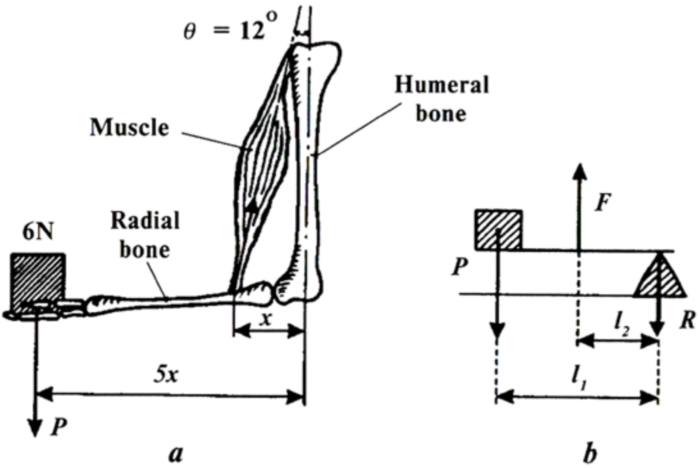


Fig. 3.4. **Lever which is composed with radial and humeral bones and muscle: *a* — diagram of biceps muscles lifting a weight in his hand; *b* — the mechanical model for this system: *F* is the upward force of the biceps; *R* is the downforce of the joint; *P* is the weight; l_1 and l_2 are the lever arms**

Control Questions and Problems

1. What studies mechanics? kinematics? statics?
2. What is the material point?
3. Define average and instantaneous velocity.
4. Define average and instantaneous acelleration.
5. Formulate the first, second and third laws of Newton.
6. Formulate the Universal Law of Gravity.
7. What is the elastic deformation?
8. Formulate Hooke's law.
9. What is the work? energy?

10 What is the relationship between linear and angular velocity?

11. What is the lever?

Chapter 4. BIOMECHANICS

Biomechanics is the branch of biophysics that examines the body in terms of its mechanical structure and properties, and the locomotion and growth of living organism from the point of view of mechanical laws and principles.

4.1. ISOMETRY AND ALLOMETRY

All living organisms are characterized by physiological and mechanical parameters – mass, size, length [21]. If the transition from a small living organisms to larger one is accompanied by a proportional change of the relationship among physiological and mechanical parameters, such a dependence is called isometry (fig. 4.1). Isometry can be described as a straight line relationship:

$$y = f(x) \qquad (4.1)$$

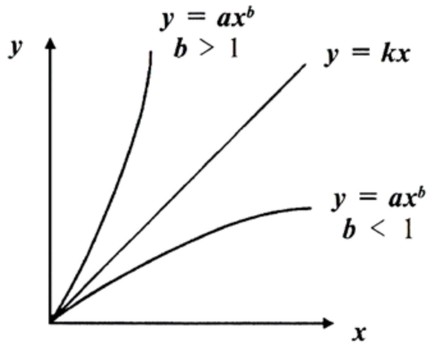


Fig.4.1. **Isometric and allometric relationship between physiological (*y*) and mechanical (*x*) parameters**

In real situations, dependence is described as a curvilinear relationship:

$$y = ax^b \qquad (4.2)$$

where a and b are constants. Such a dependence is called allometry (from the Greek allos meaning different). The allometric equation can be written in an logarithmic form as:

$$\lg y = \lg a + b \lg x \qquad (4.3)$$

For example, the length (L_p) and the area (S_p) of pores in a bird egg-shell are related to the mass (M_e) of the egg by way of the following allometric equations:

$$L_p = 5.126 \cdot 10^{-2}\, M_e^{0.456} \qquad (4.4)$$

$$S_p = 9.2 \cdot 10^{-3}\, M_e^{1.236} \qquad (4.5)$$

Here L_p and S_p are physiological parameters which characterize the gas exchange of the egg and M_e is a mechanical parameter.

The principle of allometry is also used for studying the relative sizes of plant parts. Usually relationships among total dry weight of trunk wood, total trunk volume, total biomass, leaf weight and *diameter at chest height* (*DBH* – the width of the trunk of a standing tree, measured at 1.3 meters above ground surface) are calculated.

For instance, a few of the useful equations using data from *Ailanthus trees*, are:

Total above-ground biomass (M_T):

$$\lg M_T\,(\text{kg}) = -0.98 + 2.506 \lg DBH(\text{cm}) \qquad (4.6)$$

Total trunk volume (V_T):

$$\lg V_T\,(\text{dm}^3) = -0.18 + 1.948 \lg DBH(\text{cm}) \qquad (4.7)$$

Allometry is useful because it allows forest parameters to be estimated without having to cut down all the trees, transport, dry, and then weigh them to obtain the answer.

4.2. MUSCULAR CONTRACTION

High animals are comprised of three main types of muscles: *skeletal* (cross-striated), *cardiac* (the heart muscle) and *smooth* (the muscles of internal organs). The skeletal muscles have the ability to contract as depicted in fig. 4.2 and appear under light a microscope as an array of *fibers* (diameter 20-80 μm).

Using an electron microscope, it is possible to observe that each fiber is comprised of a few hundred *myofibrils* (diameter 1-2 μm).

Each myofibril has a repetitive pattern of light and dark bands and each repeating unit of the myofibrillar bands is called a *sarcomere*. A sarcomere is located between so-called *Z-disks* and is composed of an array of thick *myosin* and thin *actin* filaments. The myosin filaments have ends which are supplied with *cross-bridges* which can change angle during each cycle of attachment and detachment, pulling a thick filament along a thin one.

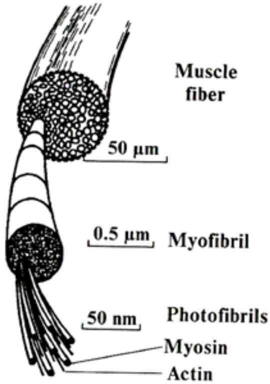


Fig.4.2. **The diagram of the components of a skeletal muscle fiber**

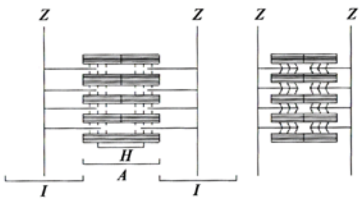


Fig. 4.3. **The diagram of sarcomer**

According to the *sliding-filament model* for the contraction mechanism (fig. 4.3), the relative sliding of the thick and thin filaments along each other induces a shortening of the distance between the two *Z*-disks and contraction of each sarcomere, and therefore of the whole muscle.

The energy for contraction is supplied by ATP. The activation and binding of the myosin-ATP complex to actin in the thin filaments occurs only in the presence of Ca^{2+} ions and the threshold concentration required to initiate muscle contraction is about 10^{-7}-10^{-8} M.

Control Questions and Problems

1. What studies the Biomechanics?
2. What is the difference between isometry and allometry?
3. What are the principal types of muscles?
4. Explain the mechanisms of muscular contruction.

Chapter 5. MECHANOBIOLOGY

Mechanobiology is a branch of biophysics that studies the effects of external mechanical factors on living organisms and their ability to respond to these factors (to provide mechanoreception).

5.1. MECHANORECEPTION

Mechanoreceptors are specialized sensory formations which convert mechanical stimuli into the activity of neural cells. The mechanoreceptors can respond to different mechanical stimuli such as *tactile sensitivity* (response to touch, pressure, and vibration), *vestibuloreception* (control of equilibrium), and *proprioception* (coordination of the relative positions of various parts of the body) [1].

5.1.1. Tactile sensitivity

There are a number of mechanoreceptors in the skin: *free ending of afferent fibers, Meissner´s corpuscles, Pacinian corpuscles, Merkel´s disks, Krause´s end-bulbs,* and *Ruffini corpuscles.* Many vertebrates also use specialized hairs, *vibrissae*, such as those around a seal’s muzzle or cat’s whiskers, which heighten the sense of touch. Vibrissae bend in contact with a solid object. Usually mechanoreceptors induce a change in the ion permeability of receptor cell membranes inducing an electrical signal, the *receptor potential*, which is transmitted to the brain. An example of mechanoreceptors is depicted in fig. 5.1.

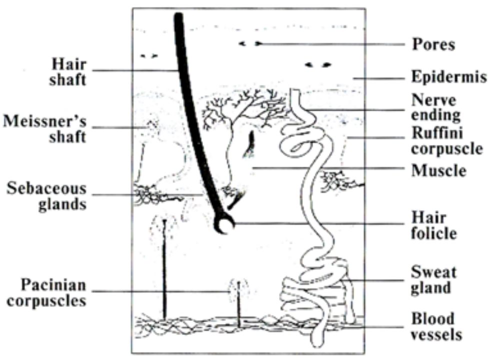


Fig.5.1. **Diagram of the various types of mechanoreceptors in the skin**

5.1.2. The Vestibular System

Vestibuloreception is the response to a change in rotary acceleration and deceleration and the direction of displacement in space. Such a response is used by humans and other animals to control their body posture and locomotion. The *vestibular system* is located in the inner ear, or *labyrinth*, and consists of three *semicircular canals* located at right angles to each other and a pair of saclike structures called the *utricle* and *saccule* (fig. 5.2).

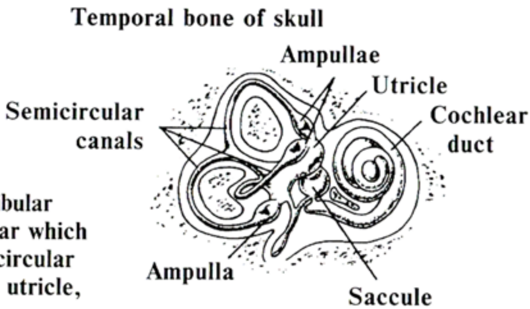


Fig. 5.2. **The vestibular system in the inner ear which contains three semicircular canals, ampullae, an utricle, and a saccule**

The utricle is supplied with receptors called *hair cells* (fig. 5.3). The cells have several hair-like projections into the endolymph and are inserted at its base to a gelatinous mass which contains calcium carbonate crystals called *otoliths* (fig. 5.4).

If the head of an animal is bent at an angle, the semicircular canals alter their orientation, while the endolymph remains at the same place due to inertia.

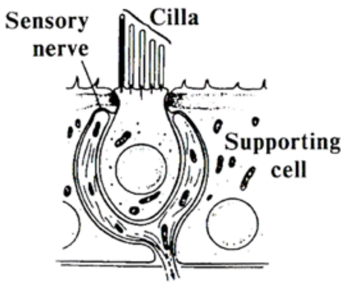
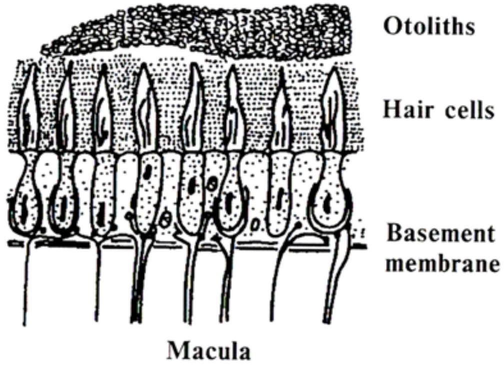


Fig. 5.3. **The hair receptor cell**

Fig. 5.4. **The receptor hairs of the utricle and saccule are clustered in the region called the macula; their gelatinous masses contain calcium carbonate crystals called otoliths**



The deflection of the otoliths by gravity results in the transmission of action potentials by the hair cells to the brain at about 100 spikes/second. Interpretation of the bending by the brain occurs through the analysis of changes in the frequency of the action potentials.

5.1.3. Proprioception

Proprioception indicates the relative positions of various parts of the body without having to use the eyes. There are two important receptor systems in the skeletal muscles of mammals: the *muscle spindle* and the *Golgi tendom organ.*

The muscle spindles are arranged in parallel to the contracting skeletal muscle fibers. The spindles respond to the relative elongation of the muscle (fig. 5.5).

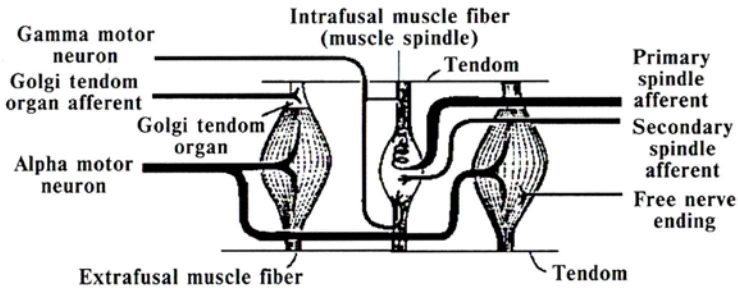


Fig. 5.5. **Muscle spindle which is in parallel with the extrafusal muscle fibers**

Elongation is transferred by the spindle sensory (afferent) nerve as action potentials to the brain. The frequency of the potentials depends on lengthening of the middle part of the skeletal muscle.

The Golgi tendom organ is presented as a slender capsule within the tendom. It is connected with 15-20 skeletal muscle fibers (fig. 5.6) and supplies information to the brain through the action potentials, the frequency of which depends on the tension developed by the muscle.

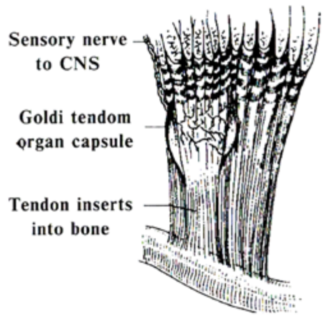


Fig. 5.6. **The Goldgi tendom organ — a stretch receptor located in the tendom of skeletal muscle**

5.1.4. System of Mechanoreception in a Fish

Mechanoreception found in many fish and amphibian species, utilizes a *lateral line system* located along each side of their body (fig. 5.7).

The lateral line system contains as series of channels at certain intervals which open to the surrounding water. The channels in fish consist of viscous gelatinous structures (*cupulae*) with the hairs connected to receptor cells (*neuromasts*).

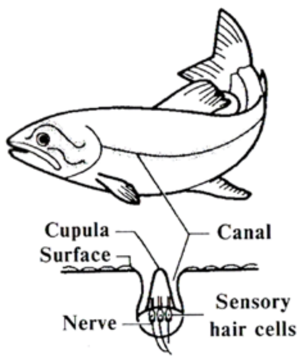


Fig. 5.7. **Lateral line canals along the fish's body and in the head region**

Water, flowing through the channels, results in a deformation of the hairs, creating an electric potential which is transmitted to the nervous system. The lateral line system makes it possible to access a minimal displacement of water, the direction of water flows, and the presence of turbulent fluids created by predators.

5.1.5. The Insect's System of Mechanoreception

Mechanoreceptors in bees react to mechanical deformation of part of the receptor. It may respond to touch, vibration of substrate, or an air current. The sensitive elements of a mechanoreceptor are the *sensila trichodea, sensila scolopophora, sensila campaniformia,* and *sensila schaetica.*

Most insects have "ears" in their legs. The mechanical stimuli provoke nerve impulses in the receptor cells, which are conveyed to the central nervous system. This allows insects, such as the sand scorpion, spiders and whirligig beetles, to detect vibrations in the substrate with their legs.

5.2. EFFECT OF MECHANICAL FACTORS ON LIVING ORGANISMS

5.2.1. Gravitation and Living Organisms

Gravitational Orientation in Higher Plants. Plants orient their roots downward and their shoot upward. The ability of plants to orient the direction of organ growth relative to the gravitational force is called *gravitropism.*

The roots which grow toward the center of the earth, demonstrate *positive gravitropism*; while shoots, which grow away from the center of the earth, exhibit *negative gravitropism.* When the plant is set on a rapidly rotating turn-table, the roots grow away from the center just as they normally grow towards the center of the earth (fig. 5.8). Specific characteristics of gravitropism are: the force of gravity is constant; there are no gradients of gravity; and it is not possible to switch on or off the force of gravity.

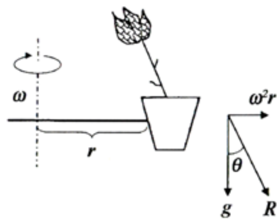


Fig. 5.8. **The plant demonstrates the growth at an angle θ to the vertical if a flower-pot is set on a rapidly rotating turn-table; this angle θ is determined by the resultant R of the gravitational g and inertial $\omega^2 r$ accelerations**

Gravitational Orientation in Mic … *y* are the most important external factors for motile microorganisms which are faced with a problem of selecting the best conditions for their survival. In addition to *photomovement*, which depends on parameters of light, such as direction, intensity, gradients of intensity and wavelength, many cells show *gravitaxis* – the ability of microorganisms to orient their direction of movement relatively to the gravitational field of the earth. Algae, such as *Euglena gracilis*, *Chlamydomonas nivalis*, *Cryptomonas*, *Peridinium gatunense*, *P. faeroense*, *Amphidinium caterea, Prorocentrum micans, Dunalialla salina,* demonstrate gravitaxis, allowing them to establish vertical distribution patterns. They are capable of active movement and daily vertical migration of up to 15 m.

5.2.2. Effect of Mechanical Factors on Plants

Many plants exhibit *nastic movements*, which occur in response to external stimuli such as touch, vibration, mechanical injuries, light, and chemical treatment. The direction of nastic movements does not depend on the direction of stimulus. It is necessary to distinguish the very rapid *seismonastic* movements and the *thigmonastic* movements. The first type of movement is caused by touch. For example, when a plant (*Mimosa pudica*) is touched, its leaflets rapidly fold downwards in just seconds. This type of response is used as a way of protection against the wind and insects and other herbivores. Seismonastic movements are related to reversible turgor changes in the *pulvini* - specialized cells at the base of the leaflets.

Thigmonastic movements are related to a response of some plants to mechanical stimulation such as shaking, falling raindrops, mechanical wounding, cutting. For example, *Pisum sativum* and *Passiflora coerulea,* display this type of response to mechanical stimuli.

5.2.3. Plant Response to Wind

In addition to the stimulation of nastic movements in plants, the wind is involved in heat and mass transfer, changes the boundary layer resistance, and the rate of evaporation. Wind can also induce significant asymmetry in plant architecture by way of either direct damage (breaking of stems or foliage) or indirect damage via materials such as salt and sand transported by it. A very important agricultural problem is lodging of cereals which can cause a decrease in harvestable yield due to poor light penetration to the canopy, damaged conducting system, and weakening of photosynthetic activity of the plant. Also noteworthy is that wind mediates the deposition and dispersion of soil, plant pollen, seeds, spores, and droplets of agrochemical substances.

VOCABULARY

English	Ukrainian	English	Ukrainian
Allometry	Алометрія	Moment of inertia	Момент інерції
Angular displacement	Кутове зміщення	Muscle	М'яз
Average acceleration	Середнє прискорення	Muscle spin	М'язове веретено
Average angular velocity	Середня кутова швидкість	Myofibril	Міофібріла
Average velocity	Середня швидкість	Neuromast	Невромаст

Continuation of Vocabulary

Averaged angular acceleration	Середнє кутове прискорення	Otolith	Отоліт
Cordiac muscle	Серцевий м'яз	Proprioception	Пропріо-рецепція
Contraction	Скорочення	Resultant force	Результуюча сила
Cross-bridges	Поперечні містки	Rigid body	Тверде тіло
Cross-striated muscle	Поперечно-посмугований м'яз	Saccule	Сакула, мішочок
Curvilinear movement	Криволінійний рух	Sarcomere	Саркомер
Density	Густина	Semicircular canal	Напівкруглий канал
Displacement	Зміщення	Sliding-filament model	Модель ковзання ниток
Elasticity	Пружність	Smooth muscle	Гладенький м'яз
Fiber	Волокно	Strain	Відносна деформація
Filaments	Нитка	Stress	Напруженість
Fulcrum	Точка опори	Tactile sensitivity	Тактильна чутливість
Golgi tendom	Сухожильний орган Гольджі	Tensile diagram	Діаграма розтягу
Instantaneous acceleration	Миттєве прискорення	Tension	Розтяг
Instantaneous angular acceleration	Миттєве кутове прискорення	The stiffness constant	Коефіцієнт жорсткості
Instantaneous angular velocity	Миттєва кутова швидкість	The vestibular system	Вестибулярний аппарат
Instantaneous velocity	Миттєва швидкість	To compress	Стискувати
Isometry	Ізометрія	To stretch	Розтягувати
Lateral line system	Система бокової лінії	Torque	Момент обертальний
Lengthening	Видовження	Touch	Дотик
Lever	Важіль	Utricle	Переддвер'я
Lever arm	Плече важеля	Weber ossicles	Веберов аппарат
Mammal	Ссавець	Weight	Вага

Control Works
Modulus 2
Mechanics, Biomechanics, Mechanobiology

Problem. The velocity of a particle moving along the x axis varies in time according to the expression $V = (20 – 3t^2)$ m/c, where t is in s.
1). Find the average acceleration in the time interval t = 0 to t = 2 s.
2). Determine the instantaneous acceleration at t = 2 s.
Answers: – 8 m/s^2; **–** 12 m/s^2.

Problem. A load of 98 kg is supported by a wire of length 1.8 m and cross-sectional area 0.12 cm^2. The wire is stretched by 0.2 cm. Find the stress, strain, and Young's modulus for the wire.
Answer: $8{\cdot}10^7$ N/m^2; $0.11{\cdot}10^{-2}$; $7.2{\cdot}10^{10}$ N/m^2.

Problem. The bone of the dog has the length l = 20 cm, surface of cross-sectional area S = 2.8 cm^2, and Young's modulus $Y = 1.9{\cdot}10^{10}$ N·m^{-2}. Find the force of elasticity which appears during the compression of 0.4 mm of the bone.
Answer: 10.6 кN.

Example. Consider the diagram of biceps muscles which lift a mass 0.6 kg in the hand (fig.3.4). The biceps are at an angle $\theta = 15^0$ to the elbow. Find the force exerted by the biceps.
Answer: 30.4 N.

Home Work. Write an allometric equation, draw an allometric diagram, and determine constants a and b for the following forestry data which have been measured for calculating relationship between trunk dry weight and diameter at breast height.

Sample	Trunk dry weight, kg	Diameter at chest height, cm
1	4.737	5.0
2	137.329	23.4
3	27.484	11.8
4	71.174	16.7
5	2.755	4.2
6	4.655	5.6
7	2.085	3.8
8	8.557	10.0
9	1.593	4.3
10	6.132	6.5
11	159.522	21.9
12	86.525	17.7
13	131.157	25.5

Control Questions and Problems

1. What is mechanoreception?
2. Explain the mechanisms of tactile sensitivity, vestibuloreception, proprioception.
3. What kind of movements exhibit many plants?

Chapter 6. FLUID AND GAS MECHANICS

6.1. PRESSURE

6.1.1. Definition of Pressure

The *pressure* is a physical quantity which characterizes the intensity of normal (perpendicular to the surface) forces with which one body acts on the surface of another. If the forces exhibit a uniform distribution along the surface, the pressure is determined as the ratio of force to area:

$$p = \frac{F}{S} \qquad (6.1)$$

where F is the magnitude of the normal force on the surface and S is the area of this surface.

If the pressure is not uniform across the surface, the following expression defines the pressure at a specific point:

$$p = \sum_{\Delta S \to 0} \frac{\Delta F}{\Delta S} = \frac{dF}{dS} \qquad (6.2)$$

The SI unit for pressure is the Pascal (1 N/m^2 = 1 Pa). The following units are also used, especially so in older literature:

1 atm = $1.01325 \cdot 10^{5}$ Pa = 1013.25 mbar = 760 mm Hg;
1 mbar = 100 Pa = 1 hPa = 0.75006 mm Hg;
1 mm Hg = 1 torr = 1.3332 mbar = 133.32 Pa;
1Pa = $9.87 \cdot 10^{-6}$ atm = $7{,}5 \cdot 10^{-3}$ mm Hg;
1 pound-force per square inch (psi) = 1 lbf/in^2 = 6894.74 Pa.

6.1.2. Variations in Pressure with Depth

The pressure at depth (d) in opened vessel is determined by:

$$p = p_A + \rho g d \qquad (6.3)$$

where p_A ($\approx 1.01 \cdot 10^5$ Pa) is the atmospheric pressure, ρ is the density of the fluid, and g is the acceleration due to gravity.

The absolute pressure (p) at a depth (d) below the surface of a liquid open to the atmosphere is *greater* than atmospheric pressure by ρgd.

Example. Calculate the pressure at the bottom of the Marianas Trench (depth 11043 m). Assume the density of water is $1 \cdot 10^3$ kg/m^3 and $p_a = 1.01 \cdot 10^5$ Pa.

Solution. Using formula (6.3), the pressure is equal to:

$p = p_A + \rho gd = 1.01 \cdot 10^5$ Pa $+ (1.0 \cdot 10^3$ kg/m^3)(9.8 m/s^2)(11043 m) = 109 MPa.

6.1.3. Physiological Effects of Increased Pressure on Humans

Pressure Problems. Some professions (e.g., Arabian sponge divers, Australian pearl divers, Japanese and Korean Ama) make their living by diving in the sea without any special equipment. When divers descend, they are sensitive to the surrounding water pressure which increases at a rate of one atmosphere for each 10 m in descent (i.e., Δp = 1 atm for Δd = 10 m). The pressure of the surrounding water is transmitted to all internal parts of the body and a state of pressure equilibrium is established where the internal pressure of the body is equal to the surrounding pressure. During ascent and descent the diver must support the pressure of air in his lungs the same as that of the surrounding water. For example, if the diver goes to 30 m underwater by holding a full breath of air, he would have 4 atm of pressure in his lungs according to Equation (6.3). When ascending, the pressure at the water surface is 1 atm, while the pressure in his lungs would be 3 atm. This pressure difference can lead to the rupture of his lungs, a phenomenon termed *pneumotorax.*

Influence of Nitrogen. The air we breathe contains 79% of nitrogen; as a consequence, our blood is full of dissolved nitrogen. According to *Henry´s law*, the amount of dissolved gas in a liquid at constant temperature is directly proportional to the partial pressure of the gas. Liquids which are under high pressure can dissolve more gas than liquids which are under low pressure. A substantial depths, the greatly elevated pressure of the air in the lungs results in the formation of the gas bubbles in the blood vessels. The spherical shape of the bubbles is distorted due to the bloodstream (fig. 6.1) and the left and right hemispheres have different radii of curvature. According to the Laplace equation [see Equation (6.22)], additional pressure produced by the surface tension is inversely proportional to the radius of curvature R of a hemispherical liquid-gas interface.

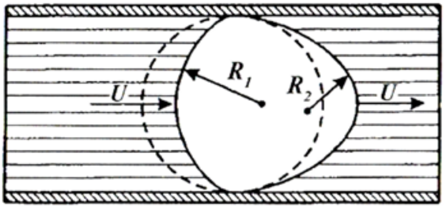


Fig. 6.1. **The deformation of a spherical shape of air bubble by the bloodstream**

The pressure difference leads to the rupture or obstruction of blood vessels; a disease called *gas embolism.* It is accompanied by an immediate loss of consciousness or convulsions. If gas embolism takes place in the blood vessels of the brain or the coronary circulation, it can result in death.

If bubbles are formed due to rapid decompression, the diver will suffer the effects of a painful disease called the *caisson disease* (from the French word *"caisse"*, a chest) or the *bends*, which leads to neuralgic pains, paralysis, distress in breathing and often collapse.

Oxygen Poisoning. When a diver is underwater, their tissues use a certain amount of dissolved oxygen from hemoglobin, the oxygen transport protein found in the erythrocytes of the blood. At sufficient depth, the pressure increases to the point that oxygen binding and transport by hemoglobin is prevented and the tissues remain saturated causing convulsions due to the high-pressure oxygen.

Carbon Dioxide Influence. Elevated carbon dioxide (i.e., more than 10%) that occurs as an individual descends can depress cellular respiration causing the diver to develop lethargy and narcosis, and finally lose unconscious.

6.1.4. Physiological Effects of Pressure on Diving Animals

The deep-sea environment is characterized by a high hydrostatic pressures which increases by approximately 1 MPa (10^6 Pa) for every 100 m in depth. There are a number of diving marine animals which can live under the pressure of tens or even hundreds of atmospheres. The depth range for different marine animals is: 200-300 m - fur seals (maximal depth is about 900 m);500-2000 m – deep-sea eel *Synaphobranchus kaupi*; 265 m – emperor penguin; 2500 m – sperm whale; 7250 – sea urchin; 7360 m – sea star; 8370 m – cuskeel fish; 10190 – sea cucumber. Jacques

Piccard, studying extreme marine depths, observed through the illuminator of his bathyscaph shrimp and fish at a depth of 10912 m. Some invertebrates and bacteria have been found near the bottom of the Marianas Trench (depth 11043 m, pressure of about 110 MPa).

What biological mechanisms allow these animals to function at such depths? One is related to the ability of these animals to exhale before the diving: for example, cetaceans can exhale about 88 % of their lung air with a single breathe while humans can only exhale only about 12 %. This causes the lungs of diving marine animals to collapsed quickly preventing atmospheric gases (nitrogen, oxygen) from entering the bloodstream. Another feature is the ability of diving animals to use oxygen from blood which has a high volume and hematocrit (a number of blood cells). As a consequence, the skeletal muscle tissue of the animals contains about 47% of the overall body oxygen. The large amount of hemoglobin in the muscles is responsible for their deep-red color. Diving animals have about ten times more of myoglobin in the muscles than terrestrial animals. In addition, they are able to decrease their heart rate during the dive, relative to that at the surface. For instance, a muskrat has about 320 heart beats per minute before diving but only 34 beats per minute at depth; on land, seals have a heart rate of 107 beats per minute, but at depth their pulse decreases to 68 beats per minute. Therefore, the ability of diving animals to collapse the lungs, store myoglobin in their muscles and to use oxygen located within the muscle cells and the blood make it possible for them to escape developing the bends.

6.1.5. Variation of Pressure with Height

The variation of pressure with height is given as:

$$p_A(z) = p_A(0)exp[-(gM_A/RT_A)]z \qquad (6.4)$$

where $p_A(0)$ is the pressure at sea level where the height (z) is 0 (i.e., z_0), g – is the acceleration due to gravity, M_A – the molar mass of the gas, R – the universal gas constant, and T_A – the temperature.

This equation is known as the *Barometric Formula* and indicates an exponential decrease in pressure with increasing elevation.

To calculate the height (z_0) of air at $T = 0\ ^0$C and an average molecular mass (M_A) of $47.3 \cdot 10^{-24}$ g:

$$z_0 = \left(\frac{kT}{M_A g}\right) = \left(\frac{1.38 \cdot 10^{-16} \cdot 273}{47.3 \cdot 10^{-24} \cdot 980}\right) = 8150 \text{ m}$$

Thus it is possible to obtain for practical purposes a suitable estimation of the variation in pressure with height above the Earth:

$$p = 760e^{-z/8150} \text{ mm Hg}$$

Example. Find the atmospheric pressure at 5000 m.

Solution. The atmospheric pressure can be find as:

$$p = 760e^{-z/8150} \text{ mm Hg} = 760\, e^{-5000/8150} = 760\, e^{-0.6135} = 760 \cdot 0.5415 = 411 \text{ mm Hg}.$$

6.1.6. Physiological Effects of Decreased Air Pressure on Humans

Mountain-climbers and balloonists often reach exceptionally high altitudes such that if they do not use special oxygen equipment they can suffer from "*mountain sickness*". The first signs of this disease occur at about 3000 m and are seen as slight changes in pulse and breathing rate, *anorexia* (an eating disorder due to loss of appetite), and a loss of body weight (about 1 kg in a week) due to decreased thirst and increased urine volume. These alterations increase substantially in the 3000-4000 m altitude range. Above 4000 m, mountain-climbing becomes extremely difficult. The primary symptoms of mountain sickness are *dyspnea* (difficult breathing), *tachycardia* (heart rate in excess of 100 beats per minute), *malaise* (vague body discomfort), *nausea* and *vomiting*, *insomnia*, and *lassitude* (a state or feeling of weariness, diminished energy, or listlessness). Maximum work capacity decreases roughly 1 % for each 100 m above 2500 m.

Balloon ascents result in physiological effects caused by decreased air pressure and low oxygen supply (*hypoxia*) which makes a transition from *compensated hypoxia* (measurable increase in heartbeat and breathing rate, but only slight loss of efficiency in performing complex tasks) at the altitudes between 3150-4750 m to *manifest hypoxia* (the respiratory and heart rates markedly increase, loss of critical judgment and muscular control, dulling of the senses, and variation of emotional state from lethargy to euphoria and even hallucinations) between 4570-6100 m and *critical hypoxia* (rapid loss of neuromuscular control, consciousness, cessation of respiration and finally death) at 6100-7260 m. An example of acute exposure to high altitude resulting in serious mental impairment is given in fig. 6.2.

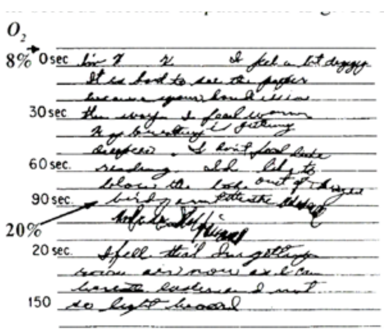


Fig. 6.2. **Effect of low oxygen concentration on mental status of patient in a climatic chamber: after exposure to severe hypoxia the patient made mistakes and his handwriting changed; when the normal air was supplied, patient recovered in about 30 seconds**

The mechanism of *altitude sickness* can be explained by the effect of altitude on the partial pressure of oxygen in the lung alveoli. The pressure varies from 160 mm Hg at sea level to 30 mm Hg at 7320 m, the level at which there is insufficient oxygen for life. Exposure to the reduced pressure at extremely high altitudes (e.g., ≈ 12000 m) can occur in airplanes due to mechanical failure or an accident. Usually airplanes are equipped with a system that pressurizes the interior to about 560 mm Hg. A loss of pressure at high altitude, therefore, is extremely dangerous for passengers.

6.1.7. Physiological Effects of Altitude on Animals

There are a number of animals which have evolved adaptations for living at high altitudes. About 10 fish species inhabit Lake Tanganyika, where the aqueous oxygen concentration ranges from 0 to 0.6 parts per million. The Lake Titicaca frog, likewise, lives at an altitude of 3812 m. The frog exhibits increased gas exchange due to extensive skin folds, and high hematocrit and erythrocyte concentrations. Thus the capacity of the frog for transporting oxygen is substantially increased.

Mules are used at Aucanquilcha, a base camp for the International High Altitude Expedition, as a transport means in the 5250-6000 m altitude range. The animals demonstrate the ability to accurately assess their capacity for work and refuse to be pushed beyond a safe limit. Other animals at high altitudes are the vicuna (5000-6000 m), domestic sheep (up to 5250 m), and horses (up to 4600 m). Birds, however, hold the high altitude records: condors (7600 m), geese (8534 m), chough (9000 m) and griffon vulture (11278 m).

6.1.8. Effects of Altitude on the Plants

Altitudinal variation of climate induces morphological and physiological changes in plants and their canopy architecture. Often the plants maintain a compact or dwarf form with small, narrow or densely pubescent leaves. The ecological zone between 3230 and 3660 m is called an *alpine* area. Here it is possible to find considerable changes in quantitative and qualitative characteristics of the fauna. In addition, there are certain changes in climatic conditions that are related to the effects of pressure, wind, humidity and precipitation, temperature, radiation and gas exchange, which in turn, also modify the fauna.

6.1.9. Osmotic Pressure

The process of *osmosis* can be considered as a special case of membrane diffusion in which only the solvent (water) moves across the membrane (via water channels), while the solute molecules are restrained by the membrane, which is therefore described as *semipermeable*. Typical values for diffusion coefficients are presented in Table 6.1.

6.1. ***Typical values for diffusion coefficients of small molecules in aqueous solutions and air (Nobel, 1983)***

Substance	Diffusion coefficient, $m^2 \cdot s^{-1}$	Substance	Diffusion coefficient, $m^2 \cdot s^{-1}$
Glucose	$0.67 \cdot 10^{-9}$	CO_2 (solution)	$1.7 \cdot 10^{-9}$
Ca^{2+} (with Cl^-)	$1.2 \cdot 10^{-9}$	CO_2 (gas)	$1.5 \cdot 10^{-5}$
K^+ (with Cl^-)	$1.9 \cdot 10^{-9}$	H_2O	$2.4 \cdot 10^{-5}$
Na^+ (with Cl^-)	$1.5 \cdot 10^{-9}$	O_2	$1.9 \cdot 10^{-5}$

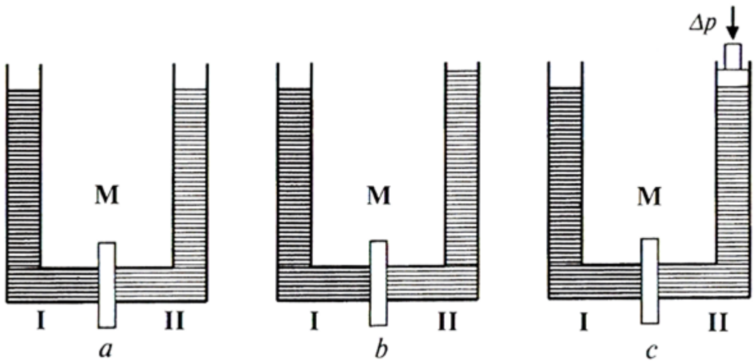


Fig. 6.3. **An ideally semipermeable membrane, which separates two solutions of different concentrations**

The pressure required to balance the osmotic flow of water is called the *osmotic* pressure. For dilute solutions, osmotic pressure (p_{osm}) obeys the *Van´t Hoff relation*:

$$p_{osm} = RTC_A \quad (6.5)$$

where R is the gas constant (R = 8,31 J·mol^{-1}·K^{-1}), T the absolute temperature, and C_A the molar concentration.

6.1.10. Osmotic Phenomena in Plants

Most animals are characterized with constant osmotic pressure which is maintained by the blood. Plant cells, in contrast, exist in a dilute aqueous environment. Osmosis in plant cells result the transfer of solvent molecules from regions of high concentration to regions of low concentration. All plants utilize water as a solvent; therefore, osmosis for plant cells means the diffusion of water through a semipermeable membrane. In order to reach a state of equilibrium, it is necessary to apply to the solution a pressure which is equivalent to osmotic pressure of solution. If water diffuses into the vacuole, its volume will be increased, increasing the outward pressure on the cell wall. The pressure exerted on the cell wall which is called *turgor pressure* (p_T). At the same time, the cell wall opposes the pressure of the cytoplasm. The condition of equilibrium can be written in as:

$$p_T - p^i_{osm} = -p^e_{osm} \quad (6.6)$$

where p^i_{osm} and p^e_{osm} are the osmotic pressures within and outside of the cell.

Osmotic pressure plays an important role in phloem transport in plants and is the driving force in cell elongation during growth.

6.2. FLUID DYNAMICS

6.2.1. The Continuity Equation

This section deals initially with a model of an *ideal fluid* which is considered to be *nonviscous* and *incompressible.* Consider a fluid flowing through a pipe of nonuniform size as in fig. 6.4. An incompressible fluid moving with steady flow through a pipe of varying cross-sectional area is described by the *equation of continuity*:

$$S_1 \cdot V_1 = S_2 \cdot V_2 \qquad (6.7)$$

That is, *the product of the area and the fluid speed at all points along the pipe is a constant.* This equation can be written as:

$$S = \frac{const}{V}. \qquad (6.8)$$

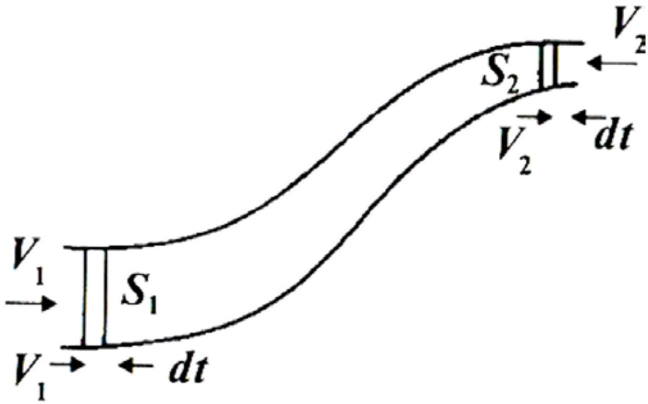


Fig. 6.4. **Flow through a tube of varying cross-section area**

6.2.2. Bernoulli's Equation

Consider a situation where the height of the tube above some reference level also changes (fig. 6.5).

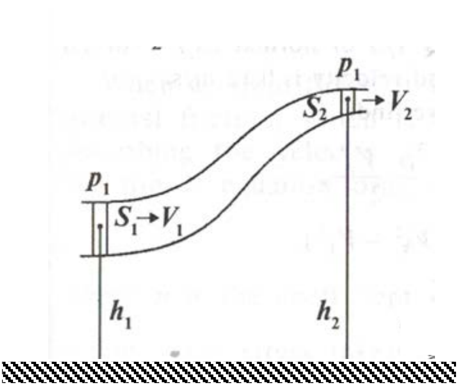


Fig. 6.4. **Flow through a tube of varying cross-section areas: the heights of the tube above some reference level are different**

Bernoulli´s equation states that the *sum of the static pressure (p), the hydrodynamic pressure (* $\frac{\rho V^2}{2}$ *)* (i.e., the kinetic energy per unit volume*)*, and *hydrostatic pressure (ρgh)* (i.e., the potential energy per unit volume) *has the same value at all points along a streamline*:

$$p + \rho \cdot g \cdot h + \frac{\rho \cdot V^2}{2} = const, \qquad (6.9)$$

where *p* is the *static pressure*, *ρ·g·h* is the *hydrostatic pressure, and* $\frac{\rho \cdot V^2}{2}$ is the *dynamic pressure* of the fluid.

In most problems of biological interest, *h* = *const*, and Bernoulli's equation becomes:

$$p + \frac{\rho \cdot V^2}{2} = const. \qquad (6.10)$$

6.2.3. Medical Application of Bernoulli's Equation

Trombosis. The appearance of clots in the blood vessels or the accumulation of plaque on the inner walls leads to a disease called trombosis. This situation is accompanied by the constriction of the vessel (fig. 6.6).

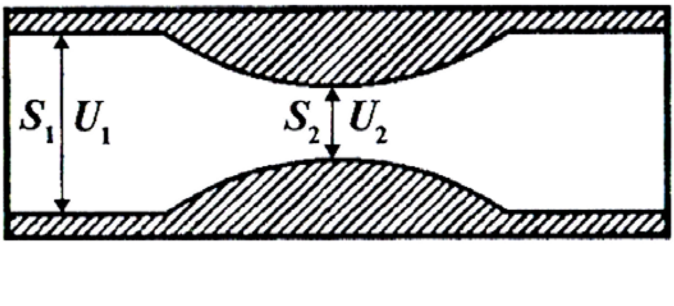


Fig. 6.6. **Constriction of blood vessel due to trombosis**

If the cross-sectional area of the vessel decreases, the fluid speed must be increased [see equation (6.8)]. As the speed increases with decreasing area, equations (6.5) and (6.7) imply that the dynamic pressure also increases, but the static pressure, in order to maintain a constant flow rate through the tube, decreases at the point of constriction. This has serious consequences for the blood vessel. If the blood speed is sufficiently high in the constricted region, the vessel may collapse under external pressure, causing a momentary interruption in blood flow. At this point the vessel reopens due to the blood pressure. As the blood rushes through the constricted artery, the internal pressure drops again and the artery closes. Such variations in blood flow are called flutter; the sound produced by this vibratory motion can be heard using a stethoscope during a routine diagnostic procedure.

Example. By what percentage would the pressure drop in an artery as the blood enters a region which has been narrowed by atherosclerotic plaque to a cross-sectional area (S_2) only 1/5 of normal (S_1)? Normal blood pressure is 100 mm Hg and the blood velocity is 0.12m/s.

Solution. Using Bernoulli´s Equation we find:

$$p_1 + \frac{\rho \cdot V_1^2}{2} = p_2 + \frac{\rho \cdot V_2^2}{2},$$

$$\Delta p = p_1 - p_2 = \frac{\rho}{2} \cdot (V_2^2 - V_1^2).$$

According to the Continuity Equation:

$$S_1 \cdot V_1 = S_2 \cdot V_2,$$

or

$$V_2 = 5 \cdot V_1.$$

Substitute for V_2 in expression for Δp:

$$\Delta p = 12 \cdot \rho \cdot V_1^2 = 12 \cdot 1000 kg \cdot m^{-3} \cdot (0{,}12 m \cdot s^{-1})^2 = 170 Pa.$$

To convert normal blood pressure from mm Hg to Pa use:

$$p_1 = \rho \cdot g \cdot h = 136000 \text{кг} \cdot \text{м}^{-3} \cdot 10 \text{м} \cdot \text{с}^{-2} \cdot 0{,}1 \text{м} = 13600 \text{Па}.$$

Percent decrease in pressure in the constricted area is:

$$\frac{\Delta p}{p} = \frac{170}{13600} \cdot 100 = 1.2\%.$$

Aneurism. This type of disorder in the circulation system is related to the dilation of blood vessels due to pathological and morphological changes in their walls (fig. 6.7).

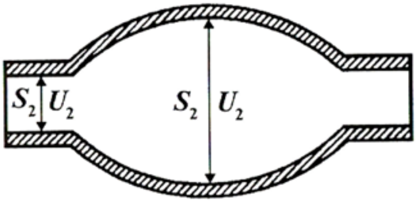


Fig. 6.7. **Dilation of blood vessel due to aneurism**

If the cross-sectional area of the blood vessel increases, the speed of blood flow will be decreased according equation 6.8. This situation causes a decrease in hydrodynamic pressure and an increase in the static pressure according to Bernoulli's equation (6.10). The increased static pressure leads to the rupture of the blood vessel and an *aneurism.*

6.2.4. Viscosity

When a liquid flows, it has an internal resistance to flow, an internal friction, which is called its *viscosity*. The simplest law describing the velocity of a flowing liquid was proposed by Newton. In equation form, *Newton´s law of viscosity* is:

$$F\Delta t = \eta \cdot S \cdot \frac{V}{\Delta x} \Delta t \qquad (6.11)$$

where η is the coefficient of viscosity; S is the area of a layer where shear stress takes place; $\frac{V}{\Delta x}$ is the rate of change of shearing strain; and Δt is the time interval.

The unit of viscosity is $Pa{\cdot}s$ and the coefficients of viscosity for several substances are given in Table 6.2.

6.2. *The viscosity of various substances*

Substance	Viscosity, Pa·s	Temperature, °C
Air	$18 \cdot 10^{-6}$	20
Air	$21 \cdot 10^{-6}$	100
Water	$1.781 \cdot 10^{-3}$	0
Water	$1.306 \cdot 10^{-3}$	10
Water	$1.002 \cdot 10^{-3}$	20
Water	$0.798 \cdot 10^{-3}$	30
Water	$0.653 \cdot 10^{-3}$	40
Whole blood	$(4-5) \cdot 10^{-3}$	20
Milk	$(1.42-1.45) \cdot 10^{-3}$	20

6.2.5. Stokes' Law

When a sphere of radius R moves with velocity V through a stationary fluid and if the motion is nonturbulent, then the viscous drag (F) on the sphere is given by *Stokes' law*:

$$F_s = 6\pi\eta RV \qquad (6.12)$$

where η is the viscosity of the fluid.

6.2.6. Erythrocyte Sedimentation Rate

The coefficient of viscosity (η) depends on temperature; the approximate viscosity-temperature relation is:

$$\eta = a \cdot e^{\frac{b}{T}} \qquad (6.13)$$

where a and b are constants and T is the absolute temperature.

The erythrocyte sedimentation rate (*ESR*) measures the distance red blood cells will fall along the length of a vertical tube over a given time period (e.g., 1 hour).

Sedimentation is normally accelerated as the temperature rises and the viscosity decreases [see equation (6.13)]:

$$V \approx \frac{1}{\eta} \qquad (6.14)$$

Sedimentation of red cells depends on the forces resisting sedimentation (e.g., negative charges on the red cell surface, the opposite stream of plasma, rigidity of red cells) and the forces accelerating sedimentation (e.g., anemia, plasma proteins). Changes in *ESR* values are associated with changes in plasma proteins which can be caused with various diseases (e.g., rheumatoid arthritis, temporal arteritis, polymyalgia rheumatica, tuberculosis and Hodgkin's).

6.2.7. Poiseuille's Law of Flow

The French physicist Poiseuille showed experimentally that the *volume (Q) of liquid flowing through a tube of length l is directly proportional to the pressure difference (p_1 - p_2) driving the liquid, and proportional to the fourth power of the tube radius (R).* The laminar flow of liquids in pipes is described by *Poiseuille's law of flow:*

$$Q = \frac{1}{\eta} \cdot \frac{\pi \cdot R^4}{8 \cdot l} \cdot (p_1 - p_2). \qquad (6.15)$$

Poiseuille's law of flow can be used to quantitative measure the viscosity (η) of liquids.

6.2.8. Sedimentation

When a sphere falls in a viscous medium, it reaches a terminal velocity when the retarding forces, viscosity ($F_s = 6 \cdot \pi \cdot \eta \cdot R \cdot V$) and buoyancy ($\vec{F}_A = \rho_m \cdot V \cdot \vec{g} = \frac{4}{3} \cdot \pi \cdot R^3 \cdot \rho_m \cdot \vec{g}$), equal the weight ($m \cdot \vec{g} = \frac{4}{3} \cdot \pi R^3 \cdot \rho_{sp} \cdot \vec{g}$) of the sphere:

$$\frac{4}{3} \cdot \pi R^3 \cdot \rho_{sp} \cdot \vec{g} = \frac{4}{3} \cdot \pi \cdot R^3 \cdot \rho_m \cdot \vec{g} + 6 \cdot \pi \cdot \eta \cdot R \cdot V \qquad (6.16)$$

where m is the mass of sphere, $R = \frac{D}{2}$ – the radius of sphere, ρ_{sp} and ρ_m – the density of the sphere and medium, and η - the viscosity of the medium.

Hence:

$$\eta = \frac{2 \cdot g \cdot R^2 \cdot t \cdot (\rho_{sp} - \rho_m)}{9 \cdot l} \qquad (6.17)$$

and the terminal velocity (also called *sedimentation velocity*) can be determined as:

$$V = g \cdot \frac{\rho_{sp} - \rho_m}{\eta} \cdot \frac{2 \cdot R^2}{9} \qquad (6.18)$$

6.2.9. Physical Principles of Ultracentrifugation

The movement of spherical particles in a centrifuge tube (fig. 6.8) eventually reach a terminal velocity determined by the frictional force ($F_s = 6 \cdot \pi \cdot \eta \cdot R \cdot V$), centripetal force ($F_{cp} = \frac{m_m V^2}{r} = m_m \omega^2 r = \rho_m \mathrm{V} \omega^2 r$), and centrifugal force ($F_{cf} = \frac{m_{sp} V^2}{r} = m_{sp} \omega^2 r = \rho_{sp} \mathrm{V} \omega^2 r$).

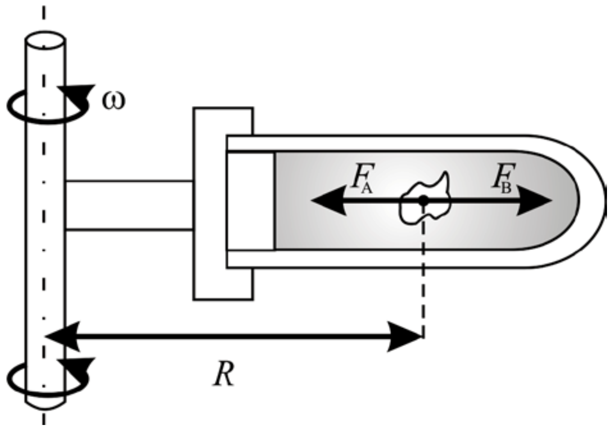


Fig. 6.8. **Movement of a particle in a centrifuge tube**

$$V = \frac{2}{9}\omega^2 r(\rho_{sp} - \rho_m) r^2/\eta \qquad (6.19)$$

where m is the mass of the spherical particle, r is the distance of the particle from the axis of rotation, ρ_{sp} and ρ_m are the density of the spherical particle and medium, V is a volume of particle, ω the angular velocity, and η viscosity of the medium.

In the case of centrifugal method g in equation (6.18) has to be replaced by $\omega^2 r$ in equation (6.19), in which ω is the angular velocity of the centrifuge and r is the distance between the particle and the center of rotation. The ratio:

$$\frac{\omega^2 r}{g} = \frac{V_{cf}}{V_g} \qquad (6.20)$$

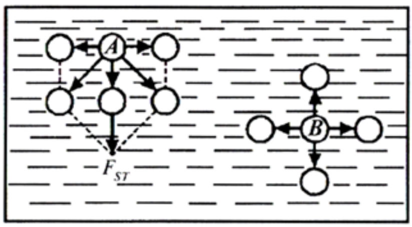
is a characteristic constant for a given molecular species in a given solvent. The development of centrifugal techniques can generate “gravitational fields” up to 400000*g*.

6.3. SURFACE TENSION

6.3.1. Mechanisms of Surface Tension

With two types of molecules (*A* and *B*) in the body of a fluid, if *A* is located at the surface of the fluid, then the net force from the side of the neighboring molecules is due to their asymmetric location (fig. 6.9 *a*). Molecules of *B* are surrounded by the symmetrically located neighbors, such that the net force is equal to zero (fig. 6.9 *b*). The net force of the surface molecules leads to the formation of a *surface tension.*

Fig. 6.9. **Interaction of molecule *A* which is located at the surface of the fluid and the molecule *B* which is surrounded by the symmetrically located neighbors with the neighboring molecules**



The surface tension force depends on the molecular species and the length (l) of the interface:

$$F_{ST} = \sigma \cdot l \qquad (6.21)$$

where σ is the coefficient of surface tension which varies with the type of fluid, impurities and temperature.

Table 6.3 gives the coefficients of surface tension of some common fluids when they are in contact with air.

6.3. Coefficients of surface tension of some common fluids

Liquid in contact with air	**Coefficient of surface tension ($N \cdot m^{-1}$)**
Water	$72.8 \cdot 10^{-3}$
Castor oil	$36.4 \cdot 10^{-3}$
Petroleum	$26 \cdot 10^{-3}$
Ethanol	$22.8 \cdot 10^{-3}$
Methanol	$22.6 \cdot 10^{-3}$
Soap solution	$25.0 \cdot 10^{-3}$
Milk	$44.0 \cdot 10^{-3}$
Blood plasma	$50.0 \cdot 10^{-3}$

Example. An insect called a pond skater can walk on water. It has six feet and the total length of the air-water interface of each foot has been estimated to be 1 mm. Assuming that the contact angle between the foot and water is sufficiently large so that the surface tension ($\sigma = 70 \cdot 10^{-3}$ N/m) acts vertically, show that this force alone can support a pond skater of mass $25 \cdot 10^{-6}$ kg.

Solution. The surface tension force for all six feet of the insect is:

$$F = 6 \cdot \sigma \cdot l = 6 \cdot 72.8 \cdot 10^{-3} \text{ m} = 436.8 \cdot 10^{-6} \text{ N}$$

The weight of insect can be found as:

$$P = m \cdot g = 25 \cdot 10^{-6} \text{ kg} \cdot 9.8 \text{ m} \cdot \text{s}^{-2} = 245 \cdot 10^{-6} \text{ N}$$

Since the surface tension force is greater that the insects weight, the pond skate is supported by the water.

6.3.2. Surface Tension and the Lung

The surface of human lungs has a specific and highly invaginated shape which is characterized by tiny air spaces called alveoli (fig. 6.10). The blood-epithelium-air interface of the lungs is very large and is approximately equal to the area of a tennis court. Changes of surface tension in the lungs are responsible for a respiratory disease in new born babies, called the hyaline membrane disease, which is characterized by the deposition of hyaline substance on the internal surface of the alveoli.

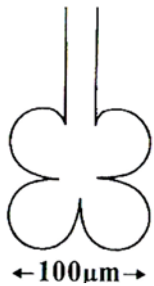


Fig 6.10.
Cross-section of an alveole

The treatment of this disease is associated with the application of surfactants, species which are able to reduce surface tension at the blood-air interface in the lungs.

6.3.3. Capillarity

A phenomenon caused by the surface tension at the interface of two nonmixing media is called *capillarity* and is observed when a distorted surface of a liquid leads to an elevation or depression of the liquid when in contact with a solid. It is necessary to take into account the effects of two opposing forces: *adhesion*, the attractive (or repulsive) force between the molecules of the liquid and those of the container, and *cohesion*, the attractive force between the molecules of the liquid. When the liquid-gas interface is curved, the resultant surface tension produces an additional pressure difference across the interface. For a hemispherical liquid-gas interface having radius of curvature R, the pressure difference is given by the *Laplace equation*:

$$\Delta p = \pm \frac{2 \cdot \sigma}{R} \qquad (6.22)$$

where σ is coefficient of surface tension of the liquid.

If the interface is not spherical, the Laplace equation is:

$$\Delta p = \pm \alpha \cdot \left(\frac{1}{R_1} + \frac{1}{R_2}\right), \qquad (6.23)$$

where R_1 and R_2 are the radii of curvature of two perpendicular planes.

The sign for Δp is positive for a concave interface and negative for a convex interface.

6.3.4. Capillary Rise

A cylindrical tube with a small internal diameter is called a *capillary*. The behavior of liquid in capillary is strongly modulated by the *wettability* of the tube walls. If the walls are wettable, the water rises in the capillary (fig. 6.11).

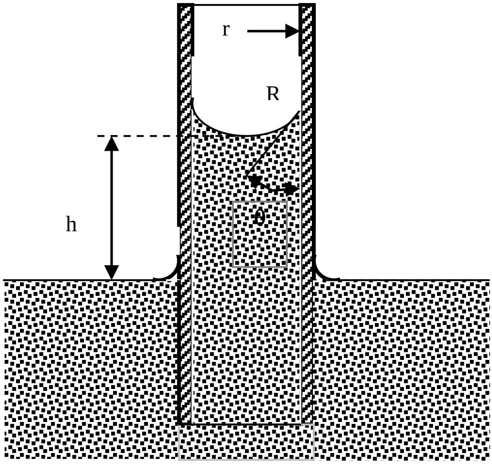


Fig. 6.11. **The fluid in a narrow tube is pulled up by the additional pressure on the hemisphere at the liquid-air interface**

For example, with water in xylem vessels, the attraction between the water molecules and the wall is great, causing the liquid to rise.
To calculate the extent of capillary rise, the balance of two forces, gravity $\pi r^2 \rho g h$ acting downward and surface tension $2\pi r \sigma \cos\theta$, must be determined. Since these forces are balanced, the extent of rise (h) is given by equating the two forces ($\pi r^2 \rho g h = 2\pi r \sigma \cos\theta$), which leads to:

$$h = \frac{2\sigma \cos\theta}{\rho g r} \qquad (6.24)$$

where ρ is the density of liquid, θ – the contact angle, g – the gravitational acceleration, $r = R\cos\theta$ – the radius of capillary and R – *the* radius of surface curvature.

Example. If a xylem vessel has a lumen radius of 20 μm, using equation 6.24, we can determine that water (the density at 20 ^{0}C is 998.2 kg/m^3, surface tension is 0.0728 N/m) will rise to the following height:

$$h = \frac{2\sigma\cos\theta}{\rho g r} = \frac{2\cdot 72.8\cdot 10^{-3} N\cdot m^{-1}\cos 90^0}{998.2kg\cdot m^{-3}\cdot 9.8m\cdot s^{-2}\cdot 20\cdot 10^{-6} m} =$$

$$\frac{1.49\cdot 10^{-5} m^2}{20\cdot 10^{-6}(m)} = 0.745 \text{ m}$$

Such a capillary rise would be sufficient to account for the upward movement of water in small plants (≤ 1 m in height).

6.3.5. Nanomedicine*

Nanomedicine is the application of nanotechnology (the engineering of tiny machines) to the prevention and treatment of disease in the human body.

Nanotechnology is a branch of engineering that deals with the design and manufacture of extremely small electronic circuits and mechanical devices built at the molecular level of matter. The Institute of Nanotechnology in the U.K. expresses it as "science and technology where dimensions and tolerances in the range of 0.1 nanometer (nm) to 100 nm play a critical role."

The term "nanotechnology" was originally coined by Norio Taniguchi in 1974.

Nanorobots are nanodevices that will be used for the purpose of maintaining and protecting the human body against pathogens. They will have a diameter of about 0.5 to 3 microns and will be constructed out of parts with dimensions in the range of 1 to 100 nanometers. The main element used will be carbon in the form of diamond/fullerene nanocomposites because of the strength and chemical inertness of these forms.

Imagine going to the doctor to get treatment for a persistent fever. Instead of giving you a pill or a shot, the doctor refers you to a special medical team which implants a tiny robot into your bloodstream. The robot detects the cause of your fever, travels to the appropriate system and provides a dose of medication directly to the infected area.

* Nanomedicine http://whatis.techtarget.com/definition/nanomedicine

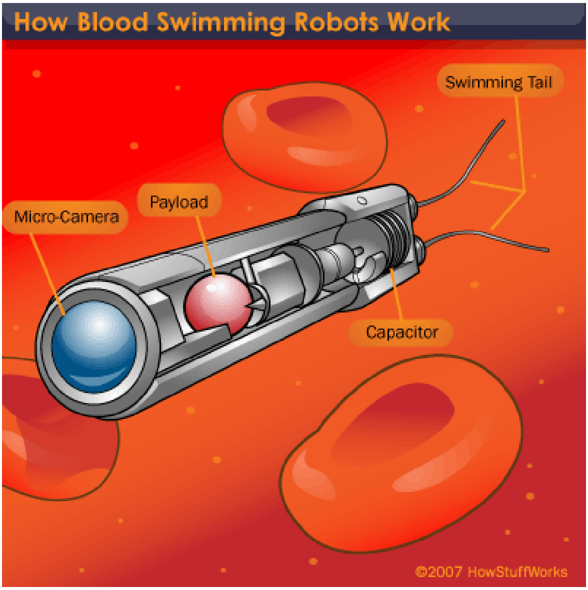


Fig. 6.12. **The robot swims through the arteries and veins using a pair of tail appendages** [How Nanorobots Will Work http://electronics.howstuffworks.com/nanorobot.htm]

Surprisingly, we're not that far off from seeing devices like this actually used in medical procedures. They're called *nanorobots* and engineering teams around the world are working to design robots that will eventually be used to treat everything from hemophilia to cancer.

Respirocytes are hypothetical, microscopic, artificial red blood cells that can emulate the function of its organic counterpart, only with 200 times the efficiency, so as to supplement or replace the function of much of the human body's normal respiratory system.

Still entirely theoretical, respirocytes would measure 1 micrometer in diameter. In the original paper by Robert Freitas, titled, "A Mechanical Artificial Red Blood Cell: Exploratory Design in Medical Nanotechnology"(1998), it was proposed that respirocytes would mimic the action of the natural hemoglobin-filled red blood cells.

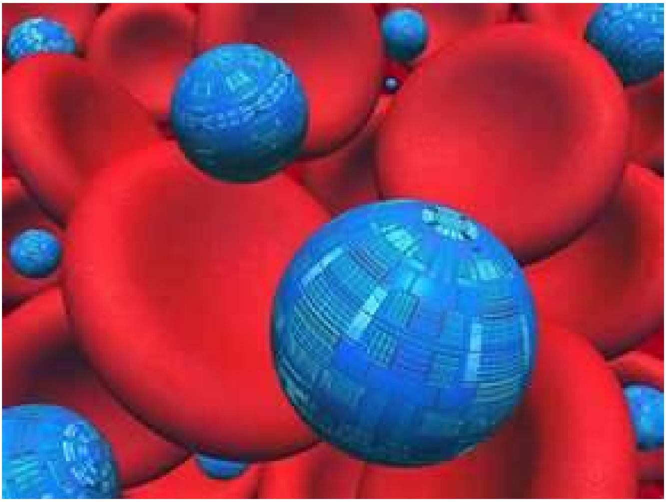


Fig. 6.13. **Respirocytes with Red Cells**

Control Works
Modulus 3
Fluid and Gas Mechanics

Example. Calculate the atmospheric pressure in Pa at the top of Mount Everest which is 10000 m above sea level.

Answer: $0.219 \cdot 10^5$ Pa.

Problem. Calculate the pressure at an ocean depth of 1000 m. Assume the density of water is $1 \cdot 10^3$ kg/m and $p_a = 1.01 \cdot 10^5$ Pa.

Answer: $9.90 \cdot 10^6$ Pa.

Problem. An aorta has a diameter of $8 \cdot 10^{-5}$ м^2 with blood flowing at $40 \cdot 10^{-2}$ м/s. Calculate the cross-sectional area of a vein with blood flowing at $2 \cdot 10^{-1}$ м/s.

Answer: $1.6 \cdot 10^{-4}$ м^2.

Problem. An insect called a pond skater can walk on water. It has six feet and the total length of the air-water interface of each foot has been estimated to be 1 mm. The contact angle between each foot and the water (normally sufficiently large) has been decreased by lowering the surface tension with the addition of a detergent to $\sigma = 40 \cdot 10^{-3}$ N/m. Determine whether the insect will sink or be supported by the water. The mass of insect is $25 \cdot 10^{-6}$ kg.

Problem. Sap flows upwards through the xylem in trees through vessels with diameters ranging from 20 to 400 μm. Can capillarity alone account for the sap rising to a height of 100 m in a tree such as a *Sequoia*? The density and surface tension of the sap are 10^3 kg/m^3 and $70 \cdot 10^{-3}$ N/m, respectively.

Animals Extremes!

Highest Flyer – Ruppel´s griffon vulture (*Gyps fulcus*), one collided with an airplane off the Ivory Coast in 1973 at 11278 m; a migrating Bar-headed goose (*Anser indicus*) was once seen over the Himalayan Mountains in Nepal at roughly 8534 m.

Deepest Fish – the cuskeel (*Abyssobrotula galatheae*), which reaches 20 cm in length, holds the depth record among fish at 8370 m in the Puerto Rico Trench.

Deepest Fish – the cuskeel *Abyssobrotula galatheae*

Deepest Diver – the sperm whale (*Physeter catodon*) – about 2500 m.

Human Extremes!

The record for the deepest free-dive (170 m) belongs to Ferreras who spent 2 minutes 39 seconds underwater in October 2003, plunging on a sled to the depth, and inflating a balloon at the bottom to return to the surface.

Reinhold Meissner made the first ascent of Everest without oxygen in 1978.

VOCABULARY

English	Ukrainian	English	Ukrainian
Adhesion	Адгезія	Insomnia	Безсоння
Altitude sickness	Гірська хвороба	Lassitude	Утомленість, в'ялість
Alveole	Альвеола	Lassitude	Утомленість, в'ялість
Anorexia	Анорексія (відсутність апетиту)	Lungs	Легені
Ascent	Підйом	Malaise	Нездужання
Bends	Кесонна хвороба	Manifest hypoxia	Явна гіпоксія
Bilayer	Подвійний шар	Mountain sickness	Гірська хвороба
Bradicardia	Брадикардія (зменшена частота серцевих скорочень)	Narcosis	Наркоз
Bubble	Пухірець	Nausea	Нудота
Caisson disease	Кесонна хвороба	Osmosis	Осмос
Centripetal force	Доцентрова сила	Piston	Поршень
Chough	Клушиця	Plaque	Бляшка, тромбоцит
Cohesion	Когезія	Pneumotorax	Пневмоторакс
Compensated hypoxia	Компенсована гіпоксія	Poisoning	Отруєння
Concave	Угнутий	Polymyalgia rheumatica	Поліміалгія ревматична
Contact angle	Крайовий кут	Pond skater	Водомірка
Convex	Опуклий	Rheumatoid arthritis	Ревматоїдний артрит
Critical hypoxia	Гостра гіпоксія	Semi-permeability	Напів-проникність
Descent	Спуск	Surface tension	Поверхневий натяг
Drag	Гальмування, опір	Surfactants	Сурфактант
Dyspnea	Задишка	Tachycardia	Тахікардія
Flutter	Тремтіння	Temporal arteritis	Темпоральний артеріїт
Frictional force	Сила тертя	Trench	Западина
Gas embolism	Газова емболія	Twitching	Сіпання, смикання
Hematocrit	Гематокрит	Viscosity	В'язкість
Hodgkin's disease	Хвороба Ходжкіна	Vomiting	Блювання
Hyaline membrane disease	Гіаліново-мембранна хвороба	Wettable	Змочуючий
Hypoxia	Гіпоксія		

Control Questions and Problems

1. What is the pressure? What are the main units of pressure?
2. Explain the barometric formula.
3. What is the ideal fluid? Real fluid?

4. Formulate the Continuity Equation.
5. Formulate and explain Bernoulli's equation.
6. Formulate Newton's equation for real fluids.
7.What is laminar flow? Turbulent flow?
8. Formulate Stokes' Law. For which body it is true?
9. Formulate Poiseuille's Law of Flow.
10. What is the method flyuyidyzovanoyi bath?
11. What process is called ultracentrifugation?
12. What is surface tension?
13. Formulate the Laplace Equation.

Chapter 7. ACOUSTICS

The branch of science and technology that is devoted to the production, transmission, control, processing, transformation, reception, and interaction with material media of sound, ultrasound, and infrasound waves is called *acoustics.*

7.1. HARMONIC WAVES

A *harmonic wave* has a sinusoidal (or cosinusoidal) shape (fig. 7.1); the relationship between displacement and time can be written in equation form:

$$x = A\sin(\omega t + \varphi_0) \qquad (7.1)$$

where A is a measure of maximum amplitude, ω is a measure of angular frequency, and φ_0 is a measure of the starting phase.

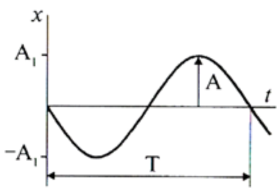


Fig.7.1. **A harmonic wave**

The maximum amplitude *refers to the maximal value of displacement the waveform achieves in one period.*

The *starting phase* of a sinusoid can be determined from the initial conditions.

wave to travel a distance of one wavelength is
ılar frequency and period are related by:

$$T = \frac{2\pi}{\omega} \qquad (7.2)$$

The *frequency* (*f*) of a harmonic wave equals the number of cycles a sine wave completes per unit of time; for instance, the number of times per second an object moves back and forth. The frequency is related to the period and angular frequency (ω) by the following relationships:

$$f = \frac{1}{T} \qquad (7.3)$$

$$\omega = 2\pi f \qquad (7.4)$$

The most common unit for *f* is *1/s* or *hertz (Hz)*.

The *energy* of a particle moving with harmonic motion is given by the following equations:

Kinetic energy of the particle:

$$E_к = \frac{mV^2}{2} = \frac{m}{2}[A\omega\cos(\omega t + \varphi_0)]^2 = \frac{mA^2\omega^2}{2}\cos^2(\omega t + \varphi_0) \qquad (7.5)$$

Potential energy of a particle:

$$E_n = \frac{kx^2}{2} = \frac{m^2\omega^2}{2}[A\omega\sin(\omega t + \varphi_0)]^2 = \frac{mA^2\omega^2}{2}\sin^2(\omega t + \varphi_0) \qquad (7.6)$$

Total energy of a particle:

$$E = E_к + E_n = \frac{mA^2\omega^2}{2}[\cos^2(\omega t + \varphi_0) + \sin^2(\omega t + \varphi_0)] = \frac{mA^2\omega^2}{2} \qquad (7.7)$$

where:

$$V = \frac{dx}{dt} = A\omega\cos(\omega t + \varphi_0) \qquad (7.8)$$

7.2. MODELING OSCILLATORY PROCESSES IN BIOLOGY

Lotka-Volterra Model. One of the first models which describes the interactions between two species in an ecosystem, a predator and a prey, was proposed in 1925 by the American biophysicist Alfred Lotka and the Italian mathematician Vito Volterra. The Lotka-Volterra model is based on differential equations.

Differential equation models make it possible to analyze a population at every moment in time. When considering two species, the model will involve two equations, one of which describes how the prey population changes and the second how the predator population changes.

Assuming the prey are rabbits and the predators are foxes, let N_1 and N_2 represent the number of rabbits and foxes, respectively, that are alive at time t. The prey population changes $\left(\frac{dN_1}{dt}\right)$ due to reproduction in proportion to the number (N_1) of rabbits:

$$\frac{dN_1}{dt} = aN_1 \qquad (7.9)$$

where a is a constant.

The prey population decreases the rabbit population at a rate that is proportional to the probability of their meeting (i.e., N_1N_2) which is described by equation:

$$\frac{dN_1}{dt} = -\ bN_1N_2 \qquad (7.10)$$

where b is a constant.

Therefore, changes in the prey population $\left(\frac{dN_1}{dt}\right)$ due to reproduction and predation mediated death can be described by the equation:

$$\frac{dN_1}{dt} = aN_1 - \ bN_1N_2 \qquad (7.11)$$

The same considerations can be applied to changes in the predator (fox) population due to death during the absence of food (rabbits) N_2 and increases due to finding (meeting) rabbits (N_1N_2):

$$\frac{dN_2}{dt} = -cN_2 + dN_1N_2 \qquad (7.12)$$

where c and d are constants.

Then the Lotka-Volterra model can be written as:

$$\left.\begin{aligned}\frac{dN_1}{dt} &= aN_1 - bN_1N_2\\ \frac{dN_2}{dt} &= -cN_2 + dN_1N_2\end{aligned}\right\} \qquad (7.13)$$

A graphical interpretation of the model (Fig. 7.2) illustrates that prey and predator populations will be in equilibrium when their rates of change are zero (i.e., births equal deaths).

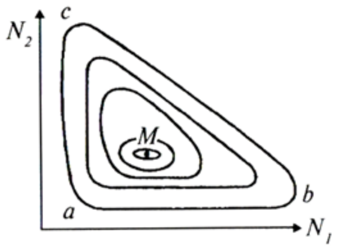


Fig. 7.2. **Prey and predator phase space**

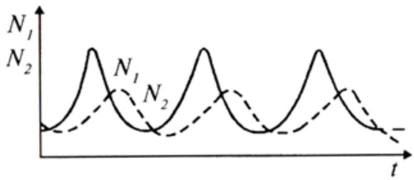


Fig. 7.3. **Prey and predator time series plot showing cycles of abundance with the predator cycles lagging behind the prey**

Hence, we can find the equilibrium *isoclines*, the lines where each species is constant, by solving the system of equations (7.13) when $\frac{dN_1}{dt} = \frac{dN_2}{dt} = 0$. Excluding time ($t$), the following expression is obtained:

$$\frac{dN_1}{dN_2} = \frac{Q(N_1, N_2)}{P(N_1, N_2)}. \qquad (7.14)$$

Solution of this equation gives a number of isoclines in predator-prey phase space N_1, N_2 (Fig. 7.2). It is possible to distinguish the following regions:

a-*b* – the prey population is growing because of the small population of predators; *b*-*c* – the predator population is growing while the prey is declining; *c*-*a* – both are populations declining.

A predator and prey time series plot shows cycles of abundance with the predator cycle lagging behind that of the prey (Fig. 7.3).

Formation of colonies. An oscillatory process in biology can be seen in populations of the amoebae *Dictyostelium discoidem,* which undergo periodical transitions from unicellular to a multicellular colony. The amoebae leave the spores as unicellular organisms; when nutrient deprivation takes place, the cells begin to form a colony which consists of several thousand of the cells. This process of cell aggregation is associated with the creation of a plasmodium which has a pedicle and head. The head contains the spores which are separating from it into the medium.

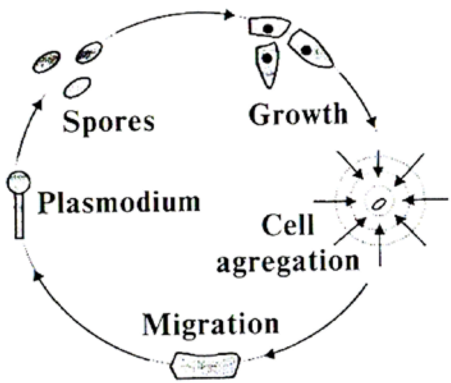


Fig. 7.4. **Formation of colony by the amoebae *Dictyostelium discoidem***

When they encounter a nutrient rich environment, they form a new colony by way of chemotactic migration (fig. 7.4).

7.3. ACOUSTIC WAVES

7.3.1. Classification of Acoustic Waves

A longitudinal wave that consists of a sequence of pressure pulses or an elastic displacement of the material, whether gas, liquid, or solid, is called an *acoustic wave.* There are three categories of acoustic waves that cover different ranges of frequency – sound, ultrasound, and infrasound waves.

7.3.2. Physical Characteristics of Sound Waves

Sound has three physical quantities: *frequency* (Ω), *intensity* (I), and *waveform* which correspond to the characteristics of sound that we hear – *pitch*, *loudness*, and *tone quality*. Sound waves that lie within the range of sensitivity of the human ear are called *audible sound waves*; these waves have a frequency ranging between approximately 20 Hz to 20000 Hz.

The *pitch* of a note is determined by the frequency; the more vibrations per second of the sound, the higher will be the pitch of the note.

The *intensity* or *loudness* of a sound is a measure of the energy impinging on a unit area of receiver surface per unit of time. The units of intensity are therefore W/m^2. The intensity of the faintest sound which can just be heard is about 10^{-12} W/m^2; the loudest tolerable sound has an intensity of approximately 1 W/m^2. Because of this wide range in intensities over which the ear operates, and because the ear can only discriminate between sounds of a certain intensity ratio whether they are loud or soft, a logarithmic rather than a linear intensity scale is used. The *intensity level* (B) of a sound wave is defined by the equation:

$$B = \lg \frac{I}{I_0} \qquad (7.15)$$

where I_0 is an arbitrary reference intensity and is conventionally taken as the threshold for hearing (i.e., 10^{-12} W/m^2). The intensity level is a dimensionless quantity and the unit is the *Bel (B)* or more commonly, the *decibel (dB)*.

$$dB = 10\lg \frac{I}{I_0} \qquad (7.16)$$

Table 7.1 gives some typical values for the sound levels from various sources or causing specific symptoms in humans.

7.1. Typical values of the sound levels from various sources or causing specific symptoms

Source of Sound	Sound Level, dB
Damage of eardrum	160
Nearby jet airplane	150
Threshold of pain	130
Rock concert	120
Subway	100
Busy traffic	80
Vacuum cleaner	70
Normal conversation	50
Mosquito buzzling	40
Rustling leaves	10

Example. The intensity of an ultrasound pulse produced by a bat during echolocation is about 10^{-2}W/m^2. Express this in decibels.

Solution. Using Equation (7.16), we shall find:

$$dB = 10\lg\frac{I}{I_0} = 10\lg\frac{10^{-2}}{10^{-12}} = 10\cdot 10 = 100 \text{ dB}$$

Tone quality corresponds to the complexity of the frequency composition of the sound produced by the source. A precision tuning fork will vibrate with only one frequency, producing a pure tone. However, most vibrating bodies, in addition to the *fundamental* or lowest frequency, have *harmonics* which are frequencies that are single multiplies of the fundamentals. If f is the fundamental frequency, then $2f$ is called the second harmonic. The relative amplitudes of the various harmonics are given as a *frequency spectrum*.

If a spherical body oscillates periodically, a sound wave with a spherical wave front will be produced. If P is the average power emitted by the source, then this power at any distance (r) from the source must be distributed over a spherical surface of area $4\pi r^2$. Hence, the wave intensity at distance r from the source is:

$$I = P/S = P/4\pi r^2 \qquad (7.17)$$

Example. A male deer produces a bellow in the forest. The intensity of the bellow at 1 m is $2\cdot 10^{-3}$ W/m^2. How far away can the male be heard by a female, if a sound intensity of about 10^{-8} W/m^2 is required to hear the male.

Solution. Using equation 7.17, we obtain:

$$r^2 = P/4\pi I = 2\cdot 10^{-3}\,\text{W}/4\pi\cdot(1\text{m})^2 = 2\cdot 10^{-8}\,\text{W}/4\pi\cdot(x)^2$$

$$x^2 = 2\cdot10^{-3}\,\mathrm{W}/4\pi\cdot(1\mathrm{m})^2/10^{-8}\,\mathrm{W}/4\pi = 2\cdot(3.2)^2\cdot10^2\,\mathrm{m}^2$$
$$x = 4.5\cdot10^2\,\mathrm{m}.$$

7.3.3. Physical Characteristics of Ultrasound Waves

Ultrasonic waves are longitudinal waves with frequencies over 20000 Hz, which is about the upper limit of human hearing. The primary unique features of ultrasound are its *high energy* and *rectilinearity of propagation*.

7.3.4. Physical Characteristics of Infrasound Waves

Infrasonic waves are longitudinal waves with frequencies below the audible range (i.e., less than approximately 20 Hz). Infrasound is generated by various events in nature, by numerous man-made systems, and by routine living activities and is experienced by everyone in varying degrees. Infrasound is especially dangerous, due to its strong vibrations, and it is characterized by an ability to cover long distances and circumventing obstacles with little dissipation. Not much amplitude is needed to produce negative effects on humans. Infrasound typically occurs at relatively low levels in natural environments due to thunder, air turbulence, volcanic activity, earthquakes, hurricanes, wind, large waterfalls, ocean waves and the impact of waves on beaches. Man-made structures, such as the high-powered propulsion systems of aircraft and space vehicles, ships, trains, motorcycles, atomic weapons, air heating and cooling units, compressors and transformers in closed spaces produce infrasound.

Infrasound can cause physical pressure, fear, disorientation, undesirable physical and mental symptoms, and explode matter, and incapacitate. It disrupts the normal functioning of the middle and inner ear, leading to nausea, imbalance, impaired equilibrium, immobilization, and disorientation. High infrasound intensities can cause death.

Certain animals can perceive infrasound and use it for various purposes. Whales and elephants are known to use infrasound to communicate over distances of several kilometers.

Control Questions and Problems

1. What is the simple harmonic motion?
2. Explain the equation of harmonic oscillation and its parameters.
3. Explain Lotka-Volterra Model.
4. What is Bel? Decibel?
5. Give definition of ultrasound and infrasound waves.

Chapter 8. BIOACOUSTICS

Bioacoustics is a branch of biophysics that studies sounds produced by living organisms, especially sounds involved in communication, signalization and spatial orientation due to echolocation [2, 14].

8.1. Sound Production

Human bioacoustics. Sound is produced by the vocal chords which are stimulated to vibrate by air passing through the wind pipe from the lungs. The fundamental note of a spoken word is set up by this process and the sound is then given quality when harmonics are set up in the resonating cavities of the pharynx, mouth and nose.

Animal bioacoustics. The production of sound in animals is often limited by two factors: the frequency range of muscular contractions and the size of the sound emitter. Even the fastest muscles are not able to contract faster than about 1000 times per second (1 kHz).

Birds bioacoustics. There are two types of sound signals emitted by birds: calls and songs. Calls often appear to be single elements of a bird's song. Conversely, songs tend to be longer and their acoustic structure more complex than calls. Variations in intensity, frequency, the duration of individual pulses and in the time between them, and in the spectral complexity are all evident. Species-specific song patterns are often used to communicate that a territory is occupied by a particular species.

Insect bioacoustics. There is a very wide range of sound producing and detecting devices among insects. Male *Drosophila*, for example, beats a wing in the direction of his chosen female which she tunes to using a velocity sensitive hearing device made up of sensory hairs that respond to displacements of the surrounding air. The receptors are located in the anal cerci and in the antenna.

Fish bioacoustics. The acoustic signals produced by fish are usually low-frequency and pulsatile, conforming to fixed or variable temporal patterns. Their nature confirms the importance of temporal cues for fish as opposed to the spectral or frequency characteristics which are so important to the mammalian auditory system. To humans, the sounds produced by fish are like "pops" and "crunches". They are often generated by scraping bones or teeth together, or by the rapid contraction of muscles which alter the volume of the swim bladder producing an audible sound.

8.2. Echolocation

Echolocation is the ability of animals to determine their orientation to other objects through interpretation of reflected sound. Bats, whales and dolphins are noted for this ability, though certain other mammals and birds also use echolocation. It is most often used to navigate through poor light conditions or to identify and track prey.

Echolocation permits whales, which swim at high speeds, to obtain information about their environment at much longer distances than would be possible from vision, even in the clearest water. Developing a sounding technique has probably been essential to these animals in occupying niches for high-speed predators.

The maximum dolphin echolocation range for identifying a 8-cm metal sphere has been measured at 100 m. Dolphins are capable of identifying the nature of their targets with great accuracy.

A few species of birds have developed more limited echolocation capabilities, which allows them to nest deep in caves.

Some insects, such as *noctuid moths*, have ears specially adapted to avoid predators, such as bats. The ear structure consists of a tympanic cavity, a membrane and three neurons in a scolopida formation. The system is stimulated by the ultrasonic vibrations of the bat. One specific neuron is sensitive to the low intensity vibrations picked up from distant predators, and a different neuron is sensitive to the strong vibrations of a nearby predator.

The precise mechanism involved in echolocation by animals is not completely understood. There are at present three primary hypotheses. The simplest means of locating the distance of an object involves timing the interval between the emission of a high frequency sound and the arrival of the echo. Many echolocating animals emit a sound containing both a long-duration, constant-frequency component and a frequency sweep. Other animals employ different types of pulses or pairs of short pulses.

There are two types of echolocating processes used by bats which allows bats to not only fly in darkness but even catch flying insects. The first uses short frequency modulated pulses. The second uses long continuous pure tones. The shape and duration of a typical short pulse used by the Long-Eared bat is shown in Fig. 5. The pulse is both amplitude modulated (AM) and frequency modulated (FM) so that it has some similarities to radio communication. The modulation serves many purposes. Under some conditions, such as flying in caves, the bat has to recognize which echoes are his in the midst of echoes from other bats. In addition, the modulation must somehow give the bat information on the size, shape, motion, and perhaps even the texture, of the object. When flying and searching for insects, a bat sends out pulses at a rate of about four per second; each pulse has a duration of about $1.5 \cdot 10^{-3}$ s. The frequency of a typical pulse descends from about 70 kHz to 30 kHz. The total distance traveled by the pulse and the echo is twice the distance (d) between the bat and the object. One can obtain d from the following expression $d = \frac{Vt}{2}$, where V = 340 m/s, and t is a time interval between emission and reception of the pulse. The second probable mechanism of echolocation depends on the ability of the animals to discriminate between echoes on an intensity basis. The intensity of the echo decreases as the fourth power of the distance of the animal from the object and by simply using successive measurements of the echo intensity, the animal can determine whether it is approaching or receding from the object.

Example. If a bat detects an echo from an insect, it increases the frequency of pulses to as high as 100 pulses per second. What is the bat-object distance?

Soultion. The distance (D) between the bat and insect is given by:

$$D = Vt/2 = (340 \text{ m/s}) \cdot (1/100 \text{ s})/2 = 1.7 \text{ m.}$$

The third mechanism is based on the frequency change of the echo which is called the Doppler effect.

8.3. The Doppler Effect

There is a well known train-spotter's observation that the pitch of a train's whistle changes as it passes the observer. As the train approaches, the observer hears a note which is higher than the true note and on passing, the pitch quickly falls to a lower note than the true pitch. Doppler in 1842 was the first to give an explanation for the phenomenon which has been entitled the *Doppler effect*. In the example above, if the frequency of the whistle is f_0 when the train is stationary, then the frequency (f) as detected by an observer alongside the track, differs from f_0 in relation to the speed (V) of the train. The fractional change in the apparent frequency of the whistle (i.e. $(f - f_0)/f_0$) is related to the velocity of the train by the formula:

$$(f - f_0)/f_0 = \pm V/V_s \qquad (8.1)$$

Here V_s is the speed of sound. A + sign indicates the train is approaching the observer and a – sign indicates the train is moving away from the trackside observer.

When either the source or the receiver of a propagating wave moves, there is usually a change in frequency called the *Doppler shift.* Such a shift can be used to determine the velocity of the target along the line to it, which is to say its *approach velocity*. If the transmitter generates a frequency of f_0, the velocity of the sound is V_s, and the approach velocity is a much smaller value (V_a), the received frequency is approximated by:

$$f = f_0 \left(1 + \frac{2V_a}{V_s}\right) \qquad (8.2)$$

The frequency shift is proportional to the approach velocity:

$$\Delta f = f - f_0 = \frac{2 f_0}{V_s} V_a \qquad (8.3)$$

Example. What is the Doppler frequency shift received by a bat, if the insect is immobile with respect to the bat's motion with the velocity equal to 5 m/s. The frequency of the bat's sound is 60 kHz.

Solution. We can insert the values into the Doppler shift equation (8.3):

$$\Delta f = \frac{2 f_0}{V_s} V_a = \frac{2 \cdot 60 \cdot 10^3 \, Hz}{340 m/s} 5 m/s = 1.76 \text{ kHz}$$

The Doppler effect enables one to measure the translational, rotational speed, and the frequency of flagellum beatings of microorganisms. The Doppler shift of sound waves scattered by moving erythrocytes (red blood cells) is used to measure the speed of blood flow; also the Doppler shift of light waves scattered by moving blood in the retina can be used to study blood flow there.

"I love hearing that lonesome wail of the train whistle as the magnitude of the frequency of the wave changes due to the Doppler effect."
(From R.A. Serway, 1992)

Control Questions and Problems

1. What is Bioacoustics?
2. What does it mean echolocation?
3. Explain the Doppler effect.

Chapter 9. ACOUSTOBIOLOGY

Acoustobiology is the branch of biophysics which studies of how living organisms hear sounds, and how sounds affect them physically and behaviorally [12, 24, 27].

9.1. Acoustoreception

Mammals. The *ear* is one of the most remarkable devices known to science. This section considers several of the properties and mechanisms of the ear. The ear is divided into three parts designated simply as *outer*, *middle* and *inner* ear (fig. 9.1).

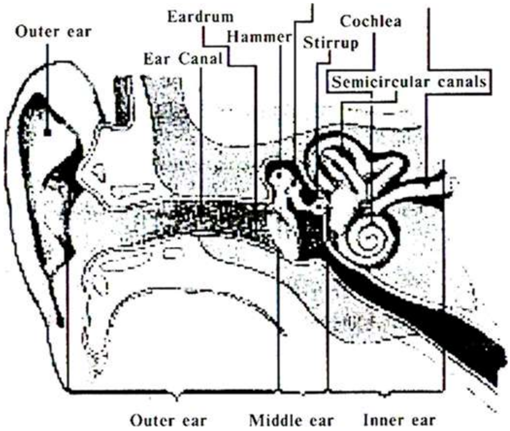


Fig. 9.1. **Diagram of the human ear**

The function of outer ear is *optimization and amplification of the important frequencies*. The outer ear plays a major role in helping us hear the frequencies associated with certain kinds of sound while at the same time reducing the effect of less important sounds. The mechanism by which this is achieved is, in part, the phenomenon of *resonance*. In sound, resonance arises from the production of standing waves in the tube consisting of the auditory canal and the middle ear. At the closed end of the tube, which is the skull surface of the middle ear, there is a node. The fundamental resonant frequency occurs when the length of the canal is equal to one-quarter of the corresponding wavelength, as shown in fig. 9.2

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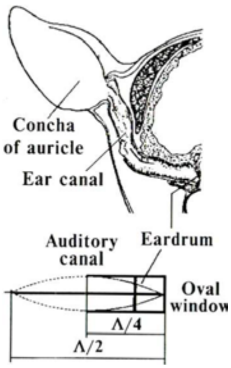


Fig. 9.2. **Formation of standing wave in the outer ear**

The middle ear has two functions – *transduction and amplification.* First, it must respond efficiently to the incoming sound disturbance. This is not a simple task since sound waves are easily reflected at surfaces. In order to "couple" effectively with the sound, the *eardrum* has to move with the air molecules as they oscillate at the sound frequency. To do this, the eardrum has to be extremely elastic and delicate.

The combined effect of the eardrum and the *ossicles*, the small bones of the middle ear, is to convert the sound energy into mechanical energy.

The *lever action* of these ossicles leads to more forceful displacement at the *oval window*, although a reduction in amplitude simultaneously takes place. The process is analogous to a *pressure intensifier* as shown in fig. 9.3.

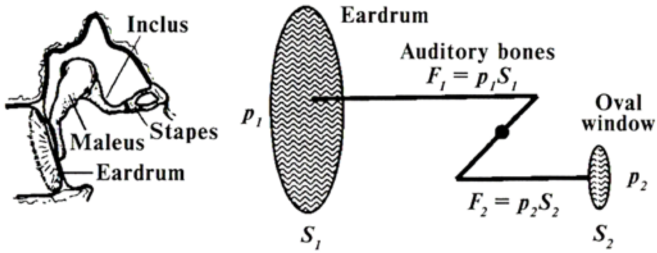


Fig. 9.3. **A model which explains the functioning of the middle ear**

The pressure is amplified according to the equations:

$$F_1 = F_2 \quad (9.1)$$

$$p_1S_1 = p_2S_2 \quad (9.2)$$

$$p_2 = (S_1/S_2)p_1 \quad (9.3)$$

Example. Compute the theoretical pressure amplification associated with the transfer of power from the outer to inner ear. The area of the tympanic membrane (eardrum) is 55 mm^2. We can express the force as a product of the pressure on the eardrum and the area of eardrum (F_1) = p_e55. The theoretical mechanical advantage of the lever system, which is created by the ossicles, is about 1.4. This means that the force (F_{ow}) on the oval window is 1.4 times F_1, or $F_{ow} = 1.4\ F_1$. Then p_1 can be expressed in terms of F_{ow} by $p_e = F_1/55 = F_{ow}/(1.4)(55) = F_{ow}/77$. The area of the oval window is about 3.2 mm^2, so the pressure on the oval window is given by $p_{ow} = F_{ow}/3.2$. The theoretical pressure amplification $p_{ow}/\ p_e = (F_{ow}/3.2)/(\ F_{ow}/77) = 24$. This value can be compared with actual experimental measurements, in which the pressure amplification has been reported to be 17.

The functions of the inner ear are *pitch resolution and detection.* Fig. 9.4 shows a highly schematicized diagram of a cross-section of the *cochlea.*

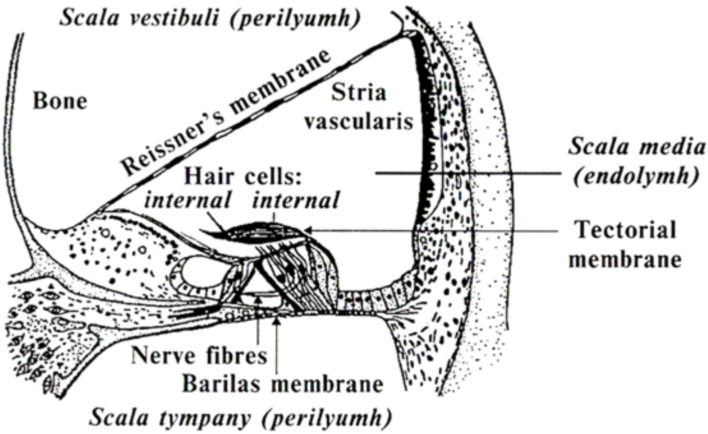


Fig. 9.4. **A cross section of the cochlea**

Essentially the organ contains two fluid-filled chambers divided by a membrane, called the *basilar membrane.* This membrane does not, however, completely separate the two chambers. A small opening, called the *helicotrema,* is present at the distal or innermost part of the system. The basilar membrane contains the *neural detecting cells,* which are small hair-like cells which are triggered by shear effects occurring between the fluid and the membrane. Thus, any lateral or sideways motion of the membrane with respect to the fluid is detected. The oval window is forced to vibrate by the action of the ossicles which, in turn, causes an oscillating pressure in the upper chamber. This pressure can be equilibrated by the membrane bulging downward. The bulging process produces the shearing effects which can be detected by the hairs which are located between the tectorial and basilar membranes (fig. 9.5).

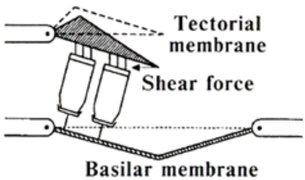


Fig. 9.5. **Schematic diagram of shearing force created between the hair cells and the tectorial membrane as a result of basilar membrane displacement**

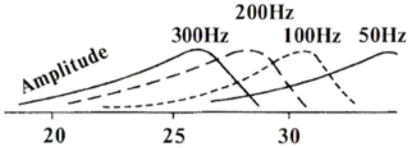


Fig. 9.6. **Theory of von Bekesy: dependence of the position of maximum vibration amplitude on the sound frequency**

in.

According to von Bekesy's theory, different frequencies will cause a maximum vibration amplitude at different points along membrane (fig. 9.6).

Birds. Hearing is particularly important when the birds rest or perch. It also facilitates communication over long distances in vegetative or arboreal environments where vision may be partially or completely occluded. Birds (like mammals) have an external ear and an ear canal which leads to a recessed ear drum. In many birds, the outer opening of the ear canal is surrounded by specialized feathers in the form of a funnel which act as an efficient sound collector. The facial ruff of certain owls is shaped either like a single parabola or as two parabolas side by side, separated by the beak at the midline. Such a design increases the animal's acoustic sensitivity. Peak sensitivity for birds occurs at 2 kHz. One of the most interesting characteristics of a birds' auditory system is the ability to resolve the small differences that exist in the frequency of most sounds, called frequency modulation. Birds are able to detect a frequency change of only 10-15 Hz. These slow or rapid changes in acoustic frequency enable a bird to recognize a member of its own species. In birds, the ability to determine the exact location of a sound source depends on a variety of factors. The barn owl, for instance, is capable of orienting to a sound source in space with an error of less than 2 degrees.

Fish have a labyrinth, or inner ear which extends their hearing to higher frequencies. Sound waves travel to chambers where small granules called *otholits* are located. These granules stimulate sensory hair cells and trigger action potentials in the neurons of the auditory nerve.

The gas bladders of some fish also provide an area of variable density. Vibrations pass through the gas bladder and travel through a pathway of small bones called *Weber ossicles.* These serve to connect the gas bladder directly with the inner ear of the fish.

9.2. Ultrasound Therapy

Ultrasound is generated by a piezoelectric transducer and can be directed into the human body by contact with the skin. As ultrasound travels through the body, it is reflected by interfaces between tissues of different densities, the larger the density change the greater the reflection. The reflected signals (echoes) are detected and analyzed to establish the picture of internal organs, a fetus in the uterus or kidney stones. The technique is called *ultrasound scanning.* The conversion of the echo pattern into a two-dimensional picture of the internal organs is the basis of *ultrasound imaging techniques. Doppler ultrasonography* examines the blood flow in the major arteries and veins and provides blood velocity measurements (the Doppler effect is discussed in Section 8.3).

There are numerous exciting new applications of ultrasound therapy in cosmetic surgery. New and current uses of ultrasound include facial and body skin rejuvenating treatments, reduction of stretch marks, treatment of contracture and scar tissue such as around breast implants, and pre- and post-operative treatment of plastic surgery patients to accelerate healing and recovery after procedures such as face lifts, tummy tucks, and liposuction. Ultrasound applied over certain creams contributes to greater effectiveness through deeper and more thorough penetration of the products. Ultrasound can be used to shatter kidney stones, research dolphin's language, train dogs and clean contact lens.

The use of ultrasound in dental diagnostics and therapy provides an alternative approach to conventional instrumentation. Patient discomfort and the need for drugs like Novocain are virtually eliminated.

9.3. The Mechanisms of Ultrasound Action

The mechanisms of action of ultrasound include: a thermal effect, which relates to the heat generated in the deeper tissues and especially the collagen; a mechanical effect, which relates to the high-speed vibrations that act on the tissue like a micromassage; a cavitation effect, which refers to the production of countless microscopic droplets of oxygen from the vibrational process; and biological effects, which include blood vessel dilatation, improved blood flow and circulation, improved lymph flow, muscle relaxation, reduced inflammation and pain relief.

Control Works
Modulus 4
Acoustics, Bioacoustics, Acoustobiology

Problem. Estimate the intensity of sound which causes pain using Table 6.1.

Answer: 10 W/m^2.

Problem. A point source emits sound waves with a power of 80 W. Find the intensity at a distance 3 m from the source.

Answer: 0.707 W/m^2.

Problem. The bats of the *Vespertilionidae* family emit short high frequency pulses. Find the time of echo arrival after emission if the distance between the bat and insect is 10 m.

Answer: 58.8 ms.

Example. Doppler ultrasound technique is able to measure blood velocity. If an artery has a typical blood velocity (about 1 m/s), what is the magnitude of the Doppler shift, if the velocity of ultrasound in the blood is 1500 m/s and the frequency is 5 MHz?

Answer: 6.7 kHz.

VOCABULARY

English	Ukrainian	English	Ukrainian
Abundance	Безліч	Loudness	Гучність
Amplitude	Амплітуда	Nausea	Нудота
Basilar membrane	Базілярна мембрана	Neural detecting cells	Нервові чутливі клітини
Cercus	Хвостовий придаток	Obstacle	Препона
Cochlea	Завитка	Ossicle	Кісточка
Contracture	Контрактура	Oval window	Овальне віконце
Crunsh	Хрускіт	Pain relief	Послаблення болю
Dissipation	Розсіювання	Pharynx	Глотка
Dilatation	Розширення	Phase space	Фазовий простір
Eardrum	Барабанна перетинка	Pitch	Висота звуку
Face lift	Підтягування зморшок на обличчі	Pop	Звук пострілу
Frequency	Частота	Predator	Хижак
Frequency spectrum	Частотний спектр	Prey	Жертва
Fundamental frequency	Основна частота	Propagation	Поширення
Harmonic	Гармоніка	Rectilinearity	Прямолінійність
Helicotrema	Гелікотрема, отвір у внутрішньому вусі	Scar tissue	Шрам, рубець
Inflammation	Запалення	Scolopidium	Сколопідій
Intensity level	Рівень інтенсивності	Starting phase	Початкова фаза
Isocline	Ізокліна	Tone quality	Тон звуку
Kidney stones	Каміння у нирках	Tympanic cavity	Барабанна порожнина
Liposuction	Видалення жиру	Waveform	Фронт хвилі

Animals Extremes!

The sensitivity of cockroaches (*Blattodeae*) to vibrations is 10^{-8} cm – the amplitude of these vibrations is equal to the diameter of hydrogen atom.

Most Powerful Sound – Finback whale (*Balaenoptera*) – 10 W, within a range of 10000 km.

Best Hearing – Barn Owl (*Tyto alba*) and Great Horned Owl (*Bubo virginianus*).

Control Questions and Problems

1. Explain the structure and function of the human ear
2. What are the functions of the outer ear?
3. How amplification of weak acoustic signals is relized in the middle ear?
4. What are the principles of the frequency analysis of sound signals in the inner ear?
5. Explain the main mechanisms of ultrasound action on living organisms.

Chapter 10. MOLECULAR PHYSICS

10.1. IDEAL GAS

An *ideal gas* is a hypothetical gas with molecules of negligible size and exert no intermolecular forces. Most gases at room temperature and atmospheric pressure behave as ideal gases. The *ideal gas law* relates the pressure (p), temperature (T), and volume (V):

$$pV = nRT \qquad (10.1)$$

where $n = m/M$ is the number of moles, m is mass of gas, M is molecular weight of the substance (g/mole), and R is the universal gas constant (8.31 J/mol·K = 0.0821 L·atm/mol·K).

The previous equation can be written as:

$$pV = NkT \qquad (10.2)$$

where N is the total number of molecules, and k the Boltzmann's constant ($1.38\cdot10^{-23}$ J/K).

10.2. REAL GAS

Real gases exhibit properties contrary to the ideal gas law; for example, real gas particles have a finite volume and measurable intermolecular forces. These two effects can be incorporated into a modified *van der Waals' equation* as:

$$(p + \frac{a}{V^2})(V - b) = RT \qquad (10.3)$$

where *a* and *b* are empirical constants.

Isotherms for a real gas are presented in fig. 10.1. Below the critical temperature (T_c), the substance could be in a liquid, liquid-vapor, or gaseous state, depending on the pressure and volume.

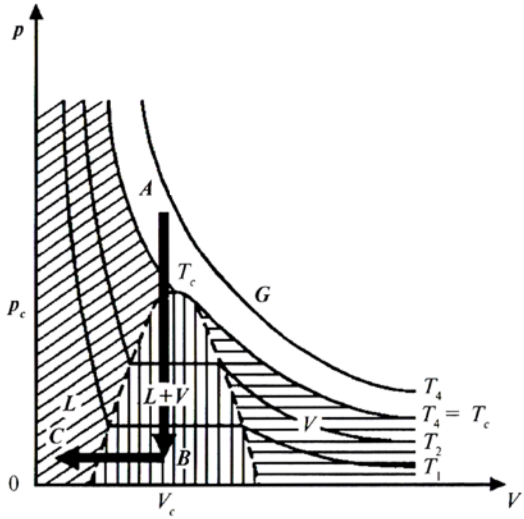


Fig. 10.1. **Isoterms of a real gas: *G* – gas; *V* – vapour; *L* – liquid; *L* + *V* – liquid and vapour; T_c – critical temperature; p_c – critical pressure; V_c – critical volume**

Liquefaction technology for a real gas is related to isochoric (AB) and isobaric (BC) processes.

10.3. HUMIDITY

10.3.1. Parameters of humidity

Water can exist in the atmosphere in three phases: gaseous, liquid and solid. It is called a *vapor* when in the gaseous phase and as water evaporates, the concentration of water molecules in the gas phase increases. Eventually an equilibrium is established when the number of molecules escaping from the liquid water equals the number being recaptured by the liquid. The equilibrium vapor pressure established between liquid water and water vapor in a closed system is known as the *saturation vapor pressure* (E).

Humidity is the content of water vapor in the air and can be expressed several ways.

Absolute humidity (a) is the mass (m) of water vapor (grams) per unit volume (V) of moist air (m^3): $a = m/V$.

Partial pressure (e) is defined as the pressure exerted by one gas in a mixture of gases.

*Relative humidity (*r*)* is the ratio of the actual partial vapor pressure of water to the saturation vapor pressure at a given temperature: r = $\frac{e}{E}\cdot 100$.

Vapor deficit (d) is the difference in vapor pressure between saturated and ambient air: $d = E - e$.

Dew point (T_d) is the temperature to which, if unsaturated air is cooled, the water vapor becomes saturated.

10.3.2. Psychrometer Equation

The psychrometer is the instrument used to determine air humidity. It consists of two thermometers – one measuring the air temperature (T_a) is the dry-bulb thermometer, and the second, the wet-bulb thermometer, has a muslin jacket which stands in a reservoir of water and measures the temperature (T_w). The wet bulb temperature is lower than that of the air due to evaporation of water from the muslin. The relationship between the two thermometer readings can be written as a *psychrometer equation:*

$$e = E_1 - A(T_a - T_w)p_A \qquad (10.4)$$

where e is the water vapor pressure, E_1 the saturated vapor pressure at the temperature of the wet-bulb thermometer, A the psychrometric coefficient

(6.62·10^{-4} K^{-1}), T_a the air temperature, T_w the wet-bulb thermometer temperature, and p_A the atmospheric pressure (mm Hg or Pa).

Control Questions and Problems

1. What is an ideal gas? Write the equation of state of ideal gas.
2. What process is called isothermal? isobaric? isochoric?
3. Formulate van der Waals' equation.
4. Define the Humidity and its principal parameters.
5. Explain the psychrometer equation.

11. MOLECULAR BIOPHYSICS

11.1. CHEMORECEPTION

Chemoreception is the ability of living organisms to perceive specific molecules in air and water. These molecules maybe important clues to the presence of specific objects in the environment and are essential to many animals in finding food, locating a mate and avoiding danger.

Chemoreception is divided into two categories: *gustation (taste)* and *olfaction (smell).* Gustatory receptors respond to dissolved molecules that come in contact with the receptors. Olfactory receptors respond to airborne molecules from external sources that may be some distance away.

Fig. 11.1. **Sensory hairs on the antennae of a moth**

Vertebtrates usually accomplish chemoreception by moving chemically rich air or water into a canal or sac that contains chemical receptors. Chemoreception is quite different between invertebrates and vertebrates. For example, planarians find food by following chemical gradients in their surroundings. Their simple chemoreceptors are found in pits on their bodies, over which they move water with cilia.

Ins in their body surface, mouthparts, antennae an ıple, smell with thousands of sensory hairs on the

About 70 percent of the adult male receptors respond to only one compound (*bombykol*), a sex attractant released by females of the species. The molecules enter the tiny pores of the hair, or sensillum, where the olfactory receptors are found. There is evidence that fish and turtles can distinguish the smell of the area (stream or beach) where they were born and use this information as a navigational tool. Salmon begin their lives in freshwater streams, where they stay from several months to as long as two years, depending upon the species. After they reach about an inch in length, the young fish swim downstream to the ocean, where they remain for two to seven years and may range 1600 km or more from their stream of origin. Salmon return to these natal streams, however, to reproduce. Many scientists believe that a combination of geographic features, temperature, magnetic, celestial and chemical cues, hearing, and other factors are involved in orientation mechanisms for salmon migration. When migrating salmon make the transition from marine into fresh water, they appear to rely primarily upon their sense of smell of rotting vegetation, insects, fish, dust released from local rocks and soils, and amino acids dissolved in water.

11.2. OLFACTORY (SMELL) MECHANISMS

11.2.1. Olfactory System

In humans, the receptors for the olfactory nerves are located in the upper part of the nasal cavity (fig. 11.2). The olfactory sense organ consists of *hair-like cells* at the end of a neuron.

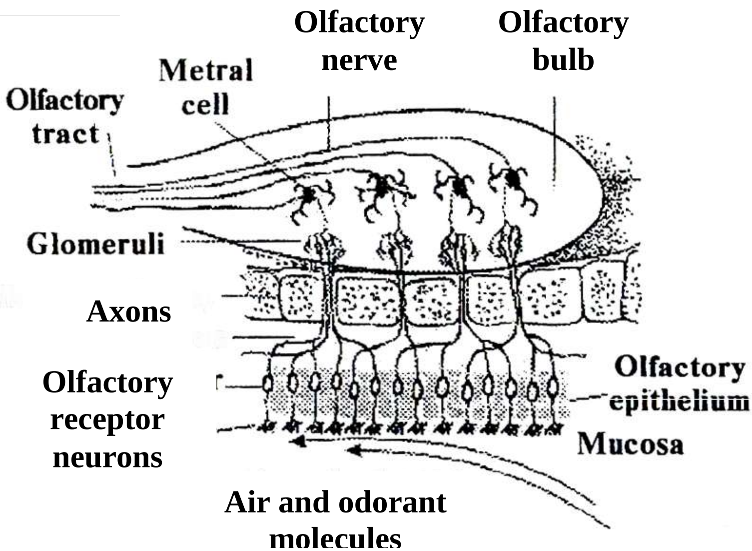


Fig. 11.2. **The olfactory sense organ in the upper part of the nasal cavity**

Canals lined with sheets of receptors within the nasal cavity are called *turbinates.* Protruding from the end of the nerve are thin cilia that are covered by mucus. Humans have about 10 cm^2 (1.6 sq in) of olfactory epithelium, whereas some dogs have 170 cm^2 (26 sq in).

In insects smells are sensed by olfactory sensory neurons in the chemosensory sensilla, which are present in insect antenna, palps and tarsa, but also on other parts of the insect body.

11.2.2. Mechanism of Olfaction

Molecules are absorbed into the mucous layer and passed to the cilia where the chemical is detected. The chemicals must be dissolved in the mucus and be absorbed in order for the olfactory receptors to react; hence, the solubility of the odorant influences perception. Thus, moisture is essential for the perception of smell.

The smell stimulates the receptor cells. Bundles of unmyelinated axons of the olfactory receptors unite to form olfactory nerve, which carry olfactory nerve impulses to the olfactory bulb. This in turn conducts the impulses to the olfactory area in the cerebral cortex of the temporal lobe of the cerebral hemisphere through the olfactory nerve.

11.3. GUSTATORY (TASTE) MECHANISMS

11.3.1. Gustatory System

The receptors for the gustatory nerves are known as *tastebuds* and are located on the tongue and the roof of the mouth (fig. 11.3). Sweet, sour, bitter and salty are the basic taste sensations resulting from stimulation of the tastebuds. These four basic tastes may have evolved to assess the basic properties of foods. Sweet taste signals food high in calories, salty foods indicate foods that help maintain water balance, sour tastes may signal foods that could be dangerous if eaten in excess, and bitter taste sensations signal toxic foods.

Insects have contact receptors called *taste hairs* or *sensilla.* At the tip of each sensillum is a tiny pore that allows molecules to reach the sensory cells. Each cell is sensitive to a different chemical. Sensilla can be located in a variety of body parts. Flies, for example, have sensilla on their feet.

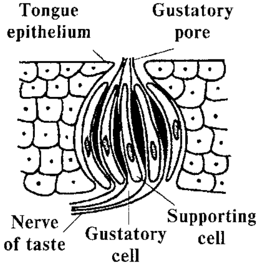


Fig. 11.3. **The receptors for the gustatory nerves (taste buds) located on the tongue and the roof of the mouth**

11.3.2. Mechanisms of Taste Reception

The chemicals present in food dissolve in the saliva and enter the taste buds through the pores, which reacts with пlycocalyx (the glycoprotein-polysaccharide), which is a molecular sieve, that sorts molecules, depending on their size, charge, and other parameters, and is adsorbed onto the cell membrane microvilli, coming into contact with the receptor protein. It is supposed that microvilli contain specific receptor sites that receive only their own molecules of substane. The result is a depolarization of the membrane and the generation of the of receptor potential. This stimulation is transmitted through the nerve fibres as electrical impulses. The nerve fibres of the taste receptor cells become part of the facial, the glossopharyngeal and the vagus nerves. These nerves pass through the brain stem. The sense of taste is perceived in the taste centre of the cerebral cortex

11.4. COMMUNICATION BETWEEN ANIMALS BY SMELL AND TASTE

Pheromones are molecules used for communication between animals. The word “pheromone” comes from the Greek words “pherein” (to carry, transfer) and “hormon” (to excite, stimulate). *Biological communication* is an action on the part of one organism (or cell) that alters the probability pattern of behavior in another organism (or cell) in an adaptive fashion. In such a way, communication occurs when one animal’s behavior can be shown to have an effect on the behavior of another. Examples of ant, bee, moth, termite and mammal pheromones and their function(s) are presented in Table 11.1.

For terrestrial animals, the long-range sex attractants are usually in the range of 200 to 300 daltons in size (15-20 carbon atoms), whereas alarm pheromones, which must act quickly, are in the range of 100-200 daltons. Pheromones that are transmitted only through water are generally more polar and may be as large as proteins. Peptides are an obvious possibility for waterborne pheromones.

11.5. PHYTOREMEDIATION[†]

Phytoremediation (from Ancient Greek φυτο (phyto), meaning ”plant”, and Latin remedium, meaning “restoring balance”) describes the treatment of environmental problems (bioremediation) through the use of

[†] Phytoremediation http://en.wikipedia.org/wiki/Phytoremediation

plants that mitigate the environmental problem without the need to excavate the contaminant material and dispose of it elsewhere.

Phytoremediation consists of mitigating pollutant concentrations in contaminated soils, water, or air, with plants able to contain, degrade, or eliminate metals, pesticides, solvents, explosives, crude oil and its derivatives, and various other contaminants from the media that contain them.

The following is a list of six different types of phytoremediation with explanations describing how they work.

Phytoextraction – uptake and concentration of substances from the environment into the plant biomass.

Phytostabilization – reducing the mobility of substances in the environment, for example, by limiting the leaching of substances from the soil.

Phytotransformation – chemical modification of environmental substances as a direct result of plant metabolism, often resulting in their inactivation, degradation (phytodegradation), or immobilization (phytostabilization).

Phytostimulation – enhancement of soil microbial activity for the degradation of contaminants, typically by organisms that associate with roots. This process is also known as rhizosphere degradation. Phytostimulation can also involve aquatic plants supporting active populations of microbial degraders, as in the stimulation of atrazine degradation by hornwort.

Phytovolatilization – removal of substances from soil or water with release into the air, sometimes as a result of phytotransformation to more volatile and/or less polluting substances.

Rhizofiltration – filtering water through a mass of roots to remove toxic substances or excess nutrients. The pollutants remain absorbed in or adsorbed to the roots.

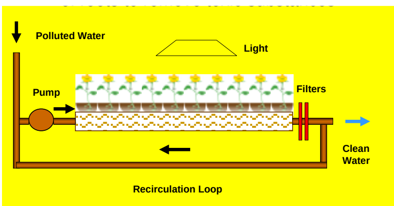


Fig. 11.4. **Purification of water through rhizofltration**

11.1. *Chemical compounds and functions of pheromones among the animals*

Compound	Function	Family	Genus
Benzaldegyde	Trail pheromone Defense Male sex pheromone	Bee, Apidae Ant, Formicidae Moth, Amphipyrinae	*Trigona* *Veromessor* *Pseudaletia*
2-Tridecanone	Alarm pheromone Defense	Ant, Formicidae Termite, Rhinotermitidae	*Acanthomyops* *Schedorhinotermes*
Dehydro-exo-brevicomin	Male sex pheromone	Mammals	Mouse, *Mus*
Exo-brevico-min	Aggregation pheromone	Insect	Bark beetle, *Dendroctonus*
(Z)-7-Dodecen-1-yl acetate	Female sex pheromone	Mammal Insect	Asian elephant, *Elephas maximus* ~140 species of moth

Control Questions and Problems
1. Define the smell.
2. What are the principal mechanisms of smell?
3. Define the taste.
4. What are the principal mechanisms of taste?
5. Describe the chemical communication of insects.

Chapter 12.THERMODYNAMICS

12.1. DEFINITION OF THERMODYNAMICS

Thermodynamics is a science which is concerned with the study of the most general properties of macroscopic physical systems which are in a state of thermodynamic equilibrium and the processes of transition between these systems. The laws of thermodynamics describe the relationship among heat flow, work, and the internal energy of a system. Thermal phenomena can be also understood using a microscopic approach, which describes what is happening on a molecular scale. For example, temperature is a measure of certain properties of molecules.

12.2. TEMPERATURE

Temperature is the property of a body or a region of space that determines whether or not there will be a net flow of heat into or out of it from a neighboring body or region and in which direction (if any) the heat will flow. Temperature is a condition with respect to heat or cold, especially as indicated by the sensation produced. But our senses are often unreliable. Various types of thermometers or pyrometers provide the quantitative measurements of the degree of heat or cold (high or low temperature, temperature of freezing or boiling). There are three temperature scale in use today, Celsius, Kelvin, and Fahrenheit.

The *Celsius temperature scale*, also called the *centigrade temperature scale*, is a scale in which the freezing point of water is 0 and the boiling point of water 100.

The *Kelvin temperature scale* is the basis for thermodynamic temperature measurements using the International System (SI) of measurement. It is defined as 1/273.16 of the triple point (equilibrium among the solid, liquid, and gaseous phases) of pure water. Such a scale has as its zero point absolute zero, the theoretical temperature at which the molecules of a substance have the lowest energy.

The *Fahrenheit temperature scale* is based on 32 as the freezing point of water and 212 as the boiling of water, the interval between the two being divided into 180 parts.

These temperature scales are depicted at the Fig. 12.1.

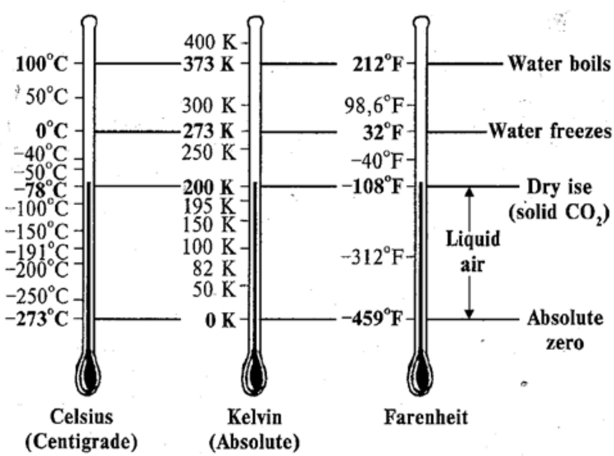


Fig. 12.1. **The temperature scales**

Conversion formulas for the interconversion of temperatures expressed on the Celsius, Kelvin or Fahrenheit scales are as followings:

$$\left.\begin{array}{l} °C = K–273.15; \\ °K = °C+273.15; \\ °C = (°F–32)5/9; \\ °F = 9/5°C+32; \\ °K = (°F–32)5/9+273.15; \\ °F = (K–273.15)9/5+32. \end{array}\right\} \qquad (12.1)$$

Example: A pan of water is heated from 25 °C to 80 °C. What is the change in its temperature on the Kelvin scale and on the Fahrenheit scale?

Solution: From the Equations (12.1), we see that the change in temperature on the Celsius equals on the change on the Kelvin scale. Therefore:

$$\Delta T_K = \Delta T_C = 80 – 25 = 55 \text{ °C} = 55 \text{ °K}$$

We also find that the change in temperature on the Fahrenheit scale is greater than the change on the Celsius scale by the factor 9/5. That is:

$$\Delta T_F = \frac{9}{5}\Delta T_C = \frac{9}{5}(80 – 25) = 99 \text{ °F}.$$

12.3. THERMAL EXPANSION OF SOLIDS AND LIQUIDS

Suppose the linear dimension of a body along some direction is l at some temperature. The length increases by the amount Δl for a change in temperature (ΔT). The basic equation for the thermal expansion of a solid is:

$$\Delta l = \alpha\, l\Delta T \qquad (12.2)$$

where α is the *average coefficient of linear expansion.*The unit of α is K^{-1}.

Because the linear dimensions of a body change with temperature, it follows that the volume (V) of a body also changes with temperature:

$$\Delta V = \beta V\Delta T = 3\alpha V\Delta T \qquad (12.3)$$

where β is the *average coefficient of volume expansion.*

Table 12.1 lists the average coefficients of linear and volume expansion for various materials.

12.1. ***Typical values of expansion coefficients for some materials at room temperature***

Material	α, K^{-1}	Material	β, K^{-1}
Lead	$29 \cdot 10^{-6}$	Air at 0°C	$36.7 \cdot 10^{-4}$
Steel	$11 \cdot 10^{-6}$	Glycerol	$4.85 \cdot 10^{-4}$
Glass ordinary	$9 \cdot 10^{-6}$	Gasoline	$1.24 \cdot 10^{-4}$
Invar (*Ni-Fe* alloy)	$0.9 \cdot 10^{-6}$	Ethanol	$1.12 \cdot 10^{-4}$

Example. A steel road track has a length 30 m when the temperature is 0 °C. What is its length on a hot day when the temperature is 40 °C?

Solution. Making use Table 12.1 and determining the change in temperature Δt = 40 °C, the increase in length, according Equation (12.2), is $\Delta l = \alpha l \Delta T = 11 \cdot 10^{-6}$ (°C)$^{-1} \cdot$30 m$\cdot$40 °C = $1.32 \cdot 10^{-2}$ m.

12.4. THERMODYNAMIC SYSTEMS

A thermodynamic system is that part of the universe that is under consideration. A real or imaginary boundary separates the system from the rest of the universe, which is referred to as the surroundings.

Thermodynamic systems are classified into three categories [11]:

- *Isolated systems* do not exchange energy or matter with the exterior;
- *Closed systems* exchange energy with the exterior but not matter;
- *Open systems* exchange both energy and matter with the exterior.

When a system is at equilibrium under a given set of conditions, it is said to be in a definite *thermodynamic state.*

12.5. THE FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics is a generalization of the law of conservation of energy and includes possible changes in internal energy.

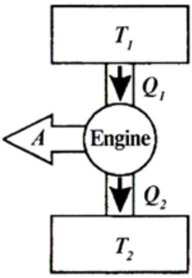
Suppose a thermodynamic system undergoes a change from an initial state to a final state in which Q units of heat are absorbed (or removed) and A is the work done by (or on) the system. If the quantity ($Q - A$) is measured for various paths connecting the initial and final equilibrium states (that is, for various processes), one can find that $Q - A$ is the same for *all* paths connecting the initial and final states. We conclude that the quantity $Q - A$ is determined completely by the initial and final states of the system, and we call the quantity *change in* ($Q - A$) *the internal energy of the system,* which is independent of the path. The internal energy function is U and changes in the internal energy can be expressed as:

$$\Delta U = U_f - U_i = Q - A \qquad (12.4)$$

where all quantities must have the same energy units. This equation is known as the *first law of thermodynamics.*

12.6. THE SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics establishes which processes in nature may or may not occur. The field of thermodynamics evolved from a study of *heat engine* – a device that converts thermal energy into other useful forms of energy, such as mechanical and electrical energy. It is useful to represent a heat engine schematically as in fig. 12.2.



The engine (represented by the circle at the center of the diagram) absorbs a quantity of heat (Q_h) from the high-temperature reservoir. It does work (A) and gives up heat (Q_c) to a lower-temperature heat reservoir. The net work (A) done by the engine equals the net heat flowing into the engine:

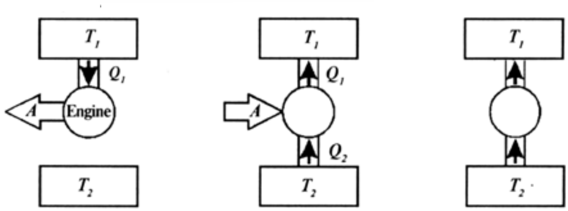
$$A = Q_h - Q_c \qquad (12.5)$$

Fig. 12.2. **Schematic representation of a heat engine that receives heat Q_1 from a hot reservoir, expels heat Q_2 to the cold reservoir, and does work A**

The *thermal efficiency* (η) of a heat engine is defined as the ratio of the net work done to the heat absorbed during one cycle:

$$\eta = \frac{A}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h} \qquad (12.6)$$

In practice, heat engines convert only a fraction of the absorbed heat into mechanical work. Based on this, the *Kelvin-Planck* form of the *second law of thermodynamics* states the following: *it is impossible to construct a heat engine that, operating in a cycle, produces no other effect that the absorption of thermal energy from a reservoir and the performance of an equal amount of work.* Fig. 12.3 is a schematic diagram of the impossible “perfect” heat engine.



a. The impossible engine *b.* Refrigerator *c.* Impossible refrigerator

Fig. 12.3. **Schematic representation of the impossible "perfect" heat engine:**

a — that receives heat Q_1 from a hot reservoir and does an equivalent amount of work; *b* — that absorbs heat Q_1 from the cold reservoir and expels heat Q_2 to the hot reservoir; work *A* is done on the refrigerator; *c* — that absorbs heat Q_1 from the cold reservoir and expels an equivalent amount of heat to the hot reservoir with $A = 0$

A refrigerator is a heat engine running in reverse. This is shown schematically in fig. 12.4, in which the engine absorbs heat (Q_c) from the cold reservoir and expels heat (Q_h) to the hot reservoir. This situation is in violation of the second law of thermodynamics, which in the form of the Clausius statement says the following: *it is impossible to construct a cyclical machine that produces no other effect than to transfer continuously from one body to another body at a higher temperature.*

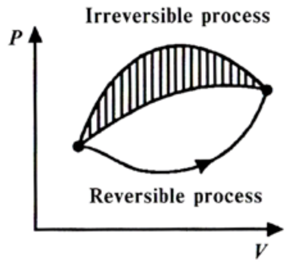


Fig. 12.4. **A reversible and irreversible processes on the *pV* diagram**

12.7. ENTROPY

The quantitative formulation of the second law of thermodynamics is given by:

$$\frac{Q_1 - Q_2}{Q_1} \leq \frac{T_1 - T_2}{T_1} \qquad (12.7)$$

where Q_1 is the heat which is absorbed from a hot reservoir at absolute temperature T_1, and Q_2 is the heat which is discarded to a cold reservoir at absolute temperature T_2. Here the symbol "=" is valid for a reversible process and "< " is used for an irreversible process.

Consider a reversible Carnot engine; from the last equation we have:

$$\frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1} \qquad (12.8)$$

or

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1} \qquad (12.9)$$

We can write:

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} = 0 \qquad (12.10)$$

As soon as Q_2 is discarded to a cold reservoir ($Q_2 < 0$), the last equation can be written as:

$$\frac{Q_1}{T_1} - \frac{(-Q_2)}{T_2} = 0 \qquad (12.11)$$

or

$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} = 0 \qquad (12.12)$$

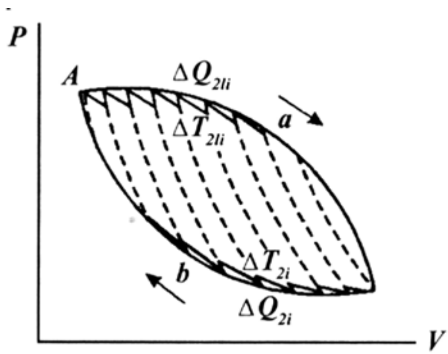


Fig. 12.5. **The cyclic process as great amount of elementary Carnot cycles**

The cyclic process can be presented as a number of elementary Carnot cycles (fig.12.5):

$$\sum_i \frac{\Delta Q_{1i}}{T_{1i}} + \sum_i \frac{\Delta Q_{2i}}{T_{2i}} = 0 \qquad (12.13)$$

In general, we can write this condition in the integral form:

$$\int_{AaB} \frac{dQ}{T} + \int_{AbB} \frac{dQ}{T} = 0 \qquad (12.14)$$

or

$$\oint \frac{dQ}{T} = 0 \qquad (12.15)$$

Here the symbol $\oint$ indicates that the integration is over a closed path.

The *change in entropy* (*dS*) between two equilibrium states is given by the heat transferred, divided by the absolute temperature of the system in this interval:

$$\frac{dQ}{T} = dS \qquad (12.16)$$

The function *S* is called *entropy*. The entropy is a measure of the amount of energy in a physical system which cannot be used to do work. It is a measure of the disorder present in a system [11,13].

At the end of the cycle, be it reversible or irreversible, there is no change in the system's entropy because it has returned to its original state. For irreversible cycles, it means that the system expels more heat to the exterior. This may be summarized as follows:

For a reversible state: $dS = \frac{dQ}{T}; \ \oint S = \oint \frac{dQ}{T} = 0. \qquad (12.17)$

For an irreversible state: $dS > \frac{dQ}{T}; \ \oint S = 0, \ \oint \frac{dQ}{T} < 0 \qquad (12.18)$

The statement can be made more precise by expressing the entropy change (dS) as a sum of two parts:

$$dS = d_eS + d_iS \qquad (12.19)$$

where d_eS is the change of the system's entropy due to exchange of energy and matter and d_iS is the change in entropy due to irreversible processes within the system. The quantity d_eS could be positive or negative, but d_iS can only be greater than or equal to zero.

The main tendencies of the entropy exchange are:

a. *For isolated systems*, since there is no exchange of energy or matter:

$$d_eS = 0 \text{ and } d_iS \geq 0 \qquad (12.20)$$

b. *For closed systems* that exchange energy but not matter:

$$d_eS = \frac{dQ}{T} = \frac{dU + pdV}{T} \text{ and } d_iS \geq 0 \qquad (12.21)$$

For open systems that exchange both matter and energy:

`

$$d_eS = \frac{dU + pdV}{T} + (d_eS)_{matter} \text{ and } d_iS \geq 0 \qquad (12.22)$$

Whether we consider isolated, closed or open systems, $d_iS \geq 0$. This is the statement of the Second Law in its most general form.

12.8. THE EQUILIBRIUM STATE

Entropy and the second law of thermodynamics provide the key to understanding equilibrium. An isolated system may undergo various spontaneous changes, some of which will increase its entropy. If the total entropy increases during a process, as it usually does, the process is irreversible – it is impossible to return to the starting point, leaving no other traces, since that would require a decrease in the total entropy, which is impossible. Once entropy has increased, it cannot decrease again.

An isolated system therefore approaches a state in which entropy has the highest possible value ($S \rightarrow S_{max}$) – this is a *state of equilibrium.* In this state, the entropy of the system cannot increase (because it is already at a maximum) and it cannot decrease (because that would violate the second law of thermodynamics ($d_iS \geq 0$)). The only changes allowed are those in which entropy remains constant.

Control Questions and Problems

1. Describe the types of thermodynamic systems. What are the signs isolated, closed and open thermodynamic systems?

3. What is the thermodynamic parameter? thermodynamic process?

4. Define the internal energy.

5. Formulate the First Law of Thermodynamics.

8. What is the heat engine?

9. Define the thermal efficiency.

10. Formulate the Second Law of Thermodynamics.

11. What processes are called reversible? irreversible?

12. Define the entropy.

13. Describe the main tendencies of the enthropy exchange.

Chapter 13. THERMOREGULATION

13.1. PATTERN OF BODY TEMPERATURE

Temperature of a body directly reflects that of the environment among cold-blooded (*poikilothermic*) animals, such as insects, snakes and lizards. These creatures maintain safe body temperatures mainly by moving into locations of favourable temperature (e.g., in the shade of a desert rock). Warm-blooded (*homoiothermic*) organisms normally keep practically constant body temperatures, independent of environment. Homoiothermic animals, including man, are able to control their body temperature not only by moving into favourable environments but also through internal regulatory effects on the nervous system modulating heat production and loss.

A more recent and sensible terminology separates organisms into *endotherms*, who have a body temperature that is primarily dependent on internally generated metabolic heat, and *ectotherms*, who have a body temperature that is primarily dependent on external heat sources (the Sun or a heated substrate). These terms, therefore, emphasize the heat sources used, rather than the setting or constancy of achieved body temperature.

There are dual setpoint regulatory systems in mammalian and reptilian nervous systems, with separate *neural thermostats* for controlling heat gain and heat loss. Some neurons ("warm receptors") increase pulse frequency when the hypothalamic temperature rises, and are probably linked to neurons that activate heat dissipation systems such as shade-seeking, sweating or vasodilation. Other neurons ("cold receptors") decrease in pulse frequency and may initiate vasoconstriction, basking and other behavioral effects. Still others only increase in pulse frequency when the hypothalamic temperature falls below a specific set-point; these are likely to trigger heat production mechanisms (i.e., shivering).

13.2. HEAT PRODUCTION

Vasoconstriction and vasodilation. Heat is produced in all body tissues, but particularly in the core organs of a resting animal and in muscles during activity. Heat must be distributed around the body, principally by the blood or other body fluids, and dissipated at the surface according to need. The simplest form of thermal control is to manage the rate and volume of the flow of blood to the surface relative to the core.

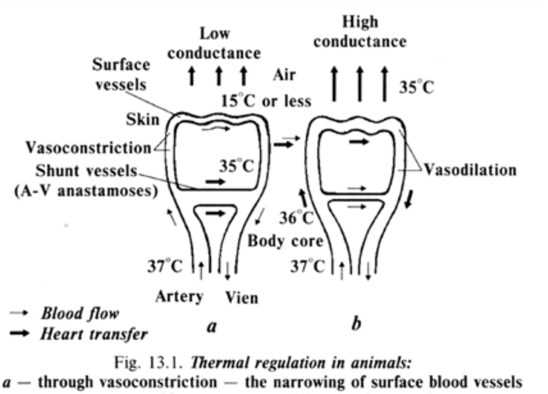


Fig. 13.1. *Thermal regulation in animals:*
a — through vasoconstriction — the narrowing of surface blood vessels in response to cold temperature and keeping heat in the core;
b — through vasodilation — the expansion of a surface blood vessels in response to warm temperatures

It is possible to distinguish *vasoconstriction* – the narrowing of surface blood vessels in response to cold temperature, keeping heat in the core (fig. 13.1*a*), and *vasodilation* – the expansion of a surface blood vessels in response to warm temperatures (fig. 13.1*b*).

Fig. 13.2. **The incredibly large ears of fennec assist in thermoregulation in its North Africa desert habitat**

For example, elephants use their large ears for thermoregulation, to cool themselves in the hot equatorial sun. As the elephant flaps its ears, blood vessels in the ear are cooled. The cooled blood circulates throughout the elephant and helps regulate overall body temperature. Another example, the fennec (*Fennecus zerda*), is the smallest of the wild canid species. The fennec has incredibly large ears (fig. 13.2), which measure up to 15 cm in length, making it extremely sensitive to sound. It also assists in thermoregulation, which is essential in its North Africa desert habitat.

Huddling and aggregation. Endothermic animals in polar regions, such as penguins and some seals, cluster together when the temperature drops substantially (e.g., –50 °C), typical in an Antarctic winter and when the wind speeds are over 160 kph.

Penguins form much denser huddles than seals with up to several thousand individuals, which can have a biomass of 100 tonnes. Clustering together saves as much as 80 % of the heat loss that would occur from an isolated bird.

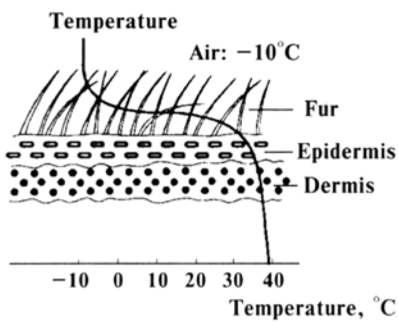


Fig. 13.3. **The temperature gradient across the highly effective fur and skin of a high-latitude animal**

Insulation. The fu 70 mm thick, is often so effecti om air temperature to normal body temperature is contained across the fur and skin (fig. 13.3).

Fur in boreal mammals varies with the season. Winter coats of animals are thicker and provide better thermal insulation than summer coats. Arctic foxes and the stoat are classic examples of sub-Arctic tundra species that grow a very dense and highly camouflaged winter coat. Insulation is the reciprocal of the total heat flux per unit area per unit of temperature difference, and therefore, have units of $°C \cdot m^{-2} \cdot W^{-1}$. Insulation may be provided by internal air sacs and fat layers, or externally by cuticular bristles of chitin or by various hairs and other structures made of keratin. Internal insulators are much less effective; a layer of blubber 60-70 cm thick has about the same insulating properties as 2 cm of good mammalian fur. Table 13.1 lists the insulation values for a cross-section of biological materials.

13.1. Insulation values of biological materials

Biological Material	**Insulation, $°C \cdot m^{-2} \cdot W^{-1}$**
Human tissue	14
Fat	38
Cattle fur	50
Pigeon feathers	99
Sheep wool	102
Goose-down feathers	122
Husky dog fur	157
Lynx fur	170
Still air	270

Animal coloration. There is an apparent paradox in animal coloration, in that the polar bear and many other polar animals are white, when black fur would appear to be beneficial in maximizing the absorption of solar radiation. The explanation for this is that white pelage makes the animals less conspicuous against a bright ice or snow. An additional reason is that for polar bears, the air space reflects visible light so that the hair appears white (it is actually translucent) and the hairs act like optical fibers which permit ultraviolet radiation to pass from the hair tips to the bear's skin, facilitating radiative heating.

Shivering. Shivering is a high-frequency reflex producing oscillatory contractions of skeletal muscles. The ATP hydrolyzed to provide energy for contractions is producing minimal physical work but substantial heat output. The intensity of shivering is linearly related to oxygen consumption. The animals are regulating the extent of their shivering to compensate for cold by generating internal heat.

Several snakes, such as the Indian python (*Python* spp.), use similar shivering mechanisms to achieve endothermic warming when they are incubating eggs (fig. 13.4).

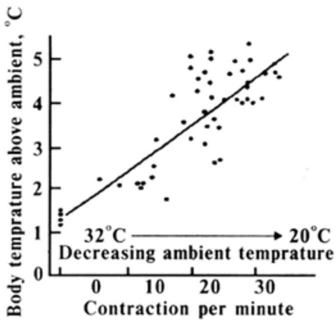


Fig. 13.4. **Thermogenetic incubation in a python; curled around her eggs, the female contracts her trunk muscles rhythmically to raise metabolic rate and increase body temperature**

The female wraps her body tightly round the clutch and produces a low-frequency but powerful shivering response, raising her body temperature and thus the egg temperature to around 30-33 °C, often 7-8 °C above ambient, thus facilitating more rapid development of the young.

Certain moths, beetles, dragonflies, flies, wasps and many bees also shiver and doing so to warm their muscles before flying.

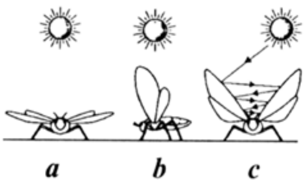


Fig. 13.5. **Basking postures which may be used in winged insects**

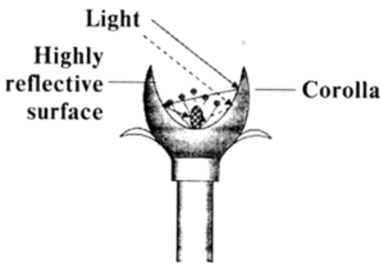


Fig. 13.6. **Arctic flowers acting as a parabolic reflectors**

Basking. This mechanism is particularly effective for small ectotherms. The temperature of moderately sized insects can be raised at least 15 °C above ambient by basking alone. Basking postures are also important (Fig. 13.5).

Several species of flowers (e.g., *Dryas integrifolia, Papaver radicatum*) are shaped like bowls and rotate via phototropism such that their corolla always point toward the Sun. Their shape acts as a parabolic reflector which concentrates radiation into the center of the flower, raising the flower's temperature by 5-8 °C above ambient (fig. 13.6). Mosquitoes, hoverflies, bloeflies and danceflies use these flowers as basking sites.

Migration. There are many endothermic examples of polar animals (e.g., caribou, reindeer, polar bears, lemmings and polar birds) that migrate to avoid very low temperatures and to find areas suitable for foraging. Long-range migration is not a very common strategy for ectotherms. The monarch butterfly (Danaus plexippus) migrates from Canada and the northern USA each year to overwinter in Mexico. Colias butterflies also migrate seasonally from northern Scandinavia to the southern Baltic regions.

13.3. HEAT EXCHANGE

13.3.1. Thermal Conductivity

Heat conduction can be viewed on an atomic level as an exchange of kinetic energy between molecules, where the less energetic particles gain energy by colliding with more energetic particles. The conduction of heat occurs only if there is a difference in temperature between two parts of the conducting medium [5]. If we consider a sheet of material of cross-section area *S*, thickness *dx*, and temperature difference *dT*, the *law of heat conduction* is:

$$Q_c = -kS\frac{dT}{dx} \qquad (13.1)$$

where the proportionality constant *(k)* is called the *thermal conductivity* of the material, and $\frac{dT}{dx}$ is the *temperature gradient* – the variation in temperature with position. The minus in this *Fourier's equation* denotes the fact that heat flows in the direction of decreasing temperature.

13.1. Thermal conductivity of a cross-section of materials

Substance	**Thermal Conductivity, $W \cdot m^{-1} \cdot K^{-1}$**	**Temperature, ^{o}C**
Metals		
Aluminium	238	25
Gold	314	25
Iron	80	25
Lead	35	25
Silver	427	25
Gases		
Air	0.0237	-10
«	0.0243	0
«	0.0250	10
«	0.0257	20
«	0.0264	30
«	0.0270	40
«	0.0277	50
Helium	0.138	20
Hydrogen	0.172	20
Nitrogen	0.0234	20
Oxygen	0.0238	20
Nonmetals		
Water	0.565	0
«	0.599	20
«	0.627	40
Concrete	2.43	20
Wood	0.126	20
Plastic	0.04	20
Biological	0.205	20
Objects	0.502	20
	0.4	20
Fat	0.036-0.063	20
Skin		
Muscles		
Fur		

Example. When a pig lies on concrete, the animal's belly and the concrete on which it lies are in contact. The temperature of the concrete's surface approximates that of the pig's belly surface. Assume that the 8-cm-thick concrete slab is on ground with a temperature of 0 °C, that belly-floor contact area is 3000 cm^2, the body temperature of pig is 30 °C, and the thermal conductivity of the concrete is 2.43 $W \cdot m^{-1} \cdot K^{-1}$.

Estimate the conductive heat transfer under steady-state conditions.

Solution. Conductive heat transfer flux from the belly to the concrete can be calculated as:

$$Q_c = -k \cdot S \cdot \frac{\Delta T}{\Delta x} =$$

$$= -2.43 \frac{W}{m \cdot K} \cdot 3000 \cdot 10^{-4} m^2 \, (0 - 30) \text{ K} / 8 \cdot 10^{-2} \text{ m} =$$

$$= - 2.43 \cdot 3 \cdot 10^{-1} \cdot (-30) / 8 \cdot 10^{-2} = 273.37 \text{ J} \cdot \text{s}^{-1}$$

13.3.2. Convection

Heat transferred by the movement of a heated substance is said to have been transferred by *convection* [5]. When the movement results from differences in density, it is referred to as *natural convection.* When the heated substance is forced to move by a fan or pump, the process is called *forced convection.*

Consider the convective heat exchange of objects with various shapes. The amount of heat conducted across the boundary layer and convected away from the flat plate (e.g., the surface of a leaf per unit time and area) by forced convection is:

$$J_C = -2k_{air} \frac{(T_{leaf} - T_{air})}{\delta} \qquad (13.2)$$

where k_{air} is the thermal conductivity coefficient of air, T_{leaf} the leaf temperature, and T_{air} the temperature of the air outside a boundary layer of thickness δ. This can be expressed as:

$$\delta(\text{mm}) = 4.0\sqrt{\frac{L(m)}{V(m/s)}} \qquad (13.3)$$

where L is the mean length of the leaf, V is the ambient wind speed, and the factor 4.0 has dimensions in $m/s^{1/2}$.

In the case of a cylinder (e.g., an animal), the heat flux density is:

$$J_C = -2k_{air}\frac{(T_{surf} - T_{air})}{r\ln(\frac{r+\delta}{r})} \qquad (13.4)$$

where r is the cylinder radius, T_{surf} surface temperature, and δ is calculated as:

$$\delta(\text{mm}) = 5.8\sqrt{\frac{D(m)}{V(m/s)}} \qquad (13.5)$$

where D is the cylinder diameter.

It is possible to use the following relation for objects of irregular shape which is known as *Newton's Law of Cooling*. It describes the rate of heat loss (J_C) in W/m^2 per unit surface area of a body in a cool air stream as:

$$J_C = k_c(T_{surf} - T_{air}) \qquad (13.6)$$

where k_c is the convection coefficient with units $W{\cdot}m^{-2}{\cdot}deg^{-1}$.

Example. Calculate the heat flux density conducted across the boundary layer and convected away from the surface of a sheep if the body of the animal approximates a cylinder with a radius of 60 cm, the surface temperature (T_{surf}) is 38 °C, the temperature of the air (T_{air}) is 20 °C, and the ambient wind speed (V) is 80 $cm{\cdot}s^{-1}$.

Solution. The average of the boundary layer (δ) is:

$$\delta = 5{,}8 \cdot \sqrt{\frac{D}{V}} = 5{,}8 \cdot \sqrt{\frac{0{,}6}{0{,}8}} = 5 \text{ mm} = 5 \cdot 10^{-3} \text{ m}$$

Using Equation (13.6) and k_{air} (0.0257 $W \cdot m^{-1} \cdot K^{-1}$ at 20 ^oC), calculate the heat flux density conducted across the boundary layer.

$$J_C = -\ 2k_{air} \frac{(T_{surf} - T_{air})}{r \ln(\frac{r+\delta}{r})} = \frac{0{,}0257 \cdot (38-20)}{0{,}3 \cdot \ln\left(\frac{0{,}3 + 0{,}005}{0{,}3}\right)} = 93 \text{ W} \cdot \text{m}^{-2}$$

13.3.3. Radiation

Two bodies at different temperatures will exchange heat even when there is no possibility of exchange by conduction or convection; the transfer of heat takes place by *radiation* [5].

The rate at which an object emits radiant energy is proportional to the fourth power of its absolute temperature. This is known as *Stefan-Boltzmann's law* which is expressed in equation form as:

$$R = \sigma S \varepsilon T^4 \qquad (13.7)$$

where R is the power radiated by the body (W); $\sigma = 5{,}67051 \cdot 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$ is a constant; S is the surface area of the object, ε is a constant called the *emissivity*, and T is the temperature in Kelvin.

When an object is in equilibrium with its surrounding, it radiates and absorbs energy at the same time:

$$R_n = Q_a - Q_e = S\sigma(aT_s^4 - \varepsilon T_e^4) \qquad (13.8)$$

where a is a constant called the *absorptivity*.

The values of constants a and ε are given in Table 13.3.

Example. If a brown cow has an effective radiant-surface area of 4 m^2 and a radiant-surface temperature averaging 27 °C, and the average temperature of the environment is − 3 °C, calculate the net flux of thermal radiant energy between an animal and its environment.

Solution. A net heat flux from animal to environment via thermal radiation can be determined from Equation (13.8):

$$R_n = Q_a - Q_e = S\sigma(aT_s^4 - \varepsilon T_e^4) =$$

$$= 4 \text{ m}^2 \cdot 5{,}67051 \cdot 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4} (0.80 \cdot 300^4 - 0.95 \cdot 270^4) = 632 \text{ W}.$$

13.3. *Radiation absorptivity and emissivity ratios for various farm-animals and humans*

Object	Absorptivity, *a*	Emissivity, ε
Cow		
white	0.50	0.95
brown	0.80	0.95
black	0.90	0.95
Pig		
white	0.50	0.95
black	0.90	0.95
Sheep		
without wool	0.60	0.95
with wool	0.75	0.95
Human organism	0.65 – 0.80	0.95

13.3.4. Evaporation

Evaporative loss of water is an excellent way for animals to dissipate heat. The rate of evaporation depends not only on the surface temperature, but also on the difference in water vapor density between the animal's surface and the environment, and on the resistance to water loss from the surface. Typical values for evaporative water loss are 7.0–20.9 $W \cdot m^{-2}$.

Control Questions and Problems

1. What are the main types of heat production?
2. What are the main types of heat exchange?

Chapter 14. THERMOBIOLOGY

14.1. THERMORECEPTION

Thermoreception is a process by which different levels of thermal energy (temperatures) are detected by living organisms [20]. Animals are supplied with specific sensory structures called *thermoreceptors* which enable them to detect thermal changes and adjust accordingly. Thermoreceptors can be divided into two classes, *cold* and *warm* receptors. At a constant temperature (within an appropriate range), thermal receptors are electrically active, the frequency of the steady discharge depending on the temperature. In most cases, the static activity of cold receptors reaches a maximum at temperatures between 20-30 °C; warm receptors are also continuously active at constant temperatures, with a maximum at 41-46 °C.

With sudden temperature changes, thermal receptors respond by way of a transient change in frequency.

14.2. THERMORECEPTION IN INVERTEBRATES

Insects are sensitive to temperature gradients on a surface of substrates. For example, honeybees (*Apis mellifera*) normally choose a temperature range of 35±1.5 °C and accurately regulate the temperature in their hive between 35-36 °C by beating their wings to circulate the air. The accuracy in temperature discrimination is 1 °C for the leech (*Hirudo medicinalis*), 0.5 °C for castorbean tick (*Ixodes ricinus*), and 0.3 °C for the slug (*Agriolimax reticulatus*). The temperature sensitivity of bloodsucking arthropods is considerably greater than most arthropods. Mosquitoes (*Aedes aegypti*) readily fly to warm-blooded creatures and display a temperature sensitivity of about 0.5 °C.

In most insects, their thermoreceptors are located in the antennae. Cockroaches (*Periplaneta americana*) have two whip-like antennae consisting of 120 to 180 ring-shaped segments that grow thinner and longer with increasing distance from the animal’s head; there are about 20 cold receptors per antenna (fig. 14.1).

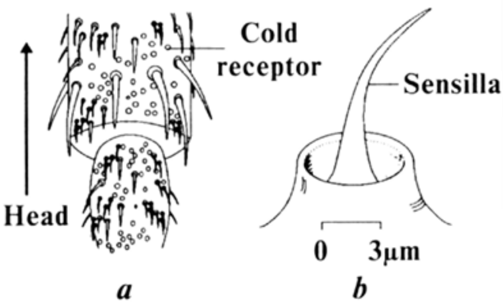


Fig. 14.1. **Thermoreceptors in the antennae of cockroach: *a* — two whiplike antennae consisting of 120 to 180 ring-shaped segments that grow thinner and longer with increasing distance from the animal′s head; *b* — a single segment**

14.3. THERMORECEPTION IN VERTEBRATES

Mammals. Detailed information is available from electrophysiological investigations of single thermosensitive nerve fibers in the skin of mammals, in particular cats and monkeys. At the site of a cold-sensitive spot on a cat's nose, a thin, myelinated nerve fiber penetrates the dermis and divides into several unmyelinated branches about 70 micrometers beneath the skin surface (fig. 14.2). Warm receptors appear to be situated in a deeper layer of the skin.

Birds. Megapodes, large-footed birds such as the Australian mallee fowl (*Leipoa ocellata*), bury their eggs. The eggs are incubated in mounds where heat is generated through the fermentation of rotting vegetation and by irradiation from the sun. The birds can control the temperature of the eggs due to the thermal sensitivity of their face or mouthparts. For extended periods of time, (e.g., about 63 days), the male is busy covering and uncovering the eggs, keeping the temperature an almost constant 34±1 °C.

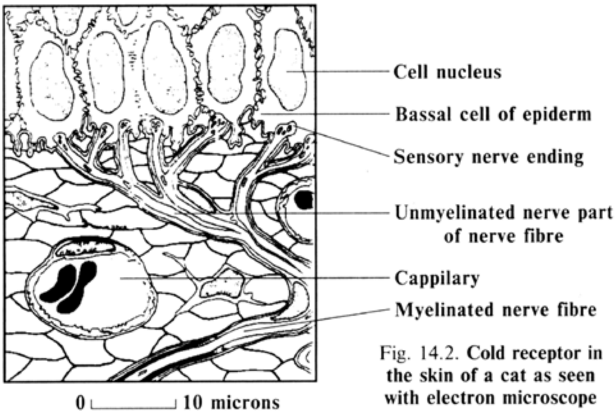


Fig. 14.2. **Cold receptor in the skin of a cat as seen with electron microscope**

Amphibians and reptiles. Rattlesnakes (*Crot alus*) and related species of pit vipers have a pair of facial pits (fig. 14.3), sense organs on the head below and in front of the eyes, which are extremely sensitive thermoreceptors. Each pit is a cavity about 5 mm deep. The sensitivity of the snake to rapid changes of temperature is 0.002 °C. The pit organs also act as a directional distance receptor.

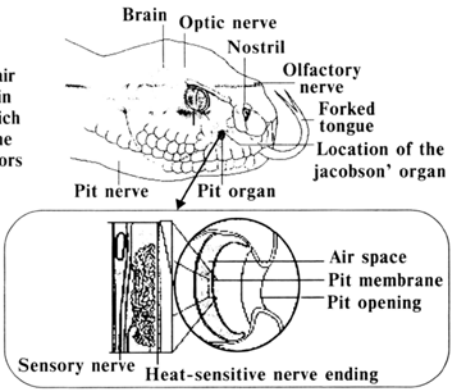


Fig. 14.3. **A pair of facial pits in rattlesnake which play role of the infrared receptors**

Fish. Many species of bony fish (teleosts) are sensitive to very sn anges of water temperature – from 0.03 °C to 0.07 °C. Practically the entire surface of the fish, including the fins, is thermosensitive. Likewise, elasmobranchs, such as rays and sharks, have distinctive sense organs, called ampullae of Lorenzini, that are highly sensitive to cooling.

4.4. EFFECTS OF TEMPERATURE ON PLANTS

Plants can survive a broad range of atmospheric temperatures – from -89 °C to 58 °C (even to about 70 °C in desert areas). Most species, however, have a much more limited temperature range, generally from somewhat above freezing to around 40 °C.

Temperature extremes have distinct effects on plants. High temperatures cause increased respiration (sometimes above the rate of photosynthesis) and transpiration. A common response to high temperature in plants is a marked change in the pattern of protein synthesis. High temperatures cause damage to the cells and tissues and low temperatures can result in poor growth, reduce energy use and increase sugar storage. Photosynthesis decreases with decreasing temperature. Low temperature injury to tropical and subtropical plants (chilling injury) results in wilting, inhibited growth, germination and reproduction, and death. The universal result of freezing is membrane damage while extracellular freezing (i.e., water external to the plasma membrane) damage causes rapid dehydration of the cells.

Flowering depends on the temperature and in some species can be partially triggered by temperature.

Control Works
Modulus 5
Molecular Physics and Biophysics, Thermodynamics, Thermoregulation, Thermobiology

Problem. An object has a temperature of 50 °F. What is its temperature in degrees Celsius and in Kelvin?
Answer: 10 °C; 283.15 K.

Problem. A structural steel beam is 15 m long when installed at 20 °C. How much will its length change over the temperature extremes of – 30 °C to 50 °C?
Answer: 1.32 cm.

Problem. A pig lying a on wood floor has its belly in contact with the floor. If the temperature of the wood surface approximates that of the surface of the pig's belly, the 2-cm-thick wood slab is on ground at a temperature of 0 °C, the belly-floor contact area is 3000 cm^2, the body temperature of the pig is 30 °C and the thermal conductivity of the wood is 0.126 $W{\cdot}m^{-1}{\cdot}K^{-1}$, what is the conductive heat transfer under steady-state conditions?
Answer: 56.7 $J{\cdot}s^{-1}$.

Problem. Calculate the heat flux density conducted across the boundary layer and convected away from the surface of an animal if the radius of the animal is 0.2 m, the surface temperature (T_{surf}) is 40 ^oC, the air temperature (T_{air}) is 20 °C and the ambient wind speed (V) is 5 $m{\cdot}s^{-1}$.
Answer: 446.96 $W{\cdot}m^{-2}$.

Problem. Calculate the thickness of the boundary layer across a flat leaf at 25 °C when the surrounding air is at 20 °C. A mean length of the leaf is 10 cm and the wind speed is 0.8 m/s.
Answer: 1.4 mm.

Problem. Calculate the net flux of thermal radiant energy between an animal and its environment if the effective radiant-surface area is 1 m^2, the radiant-surface temperature is
25 ^0C and the an average temperature of the environment is 10 °C.
Answer: 42 W.

Home Work. Find the Internet site
http://www-tech.mit.edu/Chemicool/cgi-bin/gaslaws.pl and calculate the number of moles (n) of ideal gas if the pressure (p) is 100 Pa, the temperature (T) is 20 °C and the volume (V) is 100 cm^3.

Home Work. Virtual Psychrometric Tables utilize wet and dry bulb temperatures to derive the partial pressure, saturated vapor pressure, absolute humidity, relative humidity and dew point.

Find the Internet site http://www.met.rdg.ac.uk/~swshargi/MicroMetSoft.html and calculate each of these parameters for $T_w = 20°$, $T_a = 25°$, and $p_{atm} = 760$ mm Hg.

Home Work. Find the Internet site: http://hyperphysics.phy-astr.gsu.edu/hbase/ thermo/temper.html which contains a table for the conversion of temperatures between Celsius, Kelvin and Fahrenheit. Using this table, convert your body temperature (or that of your cat or dog) to the Kelvin scale and the Fahrenheit scale.

VOCABULARY

English	Ukrainian	English	Ukrainian
Absorptivity	Поглинальна здатність	Neural thermostat	Нейронний термостат
Basking	Зігрівання на сонці	Olfaction	Нюх
Boundary layer	Граничний шар	Partial pressure	Парціальний тиск
Carnot cycle	Цикл Карно	Reversible	Необоротний
Chilling injury	Пошкодження від заморожування	Saturation vapor pressure	Пружність насиченої пари
Coloration	Зафарблення	Shivering	Тремтіння
Convection	Конвекція	Smell	Запах
Dew point	Точка роси	State of equilibrium	Рівноважний стан
Dry-bulb thermometer	Сухий термометр	Taste	Смак
Emissivity	Випромінювальна здатність	Taste-bud	Смакова брунька
Evaporation	Випаровування	Taste hairs	Смакові сосочки
Gustation	Смак	Thermal expansion	Теплове розширення
Hair-like cells	Волоскові клітини	Thermal conductivity	Теплопровідність
Heat engine	Тепловий двигун	Thermal efficiency	Коефіцієнт корисної дії

Huddling	Утворення натовпу	Triple point	Потрійна точка
Humidity	Вологість	Turbinates	Носова раковина
Insulation	Ізоляція	Vapor deficit	Дефіцит вологості
Irreversible	Оборотний	Vasoconstriction	Скорочення судини
Liquefaction	Скраплення	Vasodilation	Розширення судини

Animal Extremes!

The sensitivity of a rattle snake to rapid changes of temperature is 0.002 °C.

Evidence exists of procaryotes living at temperatures as high as 155 °C.

For land animals, the upper limit is about 50 °C for certain insects and reptiles.

Certain large polar mammals and birds can tolerate an ambient temperature of -60 °C.

Control Questions and Problems

1. Define the thermoreception.
2. Describe the thermorecerption in invertebrates.
3. Describe the thermorecerption in vertebrates.
4. How temperature affects the plant?

Chapter 15. ELECTRICITY

Electricity is the branch of physics which studies phenomena associated with stationary or moving electric charges.

15.1. BASIC CONCEPTS

At present, two critical areas of interest for a biologist studying electricity are *electrostatics* and *current electricity*. The former involves understanding the interaction of charged species, ions and molecules at the molecular and cellular level. The latter is essential for understanding electrical signaling processes that take place along both animal and plant membranes, but also for the intelligent use of the vast range of electronic equipment available to biologists.

The study of electricity is concerned with the behavior of charged particles, electric fields and magnetic fields. An *electric field* is associated with an *electric charge* distribution and its effect on other charges.

15.2. ELECTROSTATICS

15.2.1. Properties of electric charges

An electric charge has the following important properties.

1. There are two kinds of charges in nature; unlike charges attract one another and like charges repel one another;
2. The force between charges varies as the inverse square of their separation;
3. Charge is conserved;
4. Charge is quantized.

15.2.2. Coulomb's Law

Coulomb's Law: An electric force between two stationary, charged particles is inversely proportional to the square of the separation (r) between the two particles and is directed along the line joining the particles, and the force is proportional to the product of the charges (q_1 and q_2) on the two particles:

$$F = \frac{q_1 q_2}{4\pi\varepsilon\varepsilon_0 r^2} \qquad (15.1)$$

where ε is the *relative dielectric constant* of the medium separating the charged particles (ε = 1 for a vacuum and ε = 80 for water), ε_0 is the *absolute permittivity of free space* ($\varepsilon_0 = 8.8542 \cdot 10^{-12}\ C^2 m^{-2} N^{-1}$), and *r* is the distance between the centers of the charged particles.

The unit of charge is the *coulomb* (1 C = 1 A·s). The smallest unit of charge in nature is the charge on an electron or proton; this charge has a magnitude ($|e|$) of $1.60219 \cdot 10^{-19}$ C.

Example. The electron and proton of a hydrogen atom are separated by a distance of $5.3 \cdot 10^{-11}$ m. Find the magnitude of the electrical force between two particles.

Solution. From Coulomb's Law, the attractive force has the magnitude:

$$F = \frac{q_1 \cdot q_2}{4\pi\varepsilon\varepsilon_0 r^2} =$$

$$=(1.60217733 \cdot 10^{-19}\ C)^2 / (4 \cdot 3.14 \cdot 1 \cdot 8.8542 \cdot 10^{-12}\ C^2 \cdot T^{-1} \cdot m^{-2})\ (5.3 \cdot 10^{-11}\ m)^2 =$$
$$= 8.2 \cdot 10^{-8}\ N.$$

15.2.3. The Electric Field

The *electric field vector* ($\vec{E}$) at a point in space is defined as the electric force ($\vec{F}$) acting on a positive test charge placed at the point divided by the magnitude of the test charge (q_0):

$$\vec{E} = \frac{\vec{F}}{q_0} \qquad (15.2)$$

The unit of an electric field is *N/C*.
The modulus of an electric field can be defined as:

$$E = \frac{F}{q_0} = \frac{q}{4\pi\varepsilon\varepsilon_0 r^2} \qquad (15.3)$$

A convenient aid for visualizing electric field patterns is to draw lines pointing in the same direction as the electric field vector at any point. These lines, called *electric field lines* (fig. 15.1), are related to the electric field in any region of space in the following manner:

1. *The electric field vector* ($\vec{E}$) *is tangent to the electric field line at each point;*
2. *The number of lines per unit area through a surface perpendicular to the lines is proportional to the strength of the electric field (or the magnitude of the charge) in that region.*
3. *The lines must begin on positive charges and terminate on negative charges, or at infinity in the case of an excess of charge;*
4. *No two field lines can cross.*

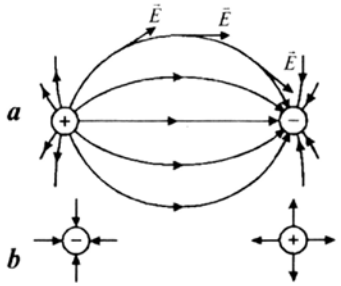


Fig. 15.1. ***Schematic diagram of the electric field: a* — for two equal and opposite charges; *b* — for point charges**

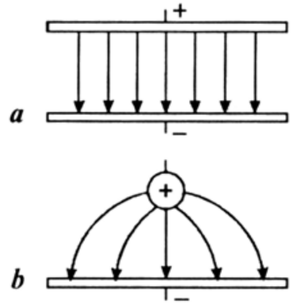


Fig. 15.2. **Uniform (*a*) and nonuniform (*b*) electric field**

An important field for consideration is the *uniform electric field*; a field that has the same magnitude and direction at all points. In the opposite situation, the field is *non-unifornm* (fig. 15.2).

15.2.4. Electric Potential

Instead of dealing directly with the potential energy of a charged particle, it is useful to introduce the more general concept of energy per unit charge.

Suppose a test charge (q_0) moves from *A* to *B* under the influence of a field ($\vec{E}$). The work (*dA*) done by the electric force ($q\,\vec{E}$) on the test charge for an infinitesimal displacement ($d\vec{x}$) is given by:

$$dA = \vec{F} \cdot d\vec{x} = q_0 \vec{E} \cdot d\vec{x} \qquad (15.4)$$

By definition, the work done by a conservative force equals the negative of the change in potential energy (*dU*); therefore:

$$dA = -\,dU = -\,q_0 \vec{E} \cdot d\vec{x} \qquad (15.5)$$

A force is *conservative* if the work done by the force acting on a particle moving between two points is independent of the path the particle takes between the points.

For a finite displacement of the test charge between points *A* and *B*, the *change in the potential energy* is given by:

$$U = U_B - U_A = -q_0 \int_A^B \vec{E} \cdot d\vec{x} \qquad (15.6)$$

where U_B and U_A are the initial and final potential energies, respectively.

The *potential difference* ($\Delta\varphi$) between points *A* and *B* is defined as the change in potential energy divided by the test charge (q_0):

$$\Delta\varphi = \varphi_B - \varphi_A = \frac{U_B}{q_0} - \frac{U_A}{q_0} = -\int_A^B \vec{E} \cdot d\vec{x} \qquad (15.7)$$

The quantity which equals the energy per unit charge ($\varphi = \frac{U}{q_0}$) is called the *electric potential* (*U*).

The unit of potential is the Joule per Coulomb, which is equal to a *volt* (1 V = 1 J/C).

15.2.5. Obtaining $\vec{E}$ from the Electric Potential

The electric field ($\vec{E}$) and the potential (*U*) are related by Equation (15.7). To calculate the electric field if the electric potential is known in a certain region, apply Equation (15.7) when there is a *uniform* electric field:

$$\Delta\varphi = -\int_A^B \vec{E} \cdot d\vec{x} = -\int_A^B E\cos 0^0 ds = -\int_A^B Eds \qquad (15.8)$$

Since *E* is constant, it can be removed from the integral sign, giving:

$$\Delta\varphi = -\int_A^B Eds = -Ed \qquad (15.9)$$

or

$$E = -\frac{\Delta\varphi}{d} \qquad (15.10)$$

where the minus sign results from the fact that point *B* is at a lower potential than point *A*.

With a non-uniform electric field, from the Equation (15.7) we can express the potential difference ($d\varphi$) between two points a distance (ds) apart as:

$$d\varphi = -\vec{E}\cdot ds \qquad (15.11)$$

If the electric field has only one component (E_x), then $\vec{E}\cdot ds$ = $E_x dx$. Therefore, Equation (15.7) becomes $d\varphi = -E_x dx$ or:

$$E_x = -\frac{d\varphi}{dx} \qquad (15.12)$$

Therefore, *the electric field is equal to the negative of the derivative of the potential with respect to some coordinate.*

In general, the electric potential is a function of all three spatial coordinates. If $\varphi(\vec{r}) = \varphi(x,y,z)$ is given in the rectangular coordinates, the electric field components are given by:

$$E_x = -\frac{\partial\varphi}{\partial x}, E_y = -\frac{\partial\varphi}{\partial y}, E_z = -\frac{\partial\varphi}{\partial z} \qquad (15.13)$$

In these expressions, the derivatives are called *partial derivatives.* From this, it follows that the unit of electric field (*N/C*) can be also be expressed as volts per meter (*V/m*).

Any surface consisting of a continuous distribution of points having the same potential is called an *equipotential surface.* Equipotential surfaces are always perpendicular to the electric field lines.

15.2.6. Motion of Charged Particles in an Uniform Electric Field

When a particle of charge q is placed in an electric field ($\vec{E}$), the electric force on the charge is $q\vec{E}$. If this is the only force exerted on the charge, then Newton's second law applied to the charge gives:

$$\vec{F} = q\vec{E} = m\vec{a} \qquad (15.14)$$

where m is the mass of the particle. The acceleration of the particle is therefore given by:

$$\vec{a} = \frac{q\vec{E}}{m} \qquad (15.15)$$

15.2.6. Oscillograph

The *oscillograph* is an electronic instrument widely used in making electrical measurements when rapidly changing electrical signals are studied, e.g. nerve action potentials or electrical signals in plants. The main component of the oscillograph is the *cathode ray tube (CRT)*, shown in fig. 15.3

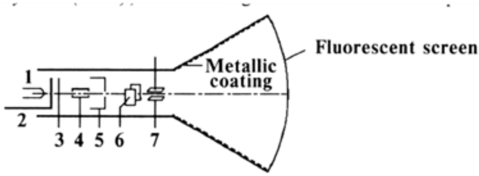


Fig. 15.3. The cathode ray tube: 1 — heater; 2 — cathode; 3 — control grid; 4 — focusing anode; 5 — accelerating anode; 6 — plates for horizontal deflection; 7 — plates for vertical deflection

The mode of operation of the CRT itself provides a simple example of the movement of charges (electrons) under the influence of electric fields. The whole interior of the tube is highly evacuated. The cathode is raised to a high temperature by the heater and electrons (cathode rays) evaporate from its surface. The *accelerating anode* is maintained at a high positive potential relative to the cathode so that there is an electric field directed between the anode and cathode. The electrons passing through the hole in the anode travel with a constant velocity from the anode to the *fluorescent screen.* The complete cathode-anode assembly is called the *electron gun.* The electrons then pass between two pairs of *deflecting plates*, the first of which controls the horizontal deflection of the beam, the second – the vertical deflection. The sweep speed is controlled by the potential difference across the horizontal plates which varies in time with a sawtooth waveform. The field across the vertical plates is controlled by the potential difference across the source under investigation, hence a two dimensional image is formed on the screen.

15.3. CURRENT ELECTRICITY

15.3.1. Electric Current

The term *electric current* is used to describe the rate of flow of charge through some region of space. If Δq is the amount of charge that passes through the area (S) in a time interval Δt, the *average current* ($< I >$) is equal to the ratio of the charge to the time interval:

$$< I > = \frac{\Delta q}{\Delta t} \qquad (15.16)$$

If the rate at which the charge flows varies in time, the current also varies in time and we define the *instantaneous current* (I) as the differential limit of the expression above:

$$I = \frac{dq}{dt} \qquad (15.17)$$

The unit of current is the *ampere* (1 A = 1 C/s).

The *current density* ($\vec{j}$) in the conductor is defined as the current per unit area:

$$j = \frac{I}{S} \qquad (15.18)$$

where I is a current, and S is the cross-sectional area of the conductor.

This expression is valid only if the current density is uniform and the surface is perpendicular to the direction of the current. In general, the current density is a *vector quantity*. That is:

$$\vec{j} = nq < \vec{V} > \qquad (15.19)$$

where n represents the number of mobile charge carriers per unit volume which move with an average speed ($< \vec{V} >$).

The unit of current density is A/m^2.

15.3.2. Current Circuits

A closed circuit consists of a source of energy (e.g., a battery), called an *electromotive force (E.M.F.)*, and a resistor (fig. 15.4).

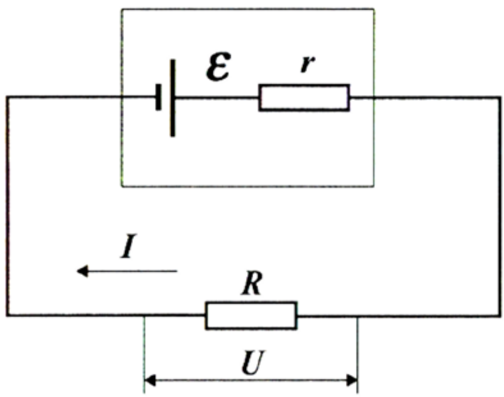


Fig. 15.4. **Diagram of simple electric circuit**

Assuming that the connecting wires have no resistance, the source of E.M.F. has its own *internal resistance (r)*. The *external resistance* (*R*), is often called the *load resistance.* The *voltage* (*U*) is the difference in electric charge between two points in a circuit.

The unit of E.M.F. and voltage is the volt; resistance has units of volt per ampere (1Ω = 1V/A).

15.3.3. Ohm's Law

Ohm's Law for part of a circuit: *The electric current* (*I*) *flowing through a given resistance* (*R*) *is equal to the applied voltage* (*U*) *divided by the resistance,* or:

$$I = \frac{U}{R} \qquad (15.20)$$

Ohm's Law for a closed circuit: *The amount of current flowing in a circuit made up of pure resistance is directly proportional to the electromotive forces impressed on the circuit and inversely proportional to the total resistance of the circuit:*

$$I = \varepsilon/(R + r) \qquad (15.21)$$

15.3.4. Kirchhoff's Rules

Complex circuits (fig. 15.5) involving more then one loop are conveniently analyzed using *Kirchhoff's rules*.

1. The sum of currents entering any junction must equal the sum of the currents leaving that junction:

$$\sum_{i=1}^{n} I_i = 0 \qquad (15.22)$$

2. The sum of the potential differences across each element around any closed-circuit loop must be zero*:*

$$\sum_{i=1}^{n} I_i R_i = \sum_{i=1}^{n} \varepsilon_i \qquad (15.23)$$

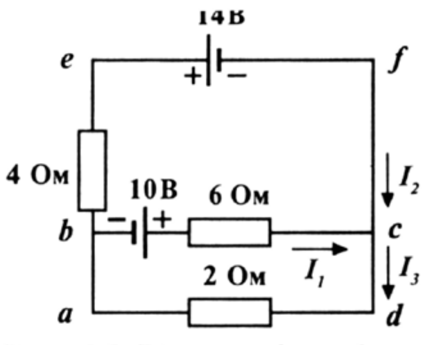


Fig. 15.5. **Diagram of complex electric circuit**

15.3.5. Joule-Lentz's Law

The *Joule-Lentz Law gives the amount of heat (Q) liberated by current (I) flowing through a resistor with resistance R for time t:*

$$Q = I^2 Rt \qquad (15.24)$$

Example. A battery has an E.M.F. of 12 V and an internal resistance of 0.05 Ω. Its terminals are connected to a load resistance of 3 Ω. Find the current in the circuit and the terminal voltage of the battery.

Solution. Using Equation (15.21), we obtain:

$$I = \varepsilon/(R + r) = 12\text{ V}/(3 + 0.05)\ \Omega = 3.93\text{ A}.$$

The terminal voltage of the battery is given by:

$$V = \varepsilon - Ir = 12\text{ V} – (3.93\text{ A})(0.05\ \Omega) = 11.8\text{ V}.$$

Control Questions and Problems

1. Define the electricity.
2. What are the properties of electric charges?
3. Formulate the Coulomb's Law.
4. What is the electric field?
5. Explain the principle of the oscillograph.
6. Formulate Ohm's Law; Kirchhoff's Rules.

Chapter 16. BIOELECTRICITY

16.1. NERNST EQUATION

If a membrane separates two *KCl* solutions of different concentrations ($K_i > K_e$) and the membrane is permeable only to potassium ions (fig. 16.1), the potassium ions will diffuse down their *concentration gradient*, taking their positive charge with them so that the outside phase will acquire a positive potential with respect to the inside.

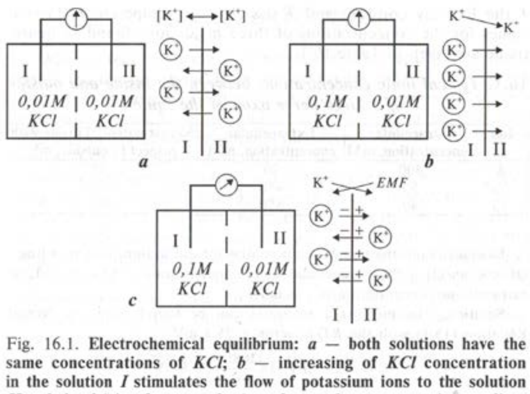


Fig. 16.1. **Electrochemical equilibrium: *a* — both solutions have the same concentrations of *KCl*; *b* — increasing of *KCl* concentration in the solution *I* stimulates the flow of potassium ions to the solution *II* and the driving force on the ions due to the concentration gradient is exactly balanced by the driving force due to the potential difference; *c* — a net diffusion of potassium ions across the membrane is equal zero**

This potential will tend to impede the subsequent movement of cations and a point will be reached when there will no longer be a net diffusion of potassium ions from inside to outside. At this point, the driving force on the ions due to the concentration gradient will be exactly balanced by the driving force due to the potential difference or *electrical gradient.* The same situation will take place when a volume of saline is enclosed within a thin membrane and placed in a volume of deionized water.

The *Nernst equation* relates the transmembrane potential difference ($\Delta\varphi$), measured with respect to the outside of the membrane, to the concentration of cations as:

$$\Delta\varphi = \varphi_e - \varphi_i = \frac{RT}{ZF}\ln\frac{C_i}{C_e} \qquad (16.1)$$

where C_i and C_e are the concentrations of the Cl^- ions inside and outside the membrane bag, Z the valence (the number of electrons added or removed to ionize the atom), R the gas constant, F the Faraday constant

16.1. *Typical ionic concentrations between the inside and outside of a large nerve axon of the squid*

Ion	Intracellular concentration, mM	Extracellular concentration, mM	Nernst potential inside with respect to outside, mV
K^+	400	20	–75
Na^+	50	450	+55
Cl^-	40	550	–66

and T the absolute temperature. Typical values for the concentrations of three major ions found in neural tissue are given in Table 16.1.

Example. Find the membrane potential for the sodium ions in a frog's tailor's muscle if the intracellular ionic concentration is 13 mM and the extracellular concentration is 108 mM.

Solution. The membrane potential can be found from the Nernst Equation (15.1) with the *RT/F* factor = 25.3 mV:

$$\Delta\varphi = 25.3\ \text{mV} \cdot \ln\frac{108}{13} = 53.6\ \text{mV}$$

16.2. RESTING POTENTIAL

Certain types of cells within the body (e.g., nerve and muscle) are encased in a semipermeable membrane that permits some substances to pass through the membrane while others are kept out. Surrounding the cells of the body are body fluids, which are conductive solutions containing ions. The principal ions are sodium (Na^+), potassium (K^+) and chloride (Cl^-). The membrane of excitable cells readily permits the entry of potassium and chloride ions but effectively blocks the entry of sodium ions. These properties of the membrane normally give rise to high potassium and low sodium ion concentrations inside the cell. This results in a potential of about -80 mV between the inside and the outside, such that the cell is said to be *polarized.* The membrane potential in the polarized state is called the *resting potential,* which is maintained until a disturbance upsets the equilibrium. The resting potential ranges in various cells from – 60 to – 100 mV. Fig. 2 illustrates a simplified cross-section of a cell at its resting potential.

16.3. ACTION POTENTIAL

When a section of the cell membrane is excited by the flow of ionic current or some form of externally applied energy, the membrane changes its diffusion characteristics, allowing some of the sodium ions to enter and potassium ions to exit the cell, altering the transmembrane potential change. As a result, the cell has a slightly positive potential on the inside; this potential is known as the *action potential* and is approximately +20 mV. A cell that has been excited and displays an action potential is said to be *depolarized*. The process of changing from the resting potential to the action potential is called *depolarization.* After a short time (e.g., 1 ms for a nerve cell or 150-300 ms for a heart muscle cell), the cell reverts to the polarized state; this process is called *repolarization.* Fig. 16.2 illustrates a depolarized cell in cross-section and fig. 16.3 shows a typical action potential waveform, beginning at the resting potential, depolarizing and then returning to the resting potential after repolarization.

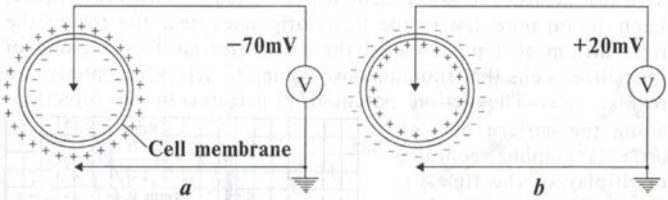


Fig. 16.2. **Polarization and depolarization of a cell:**
***a* — polarized cell with its resting potential; *b* — depolarized cell during an action potential**

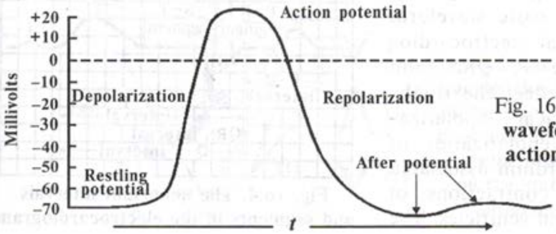


Fig. 16.3. **A typical waveform of the action potential**

16.4. PROPAGATION OF ACTION POTENTIALS

When a cell is excited and generates an action potential, an ionic current begin to flow. This process can, in turn, excite similar neighboring cells. With nerve cells that have a long fiber, the action potential is generated over a very small segment of the fiber's length, however, it is propagated in both directions from the original point of excitation. The rate at which an action potential moves down a fiber or is propagated from cell to cell is called the *propagation rate*. The velocity of the propagation rate varies widely. The usual velocity range in nerves cells is 20–140 m/s; propagation through heart muscle is slower, with an average rate of 0.2–0.4 m/s.

16.5. ELECTROCARDIOGRAPHY

The biopotentials generated by the muscles of the heart result in the *electrocardiogram* (abbreviated *ECG*) and the technique used to measure these potentials is called *electrocardiography*. Each action potential in the heart originates near the top of the right atrium at a point called the *sinoartrial node* – a group of specialized cells that spontaneously generate action potentials at a regular rate.

The action potential propagates in all directions along the surface of both atria. A graphic recording or display of the time-variant voltages produced by the myocardium during the cardiac cycle is called an *electrocardiogram*. Fig. 16.4 shows the basic waveform of a normal electrocardiogram. The *P*, *QRS*, and *T* waves reflect the rhythmic electrical depolarization and repolarization of the myocardium associated with the contractions of the atria and ventricles.

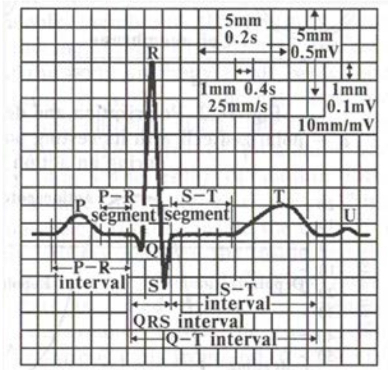


Fig. 16.4. **The important intervals and segments in the electrocardiogram**

The electrocardiogram is used clinically in diagnosting various diseases and conditions associated with the heart.

16.6. THE EINTHOVEN’S TRIANGLE

An ECG can be described in terms of the *cardiac vector*. The electrical activity of the heart corresponds to the movement of an electrical dipole which consists of a positive and a negative charge separated by a variable distance. The cardiac vector is the line joining the two charges. To fully describe the cardiac vector, its magnitude and direction must be known. Usually the cardiac vector is described by its length in three directions at 60° to each other. The resulting geometric pattern (fig. 16.5) is known as *Einthoven’s triangle*.

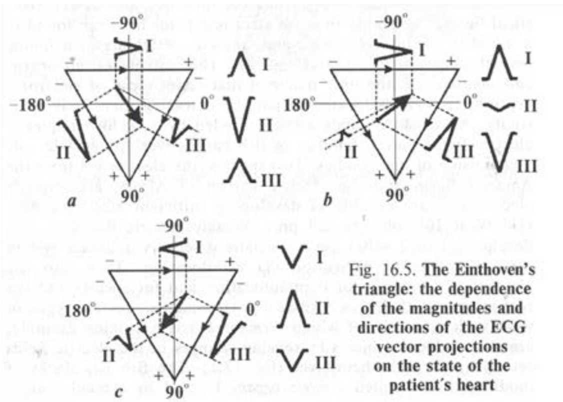


Fig. 16.5. **The Einthoven’s triangle: the dependence of the magnitudes and directions of the ECG vector projections on the state of the patient’s heart**

The sides of the triangle represent the lines along which the three projections of the ECG vector are measured. The magnitudes and directions of these projections depend strongly on the state of the patient's heart. The direction of normal cardiac vector runs between 0-+90°; the other directions correspond to various pathological situations.

16.7. OTHER BIOELECTRIC POTENTIALS

The recording of bioelectric potentials associated with muscle activity is called *electromyography*. These potentials may be measured at the surface of the body near a muscle or directly from the muscle by penetrating the skin with needle electrodes.

Electroretinography is a recording of the complex pattern of bioelectric potentials obtained from the retina of the eye, usually in response to a visual stimulus.

Electrooculography is a measure of variation in the corneal-retinal potential as affected by the position and movement of the eye.

Electrogastrography is the analysis of muscle activity associated with the peristaltic movements of the gastrointestinal tract.

Control Questions and Exercises

1. Write and formulate the Nernst Equation.
2. What is Resting Potential? Action Potential?

Chapter 17. ELECTROBIOLOGY

17.1. ELECTRIC FIELDS AND ANIMALS

A variety of aquatic organisms can produce and detect electrical fields. The ability to sense electrical fields has been found in a number of inveretebrates and aquatic vertebrates, including several species of fish, sharks and rays [3].

The platypus (*Ornithorhynchus anatinus*) is the only mammal that has a sense of electroreception. Its prey is located in part by detecting their body electricity.

All ocean animals are surrounded by very low-frequency electric fields. Seven families of fish can deliver appreciable voltage outside of their bodies.

Two species, the electric eel from the Amazon Basin and the electric catfish of Africa, are strongly electric and are capable of developing sufficient electric energy (10^3 W at 10^2 volts) to kill prey.

Weakly electric fish (i.e., can develop ≤1 or 2 volts) use a specialized sensory guidance system for environmental navigation via echolocation.

They also use electric echolocation for communication and for species and sex recognition in their low visibility environments.

Certain types of weakly electric fish, of which *Gymnarchus* is a striking example, are able to locate objects by sensing changes in the electric fields set up by the fish themselves (fig. 17.1).

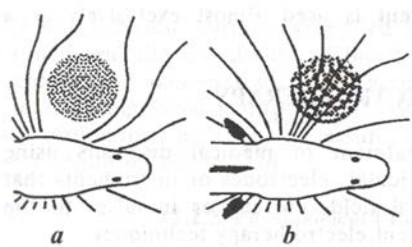


Fig. 17.1. **Certain types of weakly electric fishes, of which *Gymnarchus* is a striking example, are able to locate objects by sensing changes in the electric fields: the lines of electric field diverge from a poor conductor (*a*) and converge towards a good conductor (*b*)**

The fish has stacks of mod
located in a regular array along their
considerable electrical potential differ
17.2).

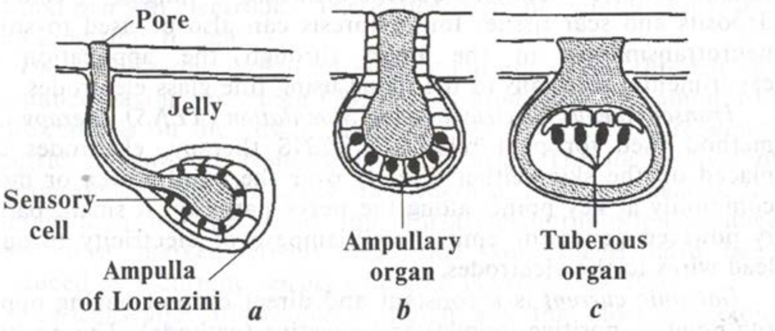


Fig. 17.2. **General structures of electroreceptive organs of fish: *a* — the ampullae of Lorenzini; *b* — the ampullary organ; *c* — the tuberous organ**

The field is pulsed by the fish, typically in a 25 ms pulse duration. The skin of the fish probably acts as an insulator except in certain regions near the head where jelly-filled pits provide conducting paths for the electric field. These pits have some type of sense organs at their base and it is these receptors that can detect very small changes in the field distribution at the head. With its receptors, a fish can detect the presence of different objects in muddy streams where the use of their eyes for catching prey or avoiding predators is impossible.

Strongly electric fish (certain freshwater eels and catfish) have enormous electrical potential, killing prey and warding off predators by delivering electric shocks of several hundreds volts. Eels have the unique ability to discharge both weak and strong electric current. The weak current is used primarily to locate and stun prey. The strong current is used almost exclusively as a weapon to attack prey.

17.2. ELECTROTHERAPY

Electrotherapy is the treatment of medical disorders using electrical methods – in particular, electrodes or instruments that apply some sort of electrical field, current or impulses to the body. There are several different electrotherapy techniques.

17.2.1. Methods of Electrotherapy

Iontophoresis is the ion transfer of topical solutions into the epidermis and mucous membranes using continuous direct current through electrodes applied to the body. This medical technology can be used for treatment of edema, skin ulcers, pain, inflammation, tendonis-bursitis-arthritis, fungus, calcium deposits and scar tissue. Iontophoresis can also be used to study neurotransmitters in the brain through the application of experimental solutions to the tissue using fine glass electrodes.

Transcutaneous Electrical Nerve Stimulation (TENS) Therapy is a method used for pain relief. In TENS therapy, electrodes are placed on the skin, either directly over the painful area or more commonly at key points along the nerve pathway. A small, battery-powered generator emits a milliampere of electricity through lead wires to the electrodes.

Galvanic current is a constant and direct current having opposite poles – positive (anode) and negative (cathode). The positive pole has an acidic reaction – soothes nerves, decreases blood supply and hardens tissues. It may be used to make flabby skin and tissues firmer, to close skin pores after a facial treatment, to decrease redness as in mild acne, and to prevent inflammation. The negative pole has an alkaline reaction – it irritates nerves, increases blood supply and softens tissues. This pole may be used to remove superfluous hair by electrolysis, to force bleaching solution into skin and to stimulate the circulation and nutrition of dry, pale skin and scalp.

Faradic current is an alternating and interrupted current capable of producing a mechanical reaction without a chemical effect. When a faradic current is applied to the body, the muscles are toned and the circulation of blood improved. It stimulates hair growth and increases glandular activity. Faradic current may be used during facial manipulations, but it cannot be used for pain or discomfort, high blood pressure, broken capillaries or a pustular condition of the skin.

17.2.2. Physiological Effects of Electricity

Electricity has at least three major effects that may be undesirable – electrolysis, heating and neuromuscular stimulation.

Electrolysis is the movement of ions in opposite directions through a medium. Electrolysis takes place when a direct current is passed through any medium which contains free ions. If two electrodes are placed on the skin, and a direct current of 100 μA is passed beneath them for a few minutes, small ulcers will be formed beneath electrodes. These ulcers can be painful and take a very long time to heal.

Thermal Heating. When an electric current passes through any substance having resistance (R), heat is produced. The amount of heat depends on the power dissipated ($Q = I^2R$). High-frequency electric currents are responsible for heating. The local effect of heating depends on the tissue, the length of time it is heated, the contact area and the blood flow. Electrical burns often produce their most marked effects near the skin. Burns have been produced by a current density of only 5 mA/mm^2 for 10 s.

Neuromuscular Stimulation is potentially the most dangerous physiological effect of electricity, in that the nervous system controls both the circulation of the blood and respiration. Because the body is a good conductor of electricity and our nerves and muscles function electrically, physiological effects occur when a current is applied to the body. If a current of sufficient amplitude is passed between a pair of surface electrodes, the muscles will contract because a stimulus is being introduced to the nerve fibers, which control the muscles. The prolonged involuntary contraction of muscles caused by an external electrical stimulus is called *tetanus*. Prolonged tetanus of the muscles between the ribs (intercostal muscles) can prevent breathing; tetanus of the heart musculature prevents blood being pumping out of the heart.

Control Works
Modulus 6
Electricity, Bioelectricity, Electrobiology

Problem. Find the magnitude of the electrical force between a bee and a mite (*Varroa Jacobsoni)*, if the charges for the bee and mite are +2.9 pC and -1.3 pC, respectively and the distance between them is 1 cm.

Answer: $3.39 \cdot 10^{-10}$ N.

Problem. A battery has an E.M.F. of 12 V and an internal resistance of 0.05 Ω. Its terminals are connected to a load resistance of 3 Ω. Calculate the power dissipated in the load resistor and the power dissipated by the internal resistance of the battery.

Answer: 46.3 W; 0.772 W.

Problem. Find the membrane potential for potassium ions in a human erythrocyte if the intracellular ionic concentration is 5 mM and extracellular concentration is 136 mM.

Answer: – 83.6 mV.

Animals Extremes!

The only mammal that has the sense of electroreception is the platypus (*Ornithorhynchus anatinus*).

VOCABULARY

English	Ukrainian	English	Ukrainian
Permittivity	Діелектрична проникність	Galvanic current	Гальванізація
Action potential	Потенціал дії	Iontophoresis	Іонофорез
Atrial	Передсердний	Junction	Вузол розгалуження
Attract	Притягувати		
Cathode ray tube	Електронно-променева трубка	Load resistance	Навантаження
Closed-circuit loop	Замкнутий контур	Neuromuscular stimulation	Нейром'язова стимуляція
Current electricity	Електродинаміка	Non-uniform	Неоднорідний
Deflecting plates	Відхиляючі пластини	Partial derivatives	Частинна похідна
Electric charge	Електричний заряд	Potential difference	Різниця потенціалів
Electric field	Електричне поле	Dielectric constant	Діелектрична стала
Electric field lines	Силові лінії електричного поля	Repel	Відштовхувати
		Resistance	Опір
Electric organ	Електричний орган	Resting potential	Потенціал спокою
Electric potential	Електричний потенціал	Sinoartrial node	Синусовий вузол
Electrolysis	Електроліз	Tetanus	Правець
Electromotive force	Електрорушійна сила	The electric field vector	Вектор напруженості електричного поля
Electron gun	Електронна гармата	Thermal heating	Теплове нагрівання
Electrostatics	Електростатика	Thermal heating	Теплове нагрівання
Equipotential surface	Еквіпотенціальна поверхня	Transcutaneous	Черезшкірний
		Uniform	Однорідний
Faradic current	Фарадізація	Uniform	Однорідний
Fluorescent screen	Флуоресцентний екран	Ventricle	Шлуночок
		Voltage	Напруга

Chapter 18. MAGNETISM

Magnetism is the branch of physics which studies phenomena associated with magnets and with moving electric charges, both of which produce magnetic fields in the space surrounding them.

18.1. MAGNETIC FIELDS

The phenomenon of magnetism was known to the Greeks as early as around 800 B.C. Legend ascribes the name *magnetite* to the shepherd Magnes, "the nails of whose shoes and the tip of whose staff stuck fast in a magnetic field while he pastured his flocks".

A *magnetic field* is defined as a region in which a magnetic force is found to be exerted on other magnets or current-carrying conductors placed in it. Magnetic fields are produced by the motion of an electric charge. A wire with current passing through it creates a magnetic field since a charge is moving through the wire. Likewise, bar magnets produce a magnetic field.

A *magnetic field vector* $\vec{B}$, sometimes called the *magnetic induction*, at some point in term of a magnetic force that would be exerted on an appropriate object $\vec{V}$a.charged p

Magnetic force (*Lorenz force*) acting on a particle with charge *q* depends on the velocity of the charge and is equal to

$$\vec{F}_M = q\left[\vec{V} \times \vec{B}\right] \qquad (18.1)$$

where $\left[\vec{V} \times \vec{B}\right]$ is the cross product of vectors $\vec{V}$ and $\vec{B}$ (fig. 18.1). The force is always perpendicular to both vectors.

The *left-hand rule* for the determination of the direction of the Lorenz force (Fig. 18.2) *is to point the four fingers of your right hand along the direction of* $\vec{V}$ *and then turn them until they point along the direction of* $\vec{B}$*; the thumb then points in the direction of* $\vec{F}_M$.

The unit of the magnetic field is the *tesla* (1 T = 1 N/A·m). There is an additonal legal subunit also - the *gauss* (1 G = 10^{-4} T). For example, the magnetic field of the Earth is about 0.5 G, while the magnetic field of a large electromagnet is about 1 T.

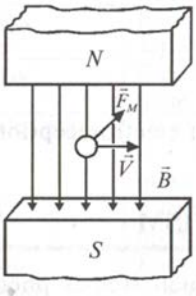


Fig. 18.1. **The Lorenz force $\vec{F}_M$ acting on a charged particle with charge *q* moving with a velocity $\vec{V}$ in the presence of a magnetic field $\vec{B}$**

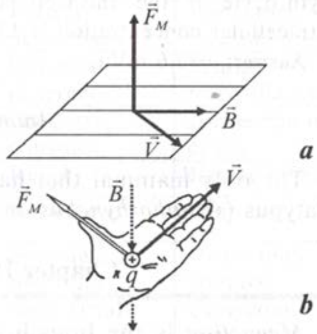


Fig. 18.2. **The Lorenz force: *a* — the directions of the magnetic force $\vec{F}_M$, velocity $\vec{V}$ of charged particle, and magnetic field $\vec{B}$;**

b **the left-hand rule for the determining the direction of the Lorenz force**

Example. A proton moves with a speed of $8{\cdot}10^6$ m/s along the *x* axis. It enters a region where there is a magnetic field of magnitude 2.5 T directed at an angle of 60° to the *x* axis. Calculate the initial magnetic force and acceleration of a proton.

Solution. Using Equation (18.1), we obtain:

$$F = qVb\sin\theta = (1.6{\cdot}10^{-19}\ \text{C})(8{\cdot}10^{6}\ \text{m/s})(2.5\ \text{T})(\sin 60°) = 2.77{\cdot}10^{-12}\ \text{N}.$$

18.2. THE MASS SPECTROMETRY

When a positively charged particle moves in a uniform external magnetic field with its initial velocity vector perpendicular to the field, the particle moves in a circle whose plane is perpendicular to the magnetic field. As the force ($\vec{F}_M$) deflects the particle, the directions of $\vec{V}$ and $\vec{F}_M$ change continuously. Therefore, the force ($\vec{F}_M$ *)* is a centripetal force. From Newton's second law, we find that:

$$F = qVB = \frac{mV^2}{r} \qquad (18.2)$$

or

$$r = \frac{mV}{qB} \qquad (18.3)$$

A *mass spectrometer* is an instrument that separates atomic and molecular ions according to their mass-to-charge ratio. A beam of ions first passes through a velocity selector and then enters a uniform magnetic field ($\vec{B}$) directed onto the target (Fig. 18.3).

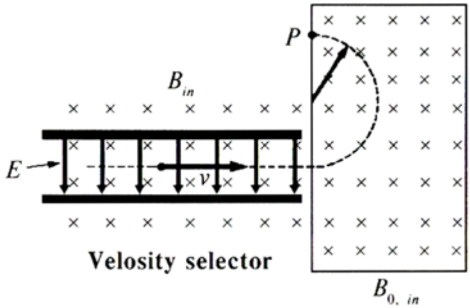


Fig. 18.3. **A mass spectrometer which consists of a velocity selector and a source of uniform magnetic field**

Upon entering the magnetic field, the ions move in a semicircle of radius *r* before striking the target at *P*. From Equation (18.3) we can express the ratio *m/q* as:

$$\frac{m}{q} = \frac{rB}{V} \qquad (18.4)$$

Therefore, one can determine *m/q* by measuring the radius of curvature and knowing the field *B*.

Example. A proton is moving in a circular orbit with a 14 cm radius in a uniform magnetic field of magnitude 0.35 T directed perpendicular to the velocity of the proton. Find the orbital speed of the proton.

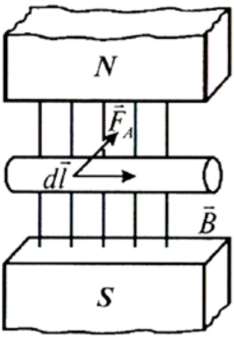
Solution. Using Equation (18.3), we obtain:

$$V = \frac{qBr}{m} = \frac{(1.6 \cdot 10^{-19} C)(0.35T)(14 \cdot 10^{-2} m)}{1.67 \cdot 10^{-27} kg} = 4.69 \cdot 10^{6} \text{ m/s}$$

18.3. AMPERE'S LAW

If a straight segment of wire of length *l*, carries a current (*I*) in a uniform external magnetic field ($\vec{B}$) (Fig. 18.4), the total magnetic force on the wire is:

$$d\vec{F} = I\left[d\vec{l} \times \vec{B}\right] \qquad (18.5)$$



where $d\vec{l}$ is a vector in the direction of the current (*I*). Thus the force on a differential length ($d\vec{l}$) of current carrying wire is the vector cross product of $d\vec{l}$ and the magnetic field ($\vec{B}$) at $d\vec{l}$.

Fig. 18.4. **Ampere's force** $\vec{F}_A$ **acting on a wire of length** $d\vec{l}$ **in the presence of a magnetic field** $\vec{B}$

18.4. MAGNETIC FIELD OF A THIN STRAIGHT CONDUCTOR

With a straight wire of infinite length, the total magnetic field at a point located at distance *a* from the wire is given as:

$$B = \frac{\mu_0 I}{2\pi a} \qquad (18.6)$$

Example. Calculate the magnetic field of a long, straight wire carrying a current of 5 A, at a distance of 4 cm from the wire.

Solution. Using Equation (18.6), we obtain:

$$B = \frac{\mu_0 I}{2\pi a} = \frac{4\pi \cdot 10^{-7} N/A^2 \cdot 5A}{2\pi \cdot 4 \cdot 10^{-2} m} = 2.5 \cdot 10^{-5}\ \text{T}.$$

18.5. FARADAY'S LAW

Let us consider the electric loop and changing magnetic field which is characterized with magnetic flux Φ_M. This magnetic flux threads through the loop and produces the electromotive force $\mathcal{E}$ in it. The relationship between ε and Φ_M is given by *Faraday's Law:*

$$\mathcal{E} = -\frac{d\Phi_M}{dt} \qquad (18.7)$$

The unit of magnetic flux is the *weber* (1 Wb = 1 T·m^2). The negative sign contained in Faraday's Law indicates the *direction* in which the induced electromotive force (E.M.F.) drives the current. The direction is significant enough to merit its designation as *Lenz´s rule* which states that the *direction of current flow is such as to oppose the inducing flux change*.

18.6. ELECTROMAGNETIC FLOW METER

If a conductor is moved in a magnetic field, the charges within it experience a force. The movement of these charges constitutes a flow of current, which, in turn, produces a force that tends to oppose the movement of the conductor. Work, therefore, has to be done to move the conductor:

$$dA = \vec{F} \cdot d\vec{x} = I(\vec{L} \times \vec{B}) \cdot d\vec{x} \qquad (18.8)$$

The power input is $P = dA/dt$, and therefore:

$$P = I\ (\vec{L} \times \vec{B}) \cdot \vec{V} \qquad (18.9)$$

where $\vec{V}$ is the velocity of the conductor. The power input is given by $P = IU$, where U is the potential difference across the ends of the conductor; therefore:

$$U = (\vec{L} \times \vec{B}) \cdot \vec{V} \qquad (18.10)$$

When $\vec{L}$, $\vec{B}$ and $\vec{V}$ are mutually perpendicular, as in the case of the electromagnetic flow meter, the previous equation simplifies to:

$$U = LBV \qquad (18.11)$$

This equation can be applied directly to the measurement of blood flow.

An *electromagnetic flow meter* for blood flow measurement consists of an electromagnet to generate a magnetic field and two electrodes to sense the flow signal. They are encapsulated in inert hard plastic in a form that permits them to fit around the blood vessel of interest (fig. 18.5).

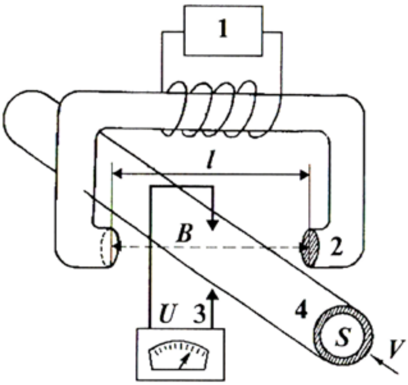


Fig. 18.5. **Electromagnetic flowmeter: *1* — signal voltage; *2* — electromagnet; *3* — readout system; *4* — blood vessel; *S* — cross-sectional area of the vessel; *V* — velocity of the blood flow; *U* — potential difference; *B* — the magnetic field; *l* — distance between the poles of magnet**

In this way the system can be used to measure the potential difference versus the blood flow.

18.7. LARGE HADRON COLLIDER‡

The *Large Hadron Collider (LHC)* is the world's largest and highest-energy particle accelerator. It was built by the European Organization for Nuclear Research (CERN) from 1998 to 2008, with the aim of allowing physicists to test the predictions of different theories of particle physics and high-energy physics, and particularly prove or disprove the existence of the hypothesized Higgs boson.

‡ Large Hadron Collider. From Wikipedia, http://en.wikipedia.org/wiki/Large_Hadron_Collider

The LHC was built in collaboration with over 10,000 scientists and engineers from over 100 countries, as well as hundreds of universities and laboratories. It lies in a tunnel 27 kilometres in circumference, as deep as 175 metres beneath the Franco-Swiss border near Geneva, Switzerland.

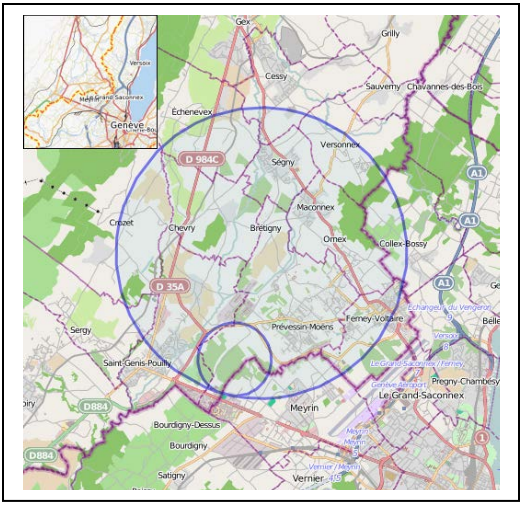


Fig. 18.6. **Map of the Large Hadron Collider at CERN**

With a budget of 7.5 billion euros (approx. $9bn as of Jun 2010), the LHC is one of the most expensive scientific instruments ever built.

The term *hadron* refers to composite particles composed of quarks held together by the strong force (as atoms and molecules are held together by the electromagnetic force). The best-known hadrons are protons and neutrons; hadrons also include mesons such as the pion and kaon, which were discovered during cosmic ray experiments in the late 1940s and early 1950s.

A *collider* is a type of a particle accelerator with directed beams of elementary particles. In particle physics colliders are used as a research tool: they accelerate particles to very high kinetic energies and let them impact other particles. Analysis of the byproducts of these collisions gives scientists good evidence of the structure of the subatomic world and the laws of nature governing it.

The *collider tunnel* contains two adjacent parallel beamlines (or beam pipes), each containing a proton beam, which travel in opposite directions around the ring. In total, over 1,600 superconducting magnets are installed, with most weighing over 27 tonnes. Approximately 96 tonnes of liquid helium is needed to keep the magnets, made of copper-clad niobium-titanium, at their operating temperature of 1.9 K (−271.25 °C), making the LHC the largest cryogenic facility in the world at liquid helium temperature.

Fig. 18.7**. Over 1,600 superconducting magnets are installed, with most weighing over 27 tonnes.**

Six detectors have been constructed at the LHC, located underground in large caverns excavated at the LHC's intersection points. Two of them, the ATLAS (**A**rgonne **T**andem **L**inear **A**ccelerator **S**ystem) experiment and the CMS (**C**ompact **M**uon **S**olenoid), are large, general purpose particle detectors.

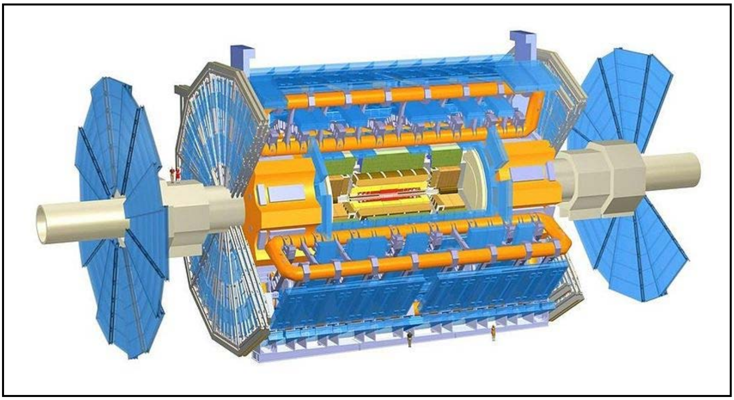


Fig. 18.8. **Computer generated cut-away view of the ATLAS detector showing its various components**

The *Higgs boson* is an elementary particle in the Standard Model of physics. All other particles in the Standard Model have been seen in experiments, but the Higgs boson, first predicted to exist in the 1960s, is difficult to create and detect. It may have finally been discovered in July 2012.

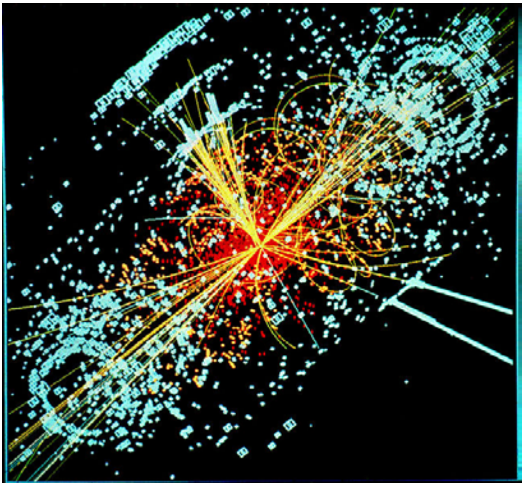


Fig. 18.9. **One possible signature of a Higgs boson from a simulated collision between two protons. It decays almost immediately into two jets of hadrons and two electrons, visible as lines**

Control Questions and Problems

1. What is magnetism?
2. What is a magnetic field?
3. What is the Lorentz force?
4. How to determine the direction of the Lorenz force?
5. Formulate Ampere’s Law.
6. Formulate Faraday’s Law.

Chapter 19. BIOMAGNETISM

19.1. MAGNETIC FIELDS IN LIVING ORGANISMS

The word *magnetography* originates from the Greek words *magnetos* meaning magnetic field and *graphi* meaning to write on. Neural tissue produces electrical potentials within the body and these potentials give rise to electrical currents in the tissue. The currents, in turn, create magnetic fields. Biomagnetic fields are also produced by currents which circulate in biological membranes, blood vessels, and around the heart (*magnetocardiography*), brain (*magnetoencephalography*), muscles (*magnetomiography*), and eyes (*magnetooculography*).

Magnetocardiography allows mapping the magnetic field around the thorax as a research tool. The magnetic field is a vector quantity and therefore, has three components at each location in space. The method of magnetocardiography is explained in fig. 19.1. Each of the three components are measured symmetrically (i.e., on both sides of the source). Such a system requires six magnetometers or six consecutive measurements with one magnetometer.

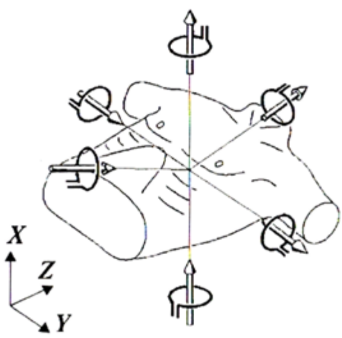


Fig. 18.6. **Principles of three-dimensional magnetocardiography through the mapping of the magnetic field around the thorax of patient**

Chapter 20. MAGNETIBIOLOGY

20.1. MAGNETIC ORIENTATION IN ANIMALS

The total intensity of the geomagnetic field is highest near the magnetic poles, at more than 60000 nT and decreases to about 26000 nT at the magnetic equator. *Magnetic orientation* means that animals use information from the magnetic field to direct and control their behavior [26].

Magnetotactic bacteria (i.e., *Magnetospirillum gryphiswaldense, Magnetobacterium bavaricum)* move “north-seekingly”, following the magnetic lines northward. Such a movement along the magnetic field lines is called *magnetotaxis*. The magnetic response is caused by small particles of *magnetite* (Fe_3O_4) arranged in chains. Their magnetic moment rotates these bacteria, whether alive or dead, into a position parallel to the field lines with their front toward the north.

Magnetic orientation in animals is characterized by a complex relationship between the stimulus and response. The orientation behavior of animals includes compass orientation, response to magnetic gradients and temporal variations, and other responses.

Some insects demonstrate a tendency to align their body axis with the cardinal axes of the magnetic field [i.e., termite queen (*Odontotermes* sp. and *Termes malabaricus*), cockchafer (*Melolontha melolontha*), resting long-horned beetle (*Hylotrupes bajulus*), cockroach (*Blatta Americana*), cricket (*Acheta domestica*), and yellow jacket (*Paravespula* sp.)]. In honeybees (*Apis melifera*), alignment responses have been described in connection with preferred resting positions and with the *waggle dance* by which bees inform their nestmates about the position of food sources.

T he salamander (*Eurycea lucifuga*) and frogs use the magnetic field for orientation when they have to quickly find the direction of the nearest shore (e.g., when they sense danger).

Fish such as goldfish (*Carassius auratus*), European eel (*Anguilla anguilla*), and rainbow trout (*Oncorhynchus mykiss*) are the vertebrates in which alignment behaviors have been reported.

Birds monitor the Earth’s magnetic field during migration using tiny grains of magnetite in their heads.

20.2. MAGNETOTHERAPY

Magnetotherapy is the treatment of certain diseases with magnets placed on the surface of the body.

There are a number of publications claiming a positive benefit from magnetic therapy for healing a cross-section of maladies (e.g., cancer), however, the U.S. Food and Drug Administration has not evaluated these claims. The information contained in these publications is not intended to diagnose, treat, cure, or prevent any disease, nor replace doctor–patient consultation.

20.3. MOBILE PHONE[§]

A *mobile phone* (also known as a cellular phone, cell phone and a hand phone) is a device that can make and receive telephone calls over a radio link while moving around a wide geographic area. It does so by connecting to a cellular network provided by a mobile phone operator, allowing access to the public telephone network.

In addition to telephony, modern mobile phones also support a wide variety of other services such as text messaging, MMS, email, Internet access, short-range wireless communications, business applications, gaming and photography.

The first hand-held mobile phone was demonstrated by John F. Mitchell and Dr Martin Cooper of Motorola in 1973, using a handset weighing around 1 kg.

The effect mobile phone radiation has on human health is the subject of recent interest and study, as a result of the enormous increase in mobile phone usage throughout the world. Mobile phones use electromagnetic radiation in the microwave range, which some believe may be harmful to human health.

On 31 May 2011, the World Health Organization confirmed that mobile phone use may represent a long-term health risk, classifying mobile phone radiation as a “carcinogenic hazard” and “possibly carcinogenic to humans” after a team of scientists reviewed peer-review studies on cell phone safety. One study of past cell phone use cited in the report showed a “40% increased risk for gliomas (brain cancer) in the highest category of heavy users (reported average: 30 minutes per day over a 10-year period).”At least some recent studies have found an association between cell phone use and certain kinds of brain and salivary gland tumors. In addition, a mobile phone can spread infectious diseases by its frequent contact with hands.

[§] Mobile Phone From Wikipedia, the Free Encyclopedia http://en.wikipedia.org/wiki/Mobile_phone

Mobile phone use while driving is common, but widely considered dangerous. Due to the number of accidents that are related to cell phone use while driving, some jurisdictions have made the use of a cell phone while driving illegal.

Problem. The magnetic field of the Earth at a certain location is directed horizontally toward the west in this field at a velocity of $6.2 \cdot 10^6$ m/s, what are the magnitude and direction of the Lorentz force?

Answer: $4.96 \cdot 10^{-17}$ N. (Yuriy, should the answer be in tesla and the direction given in degrees?)

Problem. An electron is moving with an orbital speed of $1.11 \cdot 10^7$ m/s in a uniform magnetic field directed perpendicular to the velocity of the electron. The radius of circular orbit of the electron is 7.5 cm. Find the magnitude of the magnetic field.

Answer: $8.43 \cdot 10^{-4}$ T.

Problem. A lightning bolt can carry a current of 10^4 A for a short period of time. What is the resulting magnetic field at a point 100 m from the bolt?

Answer: **5**$\cdot 10^{-6}$ T.

Animal Extremes

Magnetotactic bacteria are rotated by a geomagnetic field (about $5 \cdot 10^{-5}$ T) due to the torque exerted on their magnetite particles.

VOCABULARY

English	Ukrainian		English	Ukrainian
Bar magnet	Стрижнепо-дібний магніт		Magnetocar-diography	Магнітокар-діографія
Electromagne-tic flow meter	Електромаг-нітний вимі-рювач потоку		Magnetoence-phalography	Магнітоенце-фалографія
Magnetic field	Магнітне поле		Magnetography	Магнітографія
Magnetic field vector	Вектор маг-нітної індукції		Magnetomio-graphy	Магнітоміо-графія
Magnetic flux	Магнітний потік		Magnetoocu-lography	Магнітооку-лографія

Control Questions and Problems

1. What is the effect of magnetic field on living organisms?
2. Explain the sources of magnetic fields in living organisms.
3. Explain he principles magnetography.

Chapter 21. OPTICS

Optics is the branch of physics that deals with optical radiation, processes of its propagation and phenomena associated with the interaction of light and matter.

21.1. NATURE OF LIGHT

Light is simply a name for electromagnetic radiation that can be detected by the human eye. Electromagnetic radiation has a *dual nature* as it is found as both waves and particles. According to the classical interpretation, electromagnetic radiation consists of changing electric and magnetic fields that propagate through space forming an *electromagnetic wave* (fig. 21.1).

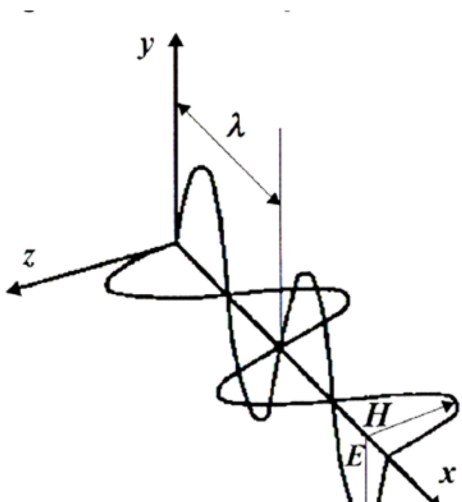


Fig.21.1. **Light as electromagnetic wave which consists of changing electric and magnetic fields and propagates through space**

The wave has amplitude – the brightness of the light, wavelength – the color of the light, and angle – its vibration or polarization. In terms of the quantum theory, electromagnetic radiation consists of particles called *photons*, which are packets (*quanta*) of energy that move at the speed of light. In the particle view of light, the brightness of the light is the number of photons, the color is the energy contained in each photon, and polarization is represented by four parameters (x, y, z, and t). Both the classical and quantum theory interpretations are correct.

1.2. GEOMETRIC OPTICS

21.2.1. Ray Approximation

In studying *geometric optics,* the term *ray approximation* is used. The first documented contribution to the scientific study of light was made by Euclid in 300 B.C. who wrote: "Light travels in straight lines called rays". To understand approximation, remember that the direction of the energy flow of a wave, which corresponds to the direction of the wave propagation, is called a *ray*. The rays of a given wave are straight lines that are perpendicular to the wavefront, as illustrated in fig. 21.2. If the wave meets a barrier with a circular opening whose diameter (d) is large relative to the wavelength ($\lambda << d$), the wave emerging from the opening continues to move in a straight line (fig. 21.3*a*).

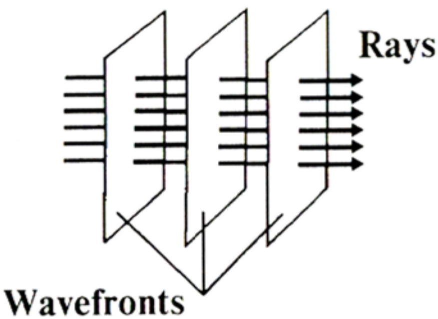


Fig. 21.2. **A plane wave propagating to the right**

On the other hand, if the diameter of the opening of the barrier is in the order of the wavelength ($\lambda \approx d$), the waves spread out from the opening in all directions due to the effect of diffraction (fig. 21.3*b*,*c*). Therefore, ray approximation is very useful for the study of mirrors, lenses, prisms, and associated optical instruments, such as microscopes, eyeglasses, cameras, and telescopes.

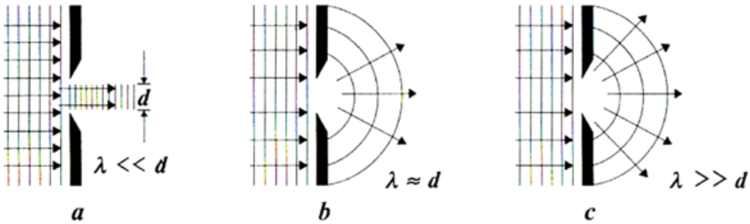


Fig.21.3. **A plane wave of wavelength** λ **is incident on a circular opening of diameter** ***d*****:** *a* – λ ;< *b* – *d* $\lambda = d$; *c* – $\lambda >> d$

21.1.2. Laws of Geometric Optics

Law of Reflection: *When a ray of light is reflected from a plane surface, the incident ray and the reflected ray all lie in the same plane; the angle of reflection equals the angle of incidence:*

$$i = r \qquad (21.1)$$

Law of Refraction*:* *When a ray of light passes from one medium to another, the incident ray, the reflected ray, and the refracted ray all lie in the same plane; the sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction:*

$$\sin i / \sin r = n \qquad (21.2)$$

The ratio sin*i* / sin*r* is known as the *refractive index* from one medium to another. It is convenient to define the refractive index of a medium to be the ratio:

$$n = \frac{c}{V} \qquad (21.3)$$

where *c* is the speed of light in a vacuum and *V* the speed of light in a medium. Refraction index values for several common materials are: air = 1.0003, water = 1.33, glass = 1.52, diamond = 2.42, lead sulfide = 3.91.'

21.1.4. Total Internal Reflection

An interesting effect, called *total internal reflection,* can occur when light attempts to move from a medium having given index of refraction (n_1) to one having a lower index of refraction (n_2) (fig. 21.4). All possible directions of the beam are indicated by rays 1 through 5. At some particular angle of incidence (i_c), called the *critical angle,* the refracted light ray will move parallel to the boundary. The value of the critical angle (θ_c) can be found from the following expression:

$$\sin\theta_c = \frac{n_2}{n_1} \qquad (21.4)$$

where n_1 is greater than n_2.

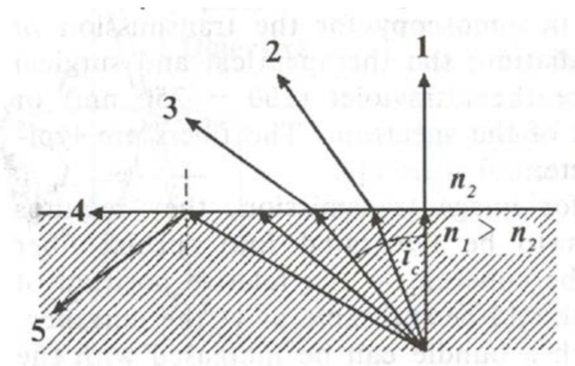


Fig. 21.4. **Total internal reflection**

For angles of incidence greater than i_c, the beam is entirely reflected at the boundary. In such a way, *total internal reflection occurs only when light attempts to move from a medium of given index of refraction to a medium of lower index of refraction.*

Example. Find the critical angle for a water-air boundary (a view from the fish's eye) if the index of refraction of water is 1.33.

Solution. Applying the equation (21.4), we find the critical angle to be

$$sin\theta_c = \frac{n_2}{n_1} = \frac{1}{1.33} = 0.752$$

$$\theta_c = 48.8^\circ$$

21.1.5. Fiber Optics

Optical fibers are devices that can be used for transporting radiation from the source to the sample (e.g., a biological tissue) for diagnostics, therapy, or surgery. An optical fiber consists of a long, thin flexible rod of transparent material. The principle of operation of a fiber is based on total internal reflection that depends on the angle of incidence of the light ray and the refractive index of the fiber (fig. 21.5).

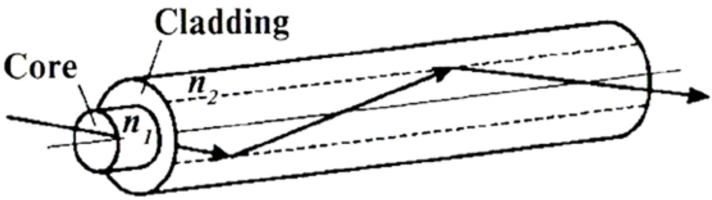


Fig. 21.5. **Principle of operation of fiber**

Usually, each fiber consists three parts: the *core* at the centre of the fiber; a concentric layer of glass called the *cladding,* which surrounds the core; and a polyurethane *jacket* that protects the fiber. The refractive index of the surrounding medium is *n* and θ is the angle of incidence.

Optical fibers are used in endoscopy for the transmission of visible (400-600 nm) radiation; therapeutical and surgical applications typically utilize the ultraviolet (200-250 nm) or infrared (~10 μm) portions of the spectrum. The fibers are typically 10 -100 μm in diameter.

When fibers are used for image transmission, they require very thin individual fibers to be fabricated into special fiber bundles. The bundle must be coherent – the relative position of each fiber at the exit end should be the same as at the entrance. The resolving power of such a bundle can be increased with the use of very small diameter (1-25 μm) fibers. A second bundle or simply a single fiber is used to illuminate the object.

21.2.5. Compound Microscopes

A *compound microscope* consists of an *objective lens* with a very short (i.e. < 1 cm) focal length (f_0) and an ocular lens with a focal length (f_e) of a few centimeters. The two lenses are separated by a distance (*L*), where *L* is much greater than either f_0 or f_e. The object, which is placed just outside the focal length of the objective lens, forms a real, inverted image at I_1, which is at or close to the focal point of the ocular lens. The ocular lens, which serves as a simple magnifier, produces at I_2 an image of the image at I_1, in which the image at I_2 is virtual and inverted. The lateral magnification (M_1) of the first image is:

$$M_1 = -\frac{s_1^{/}}{s_1} \qquad (21.4)$$

where s_1 is the object distance and $s_1^{/}$ is the inverted image distance.

Note in fig. 21.6 that $s_1^{/} \approx L$ and recall that the object is very close to the focal point of the objective lens, thus $s_1 \approx f_0$. This gives a magnification for the objective of:

$$M_1 = -\frac{L}{f_0} \qquad (21.5)$$

where L = 160 mm.

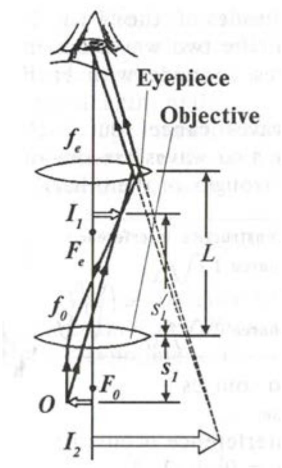


Fig. 21.6. **Diagram of a compound microscope**

The angular magnification of the ocular lens for an object (corresponding to the image at I_1) placed at the focal point is found to be:

$$m_{oc} = \frac{250mm}{f_e} \qquad (21.6)$$

where 250 mm is the nearest point to the eye.

The overall magnification of the compound microscope is defined as the product of the lateral and angular magnifications:

$$M = M_1 \cdot m_{oc} = -\frac{L}{f_0}\left(\frac{250mm}{f_e}\right) \qquad (21.7)$$

where m_{oc} is the angular magnification of the ocular lens.

The negative sign indicates that the image is inverted.

21.3. WAVE OPTICS

21.3.1. Definition of Wave Optics

Wave optics deals with the phenomena of interference, diffraction, and polarization of light. These phenomena cannot be adequately explained with ray optics, but the wave theory of light gives a satisfactory description.

21.3.2. Interference

Interference is the interaction among waves traveling in the same medium. When two waves come into contact, depending on phase differences along the waves, *constructive* or *destructive* interference will occur.

In constructive interference, the amplitude of the wave is amplified (fig. 21.7*a*). This happens when the two waves are in phase (the crests and troughs of the waves coincide with each other).

In destructive interference, the two waves cancel out each other (fig. 21.7*b*). This happens when the two waves are out of phase (the crests of one wave coincide with troughs of the other).

In order to observe interference in light waves, the following conditions should be met:

1. The sources must be *coherent*, that is, they must maintain a constant phase with respect to each other;

2. The sources must be *monochromatic*, that is, of a single wavelength; and

3. The superposition principle must apply: all interference associated with light waves arises as a result of combining the fields that constitute the individual waves.

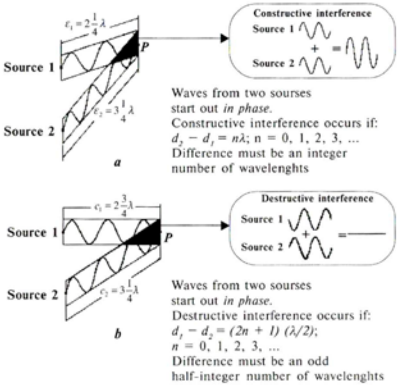
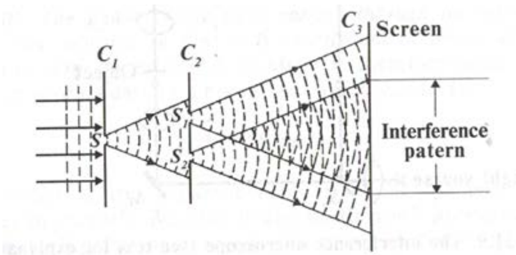


Fig. 21.7. **Schematic diagram of some of the ways the two waves can combine: *a* — amplification of the wave in constructive interference; *b* — cancellation of the wave in destructive interference**

21.3.3. Young's Double-Slit Experiment

The interference of light waves from two sources was first demonstrated by Thomas Young in 1801. A schematic diagram of this experiment is shown in fig. 21.8.



g. 21.8. **Schematic diagram of Young's duble-slit experiment**

Monochromatic light is incident on a screen C_1, which is provided by a narrow slit (S). The waves emerging from the slit arrive at a second screen C_2, which contains two narrow, parallel slits, S_1 and S_2. These two slits serve as a pair of coherent light sources because waves emerging from them originate from the same wavefront and therefore maintain a constant phase relationship. The light from the two slits produces a visible interference pattern on the third screen C_3.

21.3.4. Interference Microscopes

Interference microscopes allow small objects to be viewed without the use of staining techniques. As there is usually only a small difference in absorption (for example, between a cell and its bathing medium), there will be very little difference in amplitude between the light passing though the medium and that passing through the specimen. There will, however, be a phase difference introduced because of the refractive index difference between the medium and specimen. Since the eye cannot detect differences in phase, the purpose of the interference microscope is to convert the phase difference into an amplitude difference. One way of doing this is to use *round-the-square interference* (fig. 21.9).

The observed image arises from the sum of two light beams. One passes though the object and the other traverses a comparison slide in a manner by which the phase and amplitude of the comparison beam can be adjusted.

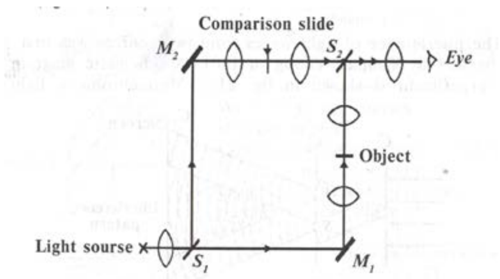


Fig. 21.9 **The interference microscope** (see text for explanation)

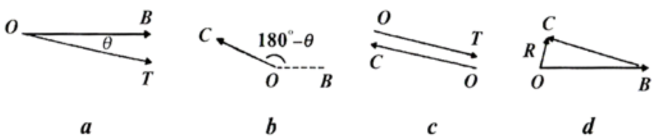


Fig. 21.10. **Vector representation of background and transmitted light: *a* — the vector *OB* represents the background light and *OT* the light transmitted through the object; *b* – *OC* represents the amplitude and phase of the light which has passed through the comparison slide; *c* — the phase of *OC* has been adjusted so that it is exactly out of phase with light transmitted through the object *OT*; *d* — the background does not appear dark as the background vector *OB* and comparison vector *OC* are not 180° out of phase**

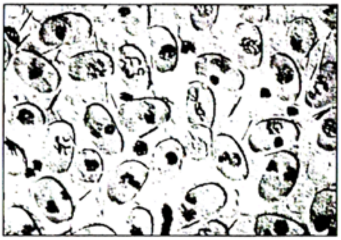


Fig. 21.11. **Pollen of Tradescantia as seen with interference microscope**

In fig. 21.10 the vector (*OB*) represents the background light and *OT* the light transmitted through the object.

As the latter has a slightly higher refractive index than the suspending medium, *OT* will be directed behind *OB* by a small angle (θ). *The phase of the light passing through the comparison slide is now adjusted so that it is exactly out of phase with light transmitted through the object.* Contrast is therefore achieved and the object appears dark in a bright surround (fig. 21.11).

21.3.5. Diffraction

Diffraction is the apparent bending of light waves around obstacles in its path. Bending is due to *Huygen's principle*, which states that *all points along a wave front act as if they were point sources*. Thus, when a wave comes against a barrier with a small opening, all but one of the effective point sources is blocked. The light coming through the opening behaves as a single point source, so that the light emerges in all directions, instead of just passing straight through the slit.

Consider light waves coming from various portions of the slit. The character of the diffraction pattern depends on the phase difference between the waves (fig. 21.12).

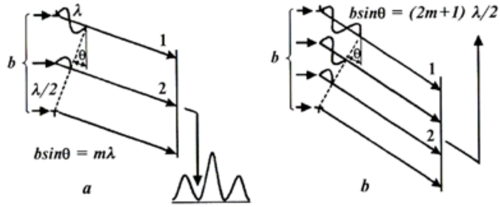


Fig. 21.12. **Mechanism of diffraction of light by a narrow slit of width *a*: *a* — condition of maximum; *b* — condition of minimum**

The conditions for minima are:

$$a\sin\theta = m\lambda, \text{ where } m = 1,2,3,\ldots \quad (21.8)$$

The conditions for maxima are:

$$a\sin\theta = \frac{(2m+1)\lambda}{2}, \text{ where } m = 1,2,3,\ldots \quad (21.9)$$

21.3.6. Measurement of Mean Erythrocyte Size

Thomas Young, in 1813, was the first to apply the principle of diffraction to the measurement of spherical objects such as human erythrocytes. The principle of the *erythrocytometer* depends on the fact that the size of the diffraction spectrum varies with the size of the red cells and its distance from the light source. The device consists of two cylinders, one of which telescopes into the other. The outer cylinder can be moved up or down thus varying the distance between the top of the outer cylinder and the bottom of the inner cylinder. A metal disk is inserted across the bore of the inner cylinder. The disk has a small central aperture to emit a beam of light producing the diffraction spectrum. At the top of the outer cylinder is a slot for holding a slide containing a thin film of blood. The distance of the film from the light source is adjusted until the inner ring of the spectrum directly overlays the inner circle of the hole. The mean size of the erythrocytes is read directly in micrometers.

21.3.7. Diffraction Grating

A *diffraction grating* consists of a large number of equally spaced parallel slits (fig. 21.13).

A grating can be made by engraving parallel lines on a glass plate using a precision machining technique.

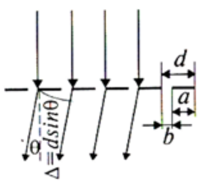


Fig. 21.13. **Diffraction grating**

The number (N) of lines can be varied from 600 to 2800 lines/mm. The slit spacing (d) equals the inverse of this number, or:

$$d = 1/N \qquad (21.10)$$

The *equation for diffraction grating* describes the condition for maxima in the interference pattern at the angle θ:

$$d\sin\theta = m\lambda \ \ (m = 0,1,2,3,\ldots) \qquad (21.11)$$

The diffraction grating is used in physics to determine precisely the wavelength of a source of light.

Example. Monochromatic light from a helium-neon laser (wavelength 632.8 nm) is incident normally on a diffraction grating containing N = 6000 lines/cm. Find the angle at which one would observe the first-order maximum.

Solution. A slit spacing d of the diffraction grating is equal to the inverse of the number N, or $d = 1/N$ = 1/6000 cm = $1.667 \cdot 10^{-6}$ m. For the first-order maximum (m = 1), we obtain from the equation for diffraction grating:

$$d\sin\theta = \lambda$$

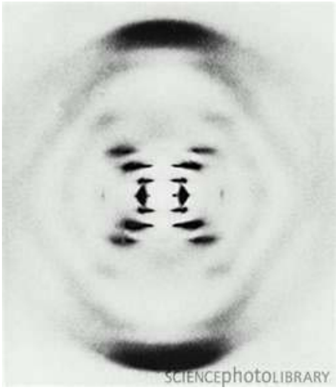
$$\sin\theta = \lambda/d = 0.3797$$

$$\theta = 22.31^{\circ}$$

21.3.8. X-Ray Diffraction and Structure of DNA

The amount of information that can be derived from the examination of any material depends ultimately on how fine a probe is used. For example, examination of biological tissue using an optical microscope is limited by the wavelength of visible light that is in the 500 nm region. The wavelength of X-rays, in contrast, is in the 0.1 nm region, so they provide an excellent probe.

In the early 1950's, J.D. Watson and F.H.C. Crick utilized X-ray diffraction techniques to deduce the double helical structure of deoxyribonucleic acid (DNA). They realized that the cross-wise pattern of the DNA X-ray diffraction picture (fig. 21.14) was due to a repeating helical structure.



Dig. 21.14. **Diffraction pattern obtained from a helical structure of DNA**

21.3.9. Polarization

Light is electromagnetic radiation consisting of electric ($\vec{E}$) and magnetic ($\vec{H}$) vectors vibrating at right angles to each other and to the direction of propagation. Conventional polarization is associated with the electric vector. An ordinary beam of light is produced by a large number of waves emitted by the atoms or molecules of the light source; the direction of vibration of the $\vec{E}$ vector changes about every 10^{-8} seconds. A wave of *unpolarized light* traveling at right angles to a plane perpendicular to the direction of propagation is depicted in fig. 21.15,*a*.

A wave is said to be *linearly polarized* if $\vec{E}$ vibrates in the same direction at all times at a particular point (fig. 21.15,*b*).

If the tip of the vector $\vec{E}$ rotates in a circle with time, the wave is said to be *circularly polarized* (fig. 21.15,*c*).

If the tip of the vector $\vec{E}$ moves in an ellipse, the wave is said to be *elliptically polarized* (fig. 21.15,*d*).

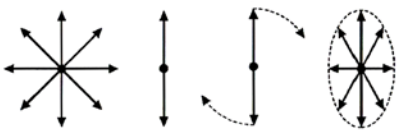


Fig. 21.15. **Representation of the vector $\vec{E}$ of: *a* — unpolarized light; *b* — linearly polarized light; *c* — circularly polarized light; *d* — elliptically polarized light. The light ray is travelling at right angles to the plane of the paper**

There are special *dichroic* crystals (e.g., tourmaline) and Polaroid films (polyvinyl alcohol) that will pass light vibrating in only one direction. Such a crystal is called the *polarizer*. If the light is plane polarized after passing through the crystal, it will be stopped by an *analyzer* placed at right angles to the polarizer.

21.3.10. Optical Activity

Optical activity is the ability of certain materials to rotate the plane of polarization of transmitted light. The angle (φ) through which the light is rotated by the material depends on the length (l) of the sample and on the concentration (C) if the substance is in solution:

$$\varphi = \alpha C\, l \qquad (21.12)$$

where α is the specific optical activity of the substance.

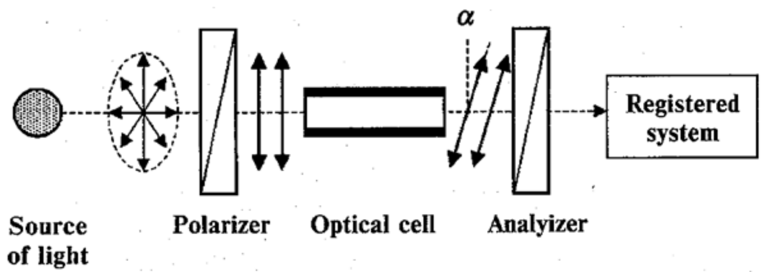


Fig. 21.16. **Polarymeter**

A *polarimeter* is a device that uses optical activity to measure the angle of rotation of polarized light. It consists of an elongated optical cell mounted between two polarizing lenses, one of which is fixed (*polarizer*) and the other free to rotate (*analyzer*). The unpolarized light that is passing through the polarizer is polarized; the analyser intercepts this polarised light beam with its transmission axis at an angle φ to the axis of the polyrizer. This angle φ is measured by the registering system (fig. 21.16).

21.4. QUANTUM OPTICS

21.4.1. Photoelectric Effect

In the latter part of the 19th century, experiments showed that when light is incident on certain metallic surfaces, electrons are emitted from the surfaces. This phenomenon is known as the *photoelectric effect* and could not be understood within the framework of classical physics.

Fig. 21.17 is a schematic diagram of an apparatus in which the photoelectric effect can occur. The evacuated glass tube contains a metal plate (the cathode) connected to the negative terminal of a battery. Another metal plate (the anode) is connected to the positive terminal of the battery. When the tube is kept in the dark, there is no current in the circuit. However, when monochromatic light of the appropriate wavelength strikes the cathode, a current is generated that can be measured.

The first successful explanation of the photoelectric effect was by Einstein in 1905.

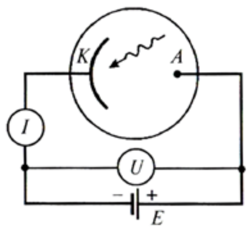


Fig. 21.17. **Circuit diagram for observing the photoelectric effect: *A* — anode; *C* — cathode**

He proposed that light not only came in waves, but also in packets of energy called photons. As a photon hits an electron, it transfers a certain amount of energy. If the energy is sufficient, the electron is ejected, striking the surface of the metal where it can be detected. According to Einstein, the law of conservation of energy during the photoelectric effect is:

$$h\nu = A + \frac{mV^2}{2} \qquad (21.13)$$

where $h\nu$ is the energy of the photon (h is Plank's constant, ν is frequency), A is the *work function* of the metal, and $\frac{mV^2}{2}$ the kinetic energy of the electron.

The work function represents the minimum energy required for the photoelectric effect to occur:

$$h\nu_{min} = A \qquad (21.14)$$

or:

$$h\frac{c}{\lambda_{max}} = A \qquad (21.15)$$

where λ_{max} is the *cutoff wavelength.*

Example. A sodium surface is illuminated with light of wavelength 300 nm. The work function for sodium is 2.46 eV (1 eV = $1.602 \cdot 10^{-19}$J). Find the kinetic energy of the ejected photoelectrons.

Solution. The energy of the illuminating photon is:

$$h\nu = \frac{hc}{\lambda} = \frac{(6.626 \cdot 10^{-34} J \cdot s)(3 \cdot 10^{8} m \cdot s^{-1})}{300 \cdot 10^{-9} m} = 6.626 \cdot 10^{-19}\text{J} = 4.14 \text{ eV}.$$

21.4.2. Laser

The term *LASER* is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Laser action can be understood by considering the main processes: pumping, spontaneous emission, stimulated emission, and absorption [16,18].

Pumping. This is a process necessary for laser action by which the particles (atoms or molecules) of the active medium are elevated to an excited electronic state by means of electrical discharge, passage of an electric current, or exposure to an intense radiant source.

Spontaneous Emission. Particles in an excited electronic state may lose all or part of their elevated energy by spontaneous emission of radiation. It is important to note that the instant at which emission occurs, the path of the resulting photon varies from excited particle to excited particle since spontaneous emission is a random process. The spontaneous radiation is *incoherent* monochromatic radiation as it is produced by one particles differs in direction and phase from that that produced by another particle (fig. 21.18).

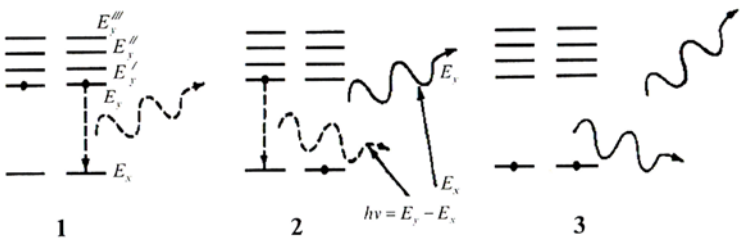


Fig. 21.18. **Diagram representing the spontaneous emission of a photon by an atom**

Stimulated Emission. This process is the basis of laser behavior. Here, the excited laser particles are struck by photons produced by spontaneous emission. Collisions of this type cause the excited particles to relax immediately to the lower energy state and to simultaneously emit a photon of exactly the same energy as the photon that stimulated the process. The emitted photon travels in exactly the same direction and is precisely in phase with the photon that caused the emission (fig. 21.19). Therefore, the stimulated emission is totally *coherent* with the incoming radiation.

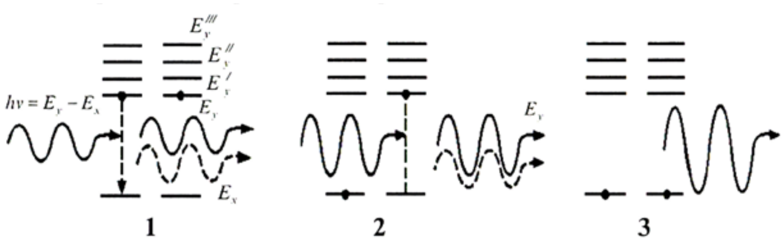


Fig. 21.19. **Diagram representing the stimulated emission of a photon by an incoming photon**

Absorption. This process competes with stimulated emission: an incident photon can cause atomic transition either upward (stimulated absorption) or downward (stimulated emission).

Population Inversion. In order to have light amplification in a laser, it is necessary for the number of photons produced by stimulated emission to exceed the number lost by absorption. This condition will prevail only when the number of particles at the higher energy state exceeds the number in the lower; in other words, a *population inversion* from the normal distribution of the energy states must exist. Fig. 21.20 contrasts the effect of incoming radiation on a non-inversed population with that on an inverted one.

Components of a Laser. A laser consists of the *active medium* (e.g., a solid crystal, a gas, a solution of an organic dye, a semiconductor), which is placed in an *optical resonator* (made from two mirrors) with a *pumping source* (fig. 21.21).

Properties of Laser Radiation. The main properties of laser radiation are monochromaticity, coherence, directionality, and brightness. Some types of lasers have the potential to change the frequency (or wavelength) of the radiation. Other laser devices produce ultra-short pulses of radiation.

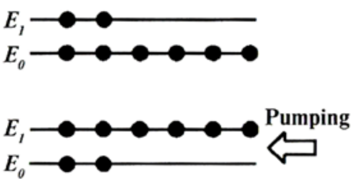


Fig. 21.20. **Inversion of population: *a* — population of the levels before pumping; *b* — population of the levels after application of pumping**

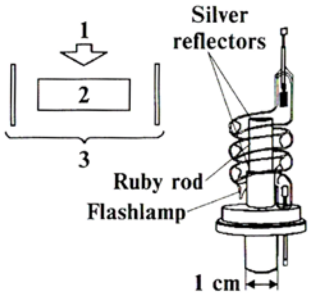


Fig. 21.21. **Components of laser: 1 — source of pumping; 2 — active medium; 3 — optical resonator made from two mirrors**

Monochromaticity indicates a high spectral purity of the radiation. Monochromatic radiation typically has a narrow spectral interval and is characterized by predominately a single frequency (or wavelength). A typical value for the monochromaticity of a He-Ne laser is approximately $\Delta\nu/\nu = 10^{-12}$ -10^{-13}.

Coherence is the coordinated movement of several wave processes in space and time. We can distinguish two types of coherence: temporal coherence – when at a given point in space there is a constant phase difference between the amplitude of the wave at two successive instances in time; and spatial coherence – which is characterised with a constant time-independent phase difference for amplitude at two different points.

For example, the degree of temporal coherence for a He-Ne laser is $\tau = 1/\Delta\nu = 10^{-4}$ s; for a ruby laser it is $\tau = 10^{-8}$ s (here $\Delta\nu$ is a bandwidth of the laser line).

Directionality is determined by the angular distribution of the laser beam. This property is the direct result of the propagation of two light waves in the optical cavity; only waves that propagate normally to the resonator mirrors participate in the formation of the laser beam. The angular distribution, or divergence, is defined as:

$$\theta = 1.22\lambda/D \qquad (21.16)$$

where D is the beam diameter and λ is the wavelength.

The divergence of gas lasers is about $10'$; solid-state lasers – $10'$-$40'$; semiconductor lasers – about 3^0. For example, the beam of a He-Ne laser with the diameter 1 mm has an angular divergence about 10^{-3} radians. Therefore if the surface of the moon was illuminated from earth with a laser spot, the diameter of the spot would be about 400 km.

Brightness of the source of electromagnetic waves is defined as the power of radiation that is emitted from the unit at the source surface through the unit solid angle. The solid angle is proportional to θ^2 (where θ is beam divergence). This is why laser beams with even a small divergence are several orders of magnitude higher in brightness than traditional sources of light. For example, the brightness of a high-pressure mercury lamp (P = 100 W) is five orders of magnitude less than the brightness of a He-Ne laser (P = 1 mW).

Applications of Lasers. Laser sources make it possible to obtain information that is difficult or impossible to obtain with conventional sources. Lasers are extremely useful due to their intensity, amount of monochromatic radiation, and the coherent nature of their output. They can be successfully applied to diagnostics, therapy, and surgery due to their unique properties – spatial and temporal coherence, frequency and intensity range, monochromaticity, and degree of control over the focal area and beam length.

Lasers can be used for remote sensing to monitor various conditions of the atmosphere, such as the amount of aerosols and gaseous air pollutants (e.g., NO_2, SO_2, and O_3) or the determination of gases in smoke plumes from a distance of several hundred meters. Likewise, laser remote sensing methods are useful for meteorological applications such as the measurement of cloud characteristics, precipitation, humidity, wind, and temperature.

Optical and laser spectroscopy methods can be utilized for the analysis of different parameters. For example in cattle-breeding, the diameter, density, orientation and pigmentation of animal hair can be quantitative determination using laser diffractometry, microfluorometry and microphotometry. Likewise, measurement of light scattering can be used to investigate the size distribution of milk particles. Using laser Doppler spectroscopy, dynamic parameters of spermatozoa and a precise estimation of sperm motility can be determined.

Laser-induced fluorescence of chlorophyll *in vivo* can be used as a nondestructive, fast and precise estimation of the health status of plants and the effect of different stresses.

Control Questions and Problems

1. What studies optics?
2. What is optical radiation?
3. Formulate the laws of geometrical optics.
4. What is the absolute refractive index? relative refractive index?
5. Explain the total internal reflection.
6. What is the the lightguide? fiberscopes?
7. Explain the principle of the microscope.
8. What is interference of light?
9. Explain the Young's Double-Slit Experiment.
10. Write and explain the equation of diffraction grating.
11. What is polarization of light?
12. Explain optical activity.
13. What is photoelectric effect?
14. Explain principle of laser operation.

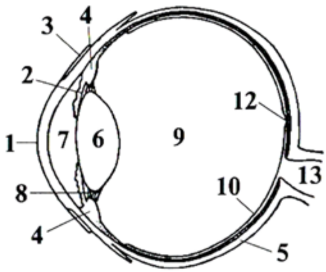
Chapter 22. PHYSIOLOGICAL OPTICS

22.1. THE EYE AS AN OPTICAL SYSTEM

Mammals. The *eye* is an extremely complex part of the body [23]. Fig. 22.1 shows the essential parts of the eye.

The front is covered by a transparent membrane called the *cornea*. Behind the cornea is clear liquid region (the *aqueous humor*), a variable aperture (the *iris* and *pupil*), and a *crystalline lens*. The iris, which is the colored portion of the eye, is a muscular diaphragm that controls the size of the pupil.

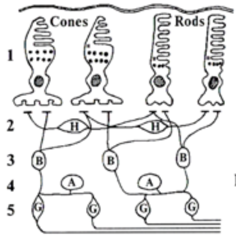
Fig. 22.1. **Lateral cross-section of the human eye: *1* — cornea; *2* — iris; *3* — conjunctiva; *4* — ciliary muscle; *5* — sclera; *6* — lens; *7* — aqueous humor; *8* — suspensory ligaments; *9* — vitreous humor; *10* — retina; *11* — optic disc; *12* — fovea; *13* — optic nerve**



The iris regulates the amount of light entering the eye by dilating the pupil when the light intensity is low and contracting the pupil when high. Light entering the eye is focused by the cornea-lens system onto the back surface of the eye, called the *retina.* The central part of retina is called the *fovea*; it is here that acuity of vision is sharpest. The spot at which the optic nerve fibers exit the eye is the *blind spot* since it does not contain receptor cells. The surface of the retina consists of millions of sensitive structures called *rods* and *cones.* Rods are for dim light and cones are for bright light and color. Both rods and cones make direct synaptic connections with the interneurons called *bipolar cells,* which connect the receptors with the *ganglion cells* (fig. 22.2).

The visual pigment found in rods of most vertebrates is *rhodopsin*, a compound consisting of a protein called *opsin* and a chromophore, *retinal*, which is responsible for the absorption of light. Light striking the receptor cells, rods and cones, produces a charge gradient across the membrane of the photoreceptor. This process is called *hyperpolarization* of the receptor cell membrane and is accompanied by a decrease in transmitter released at the chemically mediated synapse with the bipolar cell. In turn, the bipolar cell influences action potential frequencies in the ganglion cell axons that carry the action potential to the brain through the optic nerves. By this process, a distinct image of an object is observed when the image falls on the retina.

In the horse, the eyeball is asymmetrical and the surface of the retina does not form a true arc of the circle. The retina provides a longer focal length for viewing downward (F_1) than for viewing along the axis of the eye (F_2); it means that nearer objects are automatically in focus without the use of accommodation (fig. 22.3).



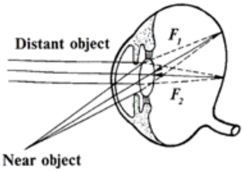


Fig.22.3. **Horse's ramp-shaped retina**

Fig.22.2. **Five major cell types of the vertebrate retina:**
1 — photoreceptor cells (either rods and cones); 2 — horizontal cells; 3 — bipolar cells; 4 — amacrine cells; 5 — ganglion cells

Birds. The eyeballs of birds are very large in relation to the size of their bodies and occupy a considerable proportion of the entire head. The size and resolution of the eye confers an adaptive advantage in that it increases their performance and security. Their visual precision facilitates finding food from several hundred feet above the ground, allowing hawks to recognize potential prey and precisely swoop down upon it. The human eye has almost 200,000 cones per square millimeter. Hawks, in contrast, which must spot small prey from considerable distances, possess about five times the number of cones as humans! Owls are active at night and as a consequence, have little need for acute daytime vision. Birds vary, therefore, not only in the shape of their eyeballs but also in their internal structure (fig. 22.4).

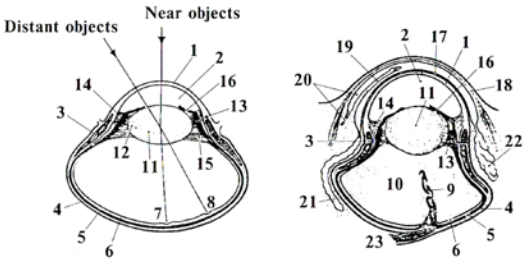


Fig. 22.4. **Sections of the eyes of various birds:**
***a* — buzzard (*Buteo*); *b* — owl (*Strigiformes*). Main elements of the eyes: *1* — cornea; *2* — aqueous humor; *3* — sclerotical ring; *4* — sclera; *5* — choroid; *6* — retina; *7* — fovea centralis; *8* — fovea lateralis; *9* — pecten; *10* — vitreous humor; *11* — lens; *12* — bulging ring of lens; *13* — ciliary muscle; *14* — pectinate zone; *15* — suspensory ligaments; *16* — iris; *17* — conjunctiva; *18* — palpebra interior; *19* — membrane nicticans; *20* — canaliculus lacrimalis; *21* — glandula nicticans; *22* — glandula lacrimalis; *23* — optic nerve**

Most birds have retina with two adjuncts to visual acuity. One is the presence of *fovea*, a small hypersensitive region in the retina where the concentration of rods and cones is the highest and therefore, vision the sharpest. The common form of fovea is a narrow band. This is especially the case with insect eaters where the fovea is elongated, minimizing the need for head movement to keep a moving insect under observation. Fast flying birds, such as swallows and swifts that catch minute insects in the air during flight, need exceptional vision. Nearly all have a double fovea. The other structure is known as the *pecten.* The pecten is a pleated fin of pigmented, highly vascular tissue. It provides a supplementary blood supply to the retina, thereby reducing the number of blood vessels in the retina. Fewer blood vessels reduce the scatter of light coming into the eye, improving vision. For predatory birds, their vision has evolved to be the sharpest in the animal kingdom. Interestingly, birds may be able to perceive ultraviolet and near-ultraviolet light, which humans cannot.

Fish. The optical system in fish is similar to that of land vertebrates; however, there are some important differences. Fish have a more spherical shaped lens and focus by changing the relative distance between the lens and the retina (fig. 22.5). Certain other vertebrates focus by changing the curvature of their lens which is flexible.

Fish also have choroids that contain a special structure, the *tapetum lucidum*, which contains very reflective guanine crystals. The crystals aid their vision in dim light. It should be noted that water is not a good visual medium due to its attenuation and refraction of light.

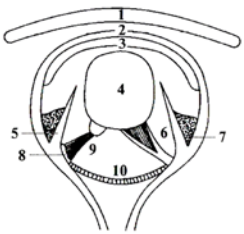


Fig. 22.5. **The eye of a Bony Fish:** ***1*** **— spectacle;** ***2*** **— scleral layer of cornea;** ***3*** **— true cornea;** ***4*** **— lens;** ***5*** **— iris;** ***6*** **— suspensory ligament of lens;** ***7*** **— annular ligament;** ***8*** **— falciform process;** ***9*** **— refractor muscle of lens;** ***10*** **— retina**

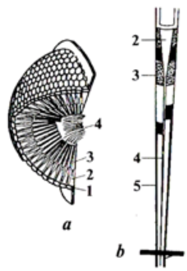


Fig. 22.6. **Compound eye of a Honey Bee.** ***a*** **— structure of a compound eye:** ***1*** **— cornea;** ***2*** **— crystalline cone;** ***3*** **— rods of a retina;** ***4*** **— optic nerve;** ***b*** **— a single ommatidium of a compound eye:** ***1*** **— crystalline lens;** ***2*** **— crystalline con;** ***3*** **— pigment cell;** ***4*** **— retinal cell (rhabdom);** ***5*** **— pigment cell**

Insects. The compound eyes of most insects consist of many separate visual elements called *ommatidia* (fig. 22.6). The receptor cells within the ommatidium each detect a very small fraction of the spectrum of light that passes through narrow channels called *rhabdomeres.* Rhabdomeres give the eye its faceted appearance.

22.2. DEFECTS OF VISION

Because of the complexity of the eye, certain defects often arise that can cause impaired vision.

Short-sight (Myopia). A short-sighted person can see nearby objects distinctly, but not distant ones. With the latter, objects focus in front of the retina due to the eyeball being too long (fig. 22.7a). The furthest distance from the eye that an object can be brought into focus on the retina is called the far point (fig. 22.7b). In order to focus parallel light on the retina, a diverging lens (spectacles) is used which forms a virtual image at the far point of the eye. The corneal-lens system can now focus light on the retina (fig. 22.7c).

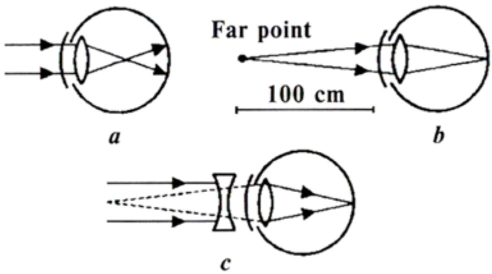


Fig. 22.7. **The short-sighted eye: *a* — the light from a distant object is brought to a focus in front of the retina; *b* — the far point — the farthest distance from the eye that an object can be brought to a focus on the retina; *c* — diverging spectacles can focus light on the retina**

Long-sight (Hypermetropia). A long-sighted person can see distant objects distinctly, but not those that are close. With the latter, objects are focused behind the retina due to the eyeball being too short (fig. 22.8a). An object at the near point, however, can be seen clearly (fig. 22.8b). A converging lens (spectacles) is used when viewing closer objects. It forms a virtual image at the near point (fig. 22.8c).

Astigmatism occurs as a result of a lack of symmetry in the cornea. When a pattern such as that in fig. 22.9 is viewed, one set of lines appears sharper than the others. The defect can be corrected by cylindrical lenses.

Spherical Aberration is found on all lenses bound by spherical surfaces. The marginal portions of the lens bring rays into a shorter focus than the central region (fig. 22.10), making the image of a point a small blurred circle.

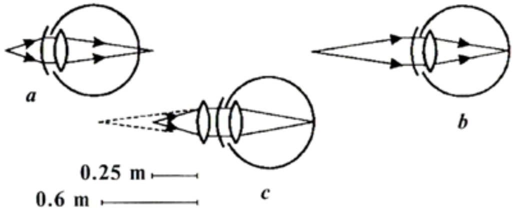


Fig. 22.8. **The long-sighted eye: *a* — the light from a near object is focused behind the eye; *b* — the near point — the distance from the eye that an object can be clearly seen; *c* — converging spectacles can focus light on the retina**

Fig. 22.9. **Astigmatism: to a person viewing this pattern, and suffering from astigmatism, one set of lines will appear sharper than the others**

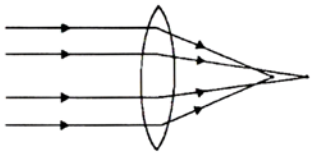


Fig. 22.10. **Spherical aberration: light from the margins is brought to a shorter focus than the central regions**

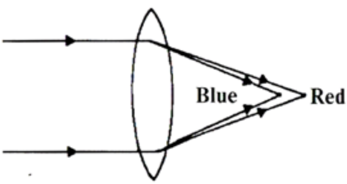


Fig. 22.11. **Chromatic aberration: shorter wavelengths are brought to a closer focal point than long wavelength**

Chromatic Aberration. All lenses made of a single material refract rays of shorter wavelengths more strongly than those of longer wavelengths and in doing so bring blue light to a shorter focus than red (fig. 22.11). The result is that the image of a point of white light is not a white point, but a blurred circle fringed with color.

Cataracts are caused by a disease that commonly occurs with old age, in which the lens becomes partially or totally opaque. One remedy for cataracts is surgical removal and replacement of the lens.

Glaucoma arises from an abnormal increase in fluid pressure inside the eyeball. The pressure increase can lead to a swelling and distortion of the lens causing pronounced myopia.

22.3. BIOLUMINESCENCE

The ability to emit light is found in a diverse cross-section of organisms – bacteria, peridineae, medusae, crustaceans, molluscs, tunicate, fish, and insects. *Bioluminescence* is an enzymatically catalyzed chemiluminescence – luminescence caused by chemical reactions. There is considerable biochemical diversity in the systems responsible for bioluminescence. Single cells (*photocytes*) to complex glands (*photophores*) may be used by animals. The most common biochemical process involves the *luciferin-luciferase system* (as in bioluminescent bacteria). The reaction involves the oxidative breakdown of a high-energy, complex organic molecule (luciferin) by an enzyme (luciferase) which releases photons of light.

The best-known role of bioluminescence is in communication among sexual partners (e.g., fireflies). Each species emits a specific light signal pattern that consists of single flashes or a modulated emission from 5 to over 40 flashes per second (fig. 22.12).

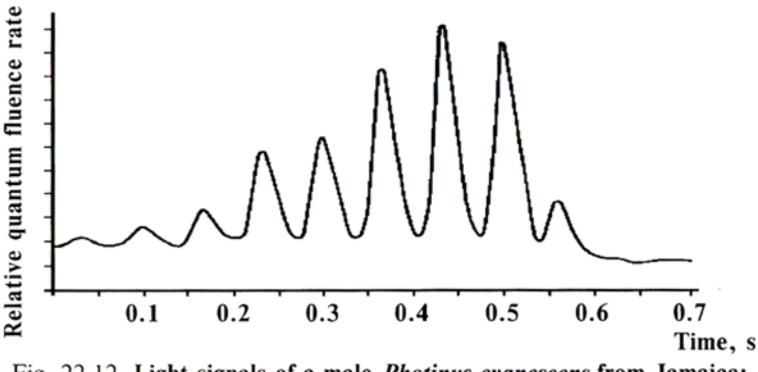


Fig. 22.12. **Light signals of a male *Photinus evanescens* from Jamaica: 11 pulses per second with a frequency of 20 Hz**

Another important behavioral factor is the timing of signaling which differs among species. For example, each species of firefly has its own time niche. Precise timing increases the chances of sexual partners finding each other, while a short time period of activity reduces the risk of being found by predators. Bioluminescence is an adaptive mechanism utilized by a number of species which inhabitant dark environments – such as many deep-sea fish species. At least 700 genera are known to use bioluminescence. Various explanations of the adaptive advantage conferred by bioluminescence are: attraction of other animals, which are captured and consumed; distracting the attention of prey; illumination of dark surroundings; production of a warning signal; defense of territory; and sexual recognition.

Fig. 22.13. **Firefly (*Pyrophorus*) from the Amarican tropics, with two light organs on its thorax behind the eyes**

The ability to produce bioluminescence can be deduced from the names of luminescent organisms (Häder, 1987): *Photobacterium phosphoerum*, *Pyrocystis*, *Pelagia noctiluca*, *Metridia lucens*, *Watasenia scintillans, Symplectotheutis luminosa*, *Pyrophorus* (fig. 22.13).

22.4. CAMOUFLAGE

Animals have evolved a diverse array of camouflages, such as: coloration that resembles their background; countershading, which makes it possible to destroy the natural patterns of brightness; disruptive coloration, which produces boundaries with the highest contrast and generates impressions of false surface relief; and shadow elimination, which modifies the form or orientation of the organism.

Some animals can change their skin or cuticle color in a manner that facilitates maintaining a constant body temperature. Color alterations occur in a layer of *iridophore* cells within the skin, where crystals cause interference reflection and hence iridescence. In the skin of species adapted to dry environments, there are 4-6 layers of iridophores that collectively comprise an area of up to 60 μm in thickness. Their presence increases the reflectance by about 65%. In insects, color change generally involves phase changes of lipids or other materials within the cuticle. Often these alterations produce a change from nearly black to a shiny metallic blue or green, depending on the ambient temperature.

Chapter 23. PHOTOBIOLOGY

Photobiology is the branch of biophysics concerned with the effect of light on living organisms [9].

23.1. ELECTROMAGNETIC SPECTRUM

The entire frequency range of electromagnetic waves is called the *electromagnetic spectrum.* Part of the spectrum is shown in fig. 23.1.

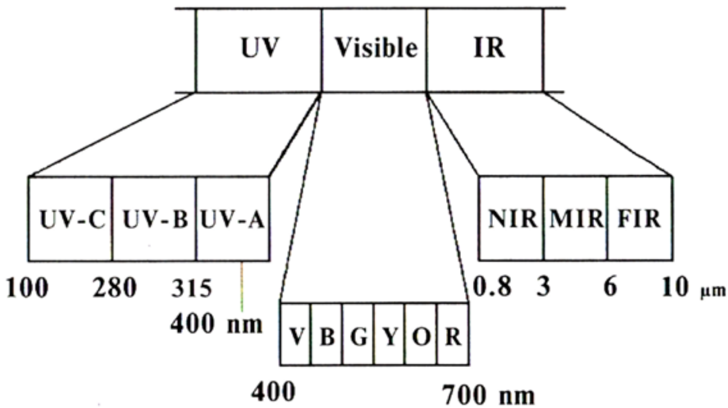


Fig. 23.1. **Scale of electromagnetic waves in ultraviolet, visible and infrared parts of spectrum**

The upper part of the top bar shows two of the most important sources of radiation (solar and thermal) and the lower part names three important bands – *ultraviolet* (290-400 nm), *visible* (400-700 nm) and *near-infrared* (700-2500 nm). The second bar shows two bands of the ultraviolet (UV-B and UV-A) and the wave bands of the visible colors.

23.2. EFFECT OF ULTRAVIOLET RADIATION ON LIVING ORGANISMS

23.2.1. Human and Animal Health

Ultraviolet radiation (UV) is generally divided into three groups, based upon the biological effectiveness of the photons in each. The UV-C range contains the shortest wavelengths (< 280 nm) and the highest energy photons, which are capable of causing ionizing reactions in the upper atmosphere. Due to absorption by ozone in the stratosphere, UV-C radiation does not reach the Earth's surface. UV-B radiation (280-320 nm), however, does reach the biosphere in small and variable quantities. The radiation is of sufficient energy to cause direct damage to chromophoric regions of absorbing macromolecules such as nucleic acids and proteins. UV-B radiation is responsible for damage to crop plants. At longer wavelengths, UV-A radiation (320-400 nm) absorption is usually less strong and is dominated by molecules with conjugated double bonds and cyclic and polycyclic molecules (e.g., isoprenoids, flavonoids, quinines, alkaloids), metal enzymes, and others. The increase in UV-B radiation entering the biosphere is associated with stratospheric ozone depletion and is likely to have a significant detrimental impact on human health.

Eye diseases. UV radiation can damage the cornea and lens of the eye. Chronic exposure to UV-B is one of several factors clearly associated with the risk of cataracts. Artificial sources of UV radiation also cause corneal damage. For example, the injury from a welder's arc is known as flash burn, welder's flash or arc eye. Other sources of UV radiation injury include sun tanning beds, carbon arcs, photographic flood lamps, lightning, electric sparks, and halogen desk lamps. Prolonged exposure to UV radiation can lead to several ocular surface disorders such as pinguecula, pterygium, climatic droplet keratopathy, and even squamous metaplasia and carcinoma.

Immune suppression. Some components of the immune system are present in the skin. UV exposure decreases the immune response to skin cancer, infectious agents, and other antigens.

Erythema. The normal acute effects of visible and ultraviolet radiation arise by photochemical change in the epidermis due to vasodilation of blood vessels seen as abnormal redness of the skin or erythema.

Melanogenesis. When exposed to UV radiation, melanocytes in the germinative layer of the skin produce melanin, which gets absorbed into the surrounding cells. This creates a protective barrier from UV radiation.

Antirickets action. Ultraviolet radiation takes part in the conversion of 7-dehydrocholesterol to previtamin D_3 in the skin, which is thermally isomerized to vitamin D_3. The vitamin affects calcium absorption and the calcification of bones; insufficient solar UV-B exposure causes rickets in children.

Germicidal irradiation. This technology involves the application of ultraviolet radiation for the sterilization of microorganisms (viruses and bacteria). Death is caused by breakage of bonds and damage to the organism's DNA.

23.2.2. Terrestrial Plants

A number of physiological and developmental processes in plants are adversely affected by UV-B radiation. The response to UV-B radiation varies among species and cultivars of the same species. As a consequence, it is necessary to use cultivars with high UV-B tolerance and facilitate the breeding new ones. Indirect affects induced by UV-B radiation include changes in plant form, dry matter allocation within the plant, the timing of developmental phases, and secondary metabolism, each of which in certain situations can be more important than direct damage caused by UV-B.

23.2.3. Aquatic Ecosystems

Exposure to solar UV-B radiation results in a significant reduction in phytoplankton productivity and damage during the early developmental stages of fish, shrimp, crab, amphibians and other aquatic animals. The high levels of exposure to solar UV-B radiation may play a role in phytoplankton distributions; even small increases in UV-B exposure could result in significant reduction in the size of the population of consumer organisms.

23.3. EFFECT OF PHOTOSYNTHTICALLY ACTIVE RADIATION ON LIVING ORGANISMS

Light is one of the most important environmental factors affecting plants. *Photosynthetically active radiation* (PAR) is radiation between 400 and 700 nm that is used by plants for photosynthesis. In this region, leaves have weak reflectance (15% maximum) and very low transmittance. Most of the radiation is absorbed by the foliar pigments, primarily chlorophyll *a* and *b* and to a lesser extent by carotenoids. The absorption maxima of chlorophyll and the carotenoids overlap, such that the presence of the carotenoids is masked in healthy green leaves. However, if the chlorophyll concentration diminishes more rapidly than that of the carotenoids due to stress or senescence, the leaves become yellow. The primary photobiological reactions in plants are photosynthesis, phototropism, photoperiodism, and photomorphogenesis.

23.3.1. Photosynthesis

Photosynthesis is a complex series of light and dark reactions in which light energy is converted into a stable form of chemical energy. It involves the absorption of light by a pigment, energy transfer, energy trapping or stabilization by *reaction centres*, and initiation of chemical reactions from donor to acceptor molecules. Two principal photochemical reactions are operating in series, and the electron acceptor of one of them (reaction 2) is reoxidized by the other reaction (reaction 1), through a chain of electron carriers. These two photochemical reactions are catalyzed by two different reaction centres, each one collecting excitation energy on its *antenna* consisting of ca. 300 chlorophyll molecules, organized in several chlorophyll-protein complexes. The functional unit consisting of a reaction centre and its antenna is defined a *photosystem (PS).* Photosystems I and II are the principal functional units in the light reactions in plants and algae. The transfer of the absorbed light energy from the photosystem reaction centre is accomplished through a series of oxidation-reduction reactions in which lead to the formation of reduced nicotinamide-adenine dinucleotide phosphate (NADPH) and adenosine triphosphate (ATP). A detailed description of photosynthesis is not within the scope of this book. It is important to note that the absorbed energy can be released as heat or radiation such as fluorescence. Chlorophyll *a* fluorescence emission represents only a very small part (~2-5 %) of the absorbed energy. The yield of chlorophyll fluorescence depends on number of complex factors. The relationship between *in vivo* chlorophyll fluorescence and photosynthetic activity in plants can be used to study the effect of various natural (e.g., high-intensity light, ultraviolet irradiation, heat, water shortage, mineral deficiency) and anthropogenic stresses (e.g., agrochemical treatments, air pollutants, ozone, acid rains, heavy metals) on plants.

23.3.2. Phototropism

Phototropism is a light mediated alteration in the pattern of plant growth due to a directional light stimulus. Growth toward a source of light is called *positive phototropism*; growth away from the source is termed *negative phototropism.* The tips of shoots normally exhibit a positive phototropic response while roots are negatively phototropic. There is considerable evidence that the change in growth rate causing the alteration in direction is controlled by a light induced differential in the concentration of the phytohormone *auxin* (indole-3-acetic acid) across the shoot.

23.3.3. Photoperiodism

Photoperiodism is a mechanism by which certain developmental processes respond to a non-directional but periodic light stimulus. Most seasonable events are triggered by the duration or pattern of light/dark cycles. Maxima in various rate measurements continue to recur roughly every 24 hours under constant illumination. Since the period of the cycle was about (but not exactly) 24 hours, they are called *circadian* ("about a day") rhythms. For example, the marine dinoflagellate *Gonyaulax polyedra* emits bright flashes of light at night, while during the day it emits much less light. Photoperiod is used to signal seasonal changes in broad cross-section of plant species at which time the growing apices is transformed from a vegetative to a floral state. Various other developmental processes in plants are controlled or influenced by photoperiod (e.g., the onset and breaking of bud dormancy in woody perennials, leaf abscission, rooting of cuttings, seed germination, bulb and tuber formation, development of frost resistance). Adults of the fruit fly *Drosophila* emerge from the pupa only during the hours near dawn. In humans, mental acuity varies with the time of day, as does body temperature, sleep, wakefulness, and hormone levels.

23.3.4. Photomorphogenesis

Photomorphogenesis is a non-directional growth, development, or differentiation process that is regulated by non-directional and non-periodic light stimuli. These include effects on seed germination, stem elongation, leaf expansion, chloroplast development, and the synthesis of chlorophyll. Typically, plants are responsive to wavelengths of light in the blue, red and far-red regions of the spectrum and are controlled through the action of several different photosensory systems. The photoreceptors for red and far-red wavelengths are known as *phytochrome* (from the Greek words for *plant* and *color*). Most plants have multiple phytochromes encoded by different genes. *Cryptochromes* are blue light receptors, two of which have been identified in plants

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23.3.5. Photomovement

Photomovement is any motile response or its alteration induced by light [17]. The light-dependent behavior of freely motile organisms such as algae and protozoa includes various light-induced movements in space. The motility of organisms can be described using well-known physical parameters: velocity ($\vec{V}$), direction ($\vec{r}$) and trajectory (*l*). These parameters can be further subdivided to more precisely characterize types of movements by organisms. For example, velocity may be linear and angular. Both linear and angular velocities may be constant or vary as a function of time. Certain classes of linear or angular velocity may be divided according to specific velocity limits inherent to a particular organism. The light stimulus, in turn, is characterized by parameters such as intensity (*I*), direction ($\vec{s}$), the spectral composition (λ), polarization (*P*), duration, frequency of light pulses, etc. Similar to movement parameters, light parameters may be divided into intensity which is characterized by absolute magnitude (*I*), gradient in space (dI/dx), and time (dI/dt).

23.3.6. Photosensitization

Photosensitization is increased sensitivity (hypersensitivity) of living organisms to light due to photochemical reactions induced by different chemical substances (photosensitizers). This phenomenon has been a problem of economic importance in livestock in various parts of the world for hundreds of years. For example, Arabs in Tunis painted white horses with henna as protection against hypericism – a disease resulting from infection by several species of Hypericium that is facilitated by excessive sunlight. How light exerted its effect was not known until O. Raab (Munich, 1900) observed that the killing of paramecia by a low concentration of acridines was greatly hastened by exposure to bright light. We now know that the general mechanism of photosensitization is related to the formation of highly reactive species (e.g., free radicals or singlet oxygen) that can lead to damage and in some instances death.

The critical factor in animals that modulates photosensitization is the sensitivity of lightly pigmented skin to sunlight (e.g., in sheep the most susceptible sites are the ears, eyelids, face, lips and coronets; in cows the teats, udder and escutcheon). The first signs of photosensitization are often restlessness, exhibited as shaking of the head and ears, rubbing or scratching of the affected parts, and seeking of relief in the shade. In more severe cases, erythema is soon apparent and oedema develops rapidly. If the photosensitization is particularly severe, the animal may become comatose and die within a few hours.

Diseases such as *hypericism* and *fagopyrism*, in which the photosensitizers are plant pigments, are the oldest known examples of photosensitization in domestic animals - sheep, cattle, goats, pigs and horses. Hypericism results from ingestion of *Hyperiicum* perforatum and fagopyrism is induced by buckwheat, Fagopyrum esculentum. Photosensitization of animals eating *Tribulus terrestris* and *Sisymbrium altissimum* has also been recognized for some time.

23.4. EFFECT OF NEAR-INFRARED RADIATION ON LIVING ORGANISMS

Visible and near-infrared radiation (400 to 2500 nm) is important in medical applications; the longer the wavelengths in the visible part of the spectrum, the deeper the penetration of the radiation into the skin (fig. 23.2).

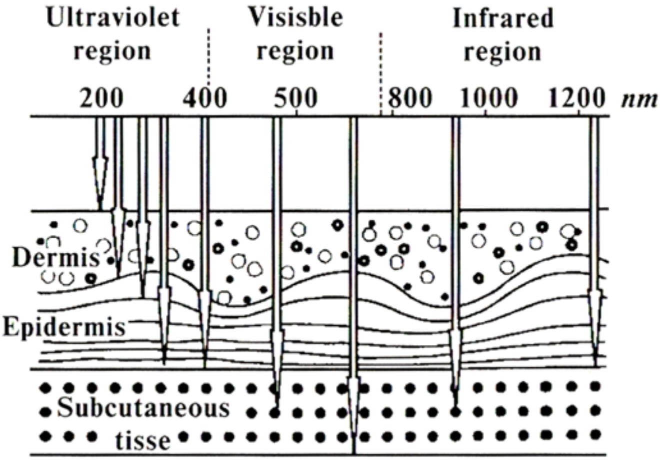

Fig. 23.2. **Penetration of light into light-colored human skin**

There are many chromophores in skin and blood: (e.g., proteins, amino acids, DNA, RNA, hemoglobin, bilirubin, melanin). Two primary spectroscopic phenomena participate in the interaction of infrared radiation with human tissue – light scattering in the region of 1.52-1.85 μm and molecular absorption (e.g., by water, fat, and protein) in the 2.0-2.5 μm region.

Tissue to be treated must be thick enough to provide absorption of NIR radiation by glucose but thin enough to allow sufficient NIR energy to pass through. Water, hemoglobin (the pigment that renders blood red), and melanin (the pigment that gives skin its color) present in human surface tissue, exert a significant affect on the absorption of optical radiation. The spectral range within the “*therapeutic window*” (fig. 23.3) is between 600 and 1300 nm due to absorption by water and pigments.

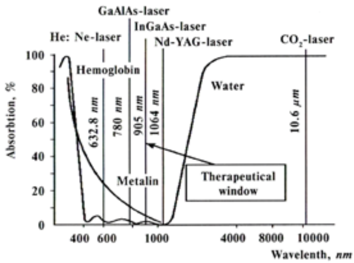

Fig. 23.3. **The “*therapeutic window*” — the spectral region between 600 and 1300 nm due to absorption by water and pigments**

A portion of this segment of the spectrum is characterized by a high reflection and transmission of radiation by green leaves. Foliar pigments, as well as cellulose found in the cell wall region, are transparent in the near-infrared part (700-1300 nm) of spectrum. For this reason, the quantity of radiation absorbed by the leaf is very small ($\leq$ 10%) with the remaining radiation either reflected or transmitted. In the 1300-2500 nm region, the optical properties of leaves are strongly affected by their water content.

23.4. ULTRAVIOLET THERAPY

Ultraviolet therapy is a treatment used for several skin diseases and to relieve certain forms of itching. Ultraviolet (UV) radiation may be administered directly or in conjugation with photoactive drugs. The most common application of UV radiation is in the treatment of *psoralen ultraviolet A (PUVA).* It is also used for the treatment of psoriasis and several other skin disorders. The treatment involves a combination of the photoactive drug psoralen with long-wave ultraviolet (UV-A) radiation. The mechanism of action is thought to be *via* the binding of psoralen (particularly 8-methoxypsoralen) to DNA in the presence of UV-A, resulting in a transient inhibition of DNA synthesis and cell division. Typical intensities used are ~100 W/m^2. Ultraviolet radiation is also widely used for severe cases of psoriasis that have not responded to other medications or in cases affecting large portions of the body. Other skin disorders such as vitiligo and atonic dermatitis can also be treated with UV radiation.

Ultraviolet Irradiation of Blood. Based on experimental investigations and clinical observations, it is possible to form a hypothesis about the positive effect of a small quantity of ultraviolet irradiated blood that is reinfused into an organism. The procedure is thought to confer a bacteriological effect, deactivate toxins, and increase the organism's resistance to infection. The method utilizes ultraviolet (UV-C) illumination of blood flowing from a vein through a quartz cuvette and then back into the animal. It has been used for the treatment of calves with bronchopneumonia, dyspepsia, rinotraheitis; cows with several hoof diseases; and horses with inflammatory ailments.

The primary photoreaction induced in the blood by UV-irradiation is the photoionization of free aromatic amino acids that results in the loss of activity of critical regulatory and immunologic proteins. The photodestruction of these proteins leads to the formation of both high- and low-molecular weight compounds with new structures and spectral properties. The new products have an antigenic nature and induce the formation of antibodies that confer polyimmunization to the organism.

23.5. PHOTOTHERAPY

Phototherapy is treatment for certain diseases of the skin using the application of light.

Red Light Phototherapy. Recently, numerous scientific papers and biomedical conference proceedings have focused on the therapeutic effect of red light, such as that from He:Ne lasers. The most promising clinical uses for He:Ne lasers have been for the treatment of inflammatory, degenerative and dystrophic diseases, such as trophic and indolent wounds, burns, injuries to tendons and bones, arthritis, and gastric ulcers. The effects of red radiation on the inflammatory processes, neuro-endocrine and nervous systems, metabolism, bioelectric activity of organism, hematologic parameters, and bone regeneration are excellent examples of the use of laser phototherapy in animals. However, it is necessary to note that specific parameters of laser radiation (coherence, monochromaticity, polarization) do not appear to be important. As a consequence, red light phototherapy can be considered as usual photobiological phenomenon.

Laser Photochemotherapy. This photomedical technique is based on the ability of the photosensitizer to accumulate and be selectively retained in malignant tissue to a greater degree than in normal tissue. As a consequence, laser irradiation can be used to preferentially destroy tumors. Laser photochemotherapy involves the injection of a photosensitizer and after an appropriate incubation period, illumination of the malignant tissue with laser radiation (48-72 hours). The photosensitizer absorbs sufficient light energy to shift the molecule from the singlet to a triplet state. The excited triplet state photosensitizer then produces either free radicals or singlet oxygen that oxidatively disrupt the cells in malignant tissue causing necrosis and death. Photosensitizers commonly employed in the laser photochemotherapy of the malignant tumors are hematoporphyrin derivatives (HpD). Secondary effects of HpD include edema and sunburn of the skin if the patient is exposed to excessive sunlight. The development of new photosensitizers without adverse side-effects represents an important research topic.

Laser Acupuncture. The ability of laser radiation to penetrate tissues allows it to be used for *acupuncture* – a medical procedure that involves the stimulation of biologically active points on the surface of the body. An example of the positioning of the acupoints on an animal is presented in Fig. 23.4.

The advantages lasers confer to acupuncture are that it is non-invasive, rapid, aseptic, and painless. Typical acupuncture parameters for laser radiation are a 1-2 mm diameter laser beam and a radiation intensity of about 1-5 mW/cm^2. Usually an optical system (laser and fiber) is used in conjunction with an electrical system that monitors skin resistance to indicate the appropriate positions for the acupoints. Changes in resistance are indicated by a sound or light signal. The duration of the laser radiation treatment is for a relatively precise time interval. Treatment effects on animals include increased phagocytosis, tissue granulation, stimulated collagen synthesis, vascularisation, acetylcholine release, production of *T*- and β–lymphocytes, increased serotonin synthesis, inhibition of prostaglandin effects in the tissue, stimulation and release of β–endorphins, and increased synthesis of ketosteroids and hydroxycorticosteroids.

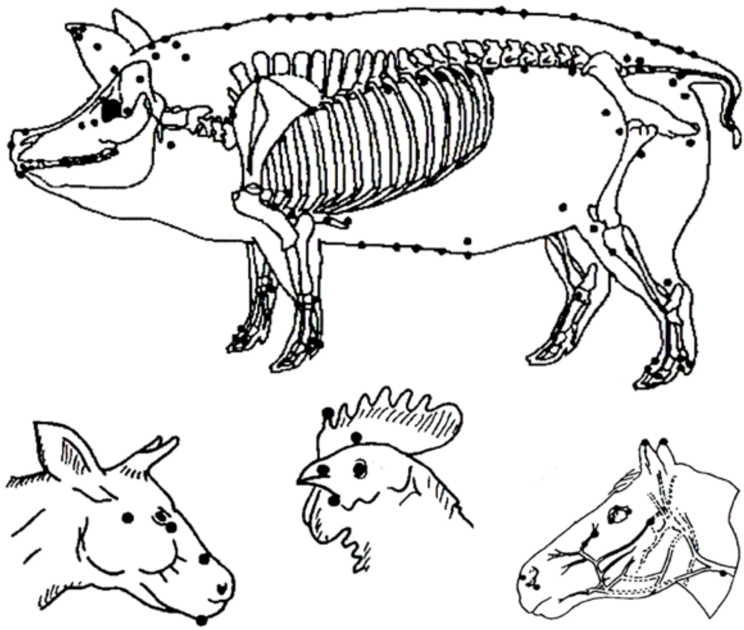

Fig. 23.4. **The typical picture of acupoints of the animal**

The adoption of laser acupuncture remains a subject of debate with the advantages of the procedure being touted by supporters and the deficiencies by opponents.

23.5. LASER SURGERY

Advantages of the CO_2-lasers. The application of lasers to veterinary surgery is based on the absorption of laser radiation by the tissue. Absorption causes heating and destruction of the cells *via* thermal, hydrodynamical or photochemical mechanisms. The CO_2-laser (10.6 μm) is currently used in all fields of surgery due to its unique properties. The advantages of CO_2-lasers as a surgical instrument are: 1) a reduction in operating time by eliminating the need to ligate most of the bleeding points; 2) a reduction of the amount of necrotic tissue and haematoma formation and, therefore, a lower infection rate; 3) the tendency of the laser beam to sterilize the wound as it cuts; 4) faster wound healing due to a combination of the first three factors; and 5) the blood vessels are sealed during cancer surgery which helps prevent the spread of the malignant cells.

Mechanisms of laser action. The thermal therapeutic effect of the CO_2-laser is caused by a denaturation and inactivation of proteins. Convection (movement due to mass transport) and conduction (movement without mass transport) are the primary means of heat transfer within the tissue. The intensity of CO_2-lasers can be varied from levels that cause little heating to the destruction of the tissue through evaporation.

The hydrodynamical mechanism of CO_2-laser irradiation is related to the strong absorption by water in the living tissue (generally ~80 % water), intense heating, and the destruction of the tissue by hydrodynamic shock waves through the explosive evaporation of the tissue. The temperature at the focal point of the laser beam is about $100^{o}C$.

The photochemical action of the laser irradiation means that the radiation energy is expended through the degradation of chemical bonds that cause the destruction of the tissue through volatilization. The mechanism can also be realized using pulsed ultraviolet laser radiation.

CO_2-laser surgery. CO_2-laser beams are strongly absorbed by living tissue, i.e., ~95% of the radiant energy is absorbed by a thin layer of cells ~200 μm thick with the energy being transformed into heat. The cutting efficiency of a CO_2-laser is proportional to the wavelength. A flexible optical system can focus laser radiation onto a ~1 mm diameter

spot. Examples of highly effective uses of CO_2-laser surgery in veterinary medicine include the castration of farm animals and the amputation of poultry wings. Disadvantages of the CO_2-laser as a surgical scalpel are the lack of mechanical contact with the tissue, thermal damage to the edges of the skin at incisions, and restricted manoeuvrability.

Laser microsurgery. The high intensities (10^8-10^9 W/cm^2) and the wide variety of wavelengths available make laser surgery an attractive tool for microsurgery. Using a laser in conjunction with a microscope allows focusing the laser beam on a very small spot (i.e., ~1 μm in diameter), such as that needed for precise surgical procedures. As a consequence, it is possible to destroy specific subcellular organelles, single cells or groups of cells. For example, laser microsurgery can be used for operating on the aero-digestive tract (mouth, throat and nose), the ears, and brain haemorrhages.

VOCABULARY

English	Ukrainian	English	Ukrainian
Active medium	Активне середовище	Interference	Інтерференція
Acupuncture	Акупунктура	Interference microscope	Інтерференцій ний мікроскоп
Analyzer	Аналізатор	Iris	Райдужна оболонка
Antirickets action	Антірахі-тична дія	Keratopathy	Кератопатія
Aqueous humor	Внутрішньо-очна рідина	Linearly polarized light	Лінійно поля-ризоване світло
Atonic dermatitis	Атонічний дерматит	Magnification	Збільшення
Bandwidth	Ширина смуги	Malignant tumor	Злоякісна пухлина
Bipolar cells	Біполярні клітини	Melanogenesis	Меланогенез
Blind spot	Оптичний диск	Monochroma-ticity	Монохрома-тичність
Brightness	Яскравість	Optical activity	Оптична активність
Broncho-pneumonia	Бронхо-пневмонія	Optical resonator	Оптичний резонатор
Fovea	Центральна ямка	Squamous metaplasia	Луската метаплазія
Ganglion cells	Гангліозні клітини	Stimulated emission	Стимульоване випромінювання
Gastric ulcer	Виразка шлунка	Temporal coherence	Часова когерентність
Germicidal irradiation	Бактеріологічне опромінювання	Total internal reflection	Повне внутріш-невідбивання

Carcinoma	Карцинома		Photoelectric effect	Фотоелектричний ефект
Coherency	Когерентність		Photosensitization	Фотосенсибілізація
Compound microscope	Складовий мікроскоп		Photosynthetically active radiation	Фотосинтетично активне випромінювання
Cones	Колбочки		Phytochrome	Фітохром
Constructive interference	Підсилення світла через інтерференцію		Polarimeter	Поляриметр
Cornea	Рогівка		Polarization	Поляризація
Critical angle	Критичний кут		Polarizer	Поляризатор
Cryptochrome	Криптохром		Population inversion	Інверсія населеності
Crystalline lens	Кришталик		Psoriasis	Псоріаз
Cutoff wavelength	Червона границя фотоефекту		Pterygium	Птеригіум, кінцівка у хребетних
Destructive interference	Послаблення світла через інтерференцію		Pumping	Накачка
Dichroic crystal	Дихроїчний кристал		Pupil	Зіниця
Diffraction	Дифракція		Ray approximation	Променеве наближення
Diffraction grating	Дифракційна решітка		Refractive index	Коефіцієнт заломлення
Directionality	Направленість		Retina	Сітківка
Divergence	Розбіжність		Rhodopsin	Родопсін
Double-slit	Подвійна щілина		Rods	Палички
Dyspepsia	Диспепсія		Rubbing	Тертя
Elliptically polarized light	Еліптично поляризоване світло		Scratching	Шкрябання
Erythema	Еритема		Spatial coherence	Просторова когерентність
Fiber optics	Світловід		Spontaneous emission	Спонтанне випромінювання

Control Works
Modulus 8
Optics, Physiological Optics, Photobiology

Problem. Explain what a fish will see if it looks upward toward the water surface at an angle of 40^0, 49^0, and 60^0 (index of refraction of water is 1.33).

Problem. The distance between the ocular and the objective lenses in a certain compound microscope is 23 cm. The focal length of the ocular lens is 2.5 cm, and the focal length of the objective is 0.4 cm. What is the overall magnification of the microscope?
Answer: 575.

Problem. Electron micrographs of the wing cover of the beetle *Serica sericea* show that it has parallel lines across it and these are 0.8 μm apart. Parallel white light falls perpendicularly on the surface of the cover and it is viewed at an angle of 45^{0} to the surface, what will be the color of the wing cover?
Answer: 450 nm? 550 nm? 650 nm?

Example. Monochromatic light from a helium-neon laser (wavelength 632.8 nm) is incident normally on a diffraction grating containing N = 6000 lines/cm. Find the angle at which one would observe the second-order maximum.
Answer: 49.41^{0}.

Problem. A sodium surface is illuminated with light of wavelength 300 nm. The work function for sodium is 2.46 eV (1 eV = $1.602\cdot10^{-19}$J). Find the cutoff wavelength for sodium.
Answer: 1.68 eV.

Animals Extremes!

Raptors, or birds of prey, including the eagles, hawks, and falcons can see up to 8 times more clearly than the sharpest human eye. A golden eagle (*Aquila chrysaetos*) can see a hare from a mile (1.6 km) away.

Control Questions and Problems

1. Explain the photobiological response of plant systems.
2. What is effect of ultraviolet radiation on living organisms?
3. Represent and identify the key elements of the visual analyzer of mammals; fish; birds; insects.
4. What is the difference between visual analyzers of horse and other animals?
5. What are the main defects of vision?

APPENDIX

Some Fundamental Constants

Symbol	Quantity	Value
c	Speed of light in vacuum	$2{,}99792458 \cdot 10^{8}\ m \cdot s^{-1}$
g	Acceleration due to gravity	$9{,}8\ m \cdot s^{-2}$
G	Gravitational constant	$6{,}67259(85)\ ) \cdot 10^{-11}\ N \cdot m^{2} \cdot kg^{-2}$
R	Universal gas constant	$8{,}3145510(70)\ J \cdot mol^{-1} \cdot K^{-1}$
k	Boltzmann´s constant	$1{,}380658(12) \cdot 10^{-23}\ J \cdot K^{-1}$
e	Elementary charge	$1{,}60217733(49)\ ) \cdot 10^{-19}\ C$
ε_0	Permittivity of free space	$8{,}854187817 \cdot 10^{-12}\ C^{2} \cdot N^{-1} \cdot m^{-2}$
μ_0	Permeability of free space	$12{,}5663761410^{-7}\ N \cdot A^{-2}$
h	Plank´s constant	$6{,}626075(40) \cdot 10^{-34}\ J \cdot s$

SI units

Space and Time

Quantity	SI-unit Symbol (name)	Additional legal units	Conversion
Length	**m** (metre)	in (inch)	1 in = 2.54 cm
		ft (foot)	1 ft = 0.3048 m
		mi (mile)	1 mi = 1.609 km
		μm (micrometer)	1 μm = 10^{-6} m
		nm (nanometer)	1 nm = 10^{-9} m
		Å (angstrom)	1 Å = 10^{-10} m
Area	$\mathbf{m^2}$	a (are)	1 a = 100 m^2
		ha (hectare)	1 ha = 10000 m^2
Volume	$\mathbf{m^3}$	l (liter)	1 l = 1 dm^3
		gal (gallon)	1 gal = 3.785 liters
Plane angle	**rad** (radian)	^{0} (degree)	$1^0 = (\pi/180)$
		$^/$ (minute)	$1^/ = 1^0/60$
		$^{//}$ (second)	$1^{//} = 1^/ /60$
Time	s (second)	min (minute)	1 min = 60 s
		h (hour)	1 h = 3600 s
		d (day)	1 d = 86 400 s
Velocity	**m/s**	km/h	1 km/h = 0.2778 m/s
Frequency	**Hz** (Hertz)	1/s	1 Hz = 1/s

Temperature and Heat

Quantity	SI-unit Symbol (name)	Additional legal units	Conversion
Temperature	**K** (kelvin)	**^{0}C** (degree Celsius) **^{0}F** (degree Fahrenheit)	$^0C = K - 273.15$; $K = {}^0C + 273.15$; $^0C = ({}^0F - 32)5/9$; $^0F = 9/5{}^0C + 32$; $K = ({}^0F - 2)5/9 + 273.15$; $^0F = (K - 73.15)9/5 + 32$.
Heat capacity, enthropy	**J/K**		
Specific heat capacity	**J/(kg·K)**		
Specific energy	**J/kg**		
Thermal conductivity	**W/(m^2·K)**		

Mechanics

Quantity	SI-unit Symbol (name)	Additional legal units	Conversion
Mass	**kg** (kilo-gram)	g (gram) t (ton) u (atomic mass unit)	$1\ g = 10^{-3}\ kg$ $1\ t = 10^3\ kg$ $1\ u = 1{,}6605402 \cdot 10^{-27}\ kg$
Moment of inertia	**kg·m^2**		
Force	**N** (newton)		$1\ N = 1\ kg \cdot m/s^2$ $1\ N = 10^5$ dyne $1\ lb = 4.448\ N$ $1\ dyne = 10^{-5}\ N$
Pressure	**N/m^2**	bar (bar) mm Hg (millimeter mercury) atm (atmos-phere) psi (pound-force per square inch)	$1\ atm = 1{,}01325 \cdot 10^5\ Pa =$ $=1013{,}25\ mbar = 760\ mm\ Hg$; $1\ mbar = 100\ Pa = 1\ hPa =$ $= 0{,}75006\ mm\ Hg$; $1\ mm\ Hg = 1\ torr = 1{,}3332\ mbar =$ $= 133{,}32\ Pa$; $1 Pa = 9{,}87 \cdot 10^{-6}\ atm = 7{,}5 \cdot 10^{-3}\ mm\ Hg$. $1\ psi = 1\ lbf/in^2 = 6894.74\ Pa$.
Energy, work	**J** (joule)	kW·hour (kilowatt-thour) eV (electron volt)	$1\ J = 10^7$ ergs $1\ kWh = 3.60 \cdot 10^6\ J$ $1\ cal = 4.186\ J$ $1\ eV = 1.6 \cdot 10^{-19}\ J$
Power	**W** (watt)		$1\ hp = 0.746\ kW$
Density	**kg/m^3**		

		La (lambert)	1 La = (1/π)10^4 cd/m² fla
		fla (footlambert)	1 fla = 3,426 cd/m²
Luminance	**cd/m²**		

Electricity and Magnetism

Quantity	SI-unit Symbol (name)	Additional legal units	Conversion
El. current	**A** (ampere)		
El. charge	**C** (coulomb)		1 C = 1 A·s
El. voltage	**V** (volt)		1 V = 1 W/A
El. resistance	**Ω** (ohm)		1 Ω = 1 V/A
El. conductivity	**S** (siemens)		1 S = 1/Ω
Capacitance	**F** (farad)		1 F = 1 C/V
Magnetic flux	**Wb** (weber)		1 Wb = 1 V·s = 1 W·s/A
Magnetic flux density	**T** (tesla)	G (gauss)	1 T = 10^4 G 1 T = 1 Wb/m²
Inductance	**H** (henry)		1 H = 1 Wb/A
Magnetic Field Strength	**A/m**	Oe (oersted)	1 Oe = 79,5775 A/m

Optics

Quantity	SI-unit Symbol (name)	Additional legal units	Conversion
Luminous intensity	**cd** (candela)	IK (international candle) NK (new candle) sb (stilb) asb (apostilb) La (lambert) fla (footlambert)	1 NK = 1,019 cd 1 NK = 1 cd 1 sb = 10^4 cd/m² 1 asb = (1/π) cd/m² 1 La = (1/π)10^4 cd/m² fla 1 fla = 3,426 cd/m²
Luminance	**cd/m²**		
Luminous flux	**lm** (lumen)		
Illuminance	**lx** (lux)	fc (footcandle)	1 fc = 10.76 lx

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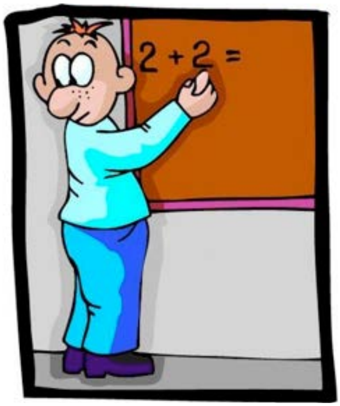
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(англійською мовою)

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The text-book “*Physics with Fundamentals of Biophysics*” published in English is intended for the students who attend the English-speaking lectures in educational institutions of Ukraine; it can be useful for the foreign students and post-graduate students, translators and everybody who is interested in English terminology in the field of physics and biophysics.

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