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SCHAUM'S OUTLINE OF

THEORY AND PROBLEMS

OF

PHYSICS FOR PRE-MED, BIOLOGY, AND ALLIED HEALTH STUDENTS

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Dr GEORGE HADEMENOS, originally from San Angelo, Texas, earned his B.S. in Physics from Angelo State University, and both his M.S. and Ph.D. in Physics from the University of Texas at Dallas. While in graduate school, he developed a strong interest in biophysics and relevant applications of physics to the medical/biological sciences. Following receipt of his doctorate, he completed a postdoctoral fellowship in nuclear medicine at the University of Massachusetts Medical Center in Worcester, Massachusetts, followed by another postdoctoral fellowship in radiological sciences at UCLA Medical Center in Los Angeles. He is currently a Visiting Assistant Professor of Physics at the University of Dallas, where, among other courses, he is teaching General Physics geared toward biology and pre-med students. He is also in the process of developing an active research program for students interested in problems of a biophysical nature.

Schaum's Outline of Theory and Problems of
PHYSICS FOR PRE-MED, BIOLOGY, AND ALLIED HEALTH STUDENTS

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This book is dedicated to:
Kelly, Alexandra, and Dr. George Kattawar,
my three greatest motivators

Preface

Schaum's Outline of Physics for Pre-Med, Biology, and Allied Health Students is a text which complements the standard physics textbook in a fundamental physics course. The book is structured in a format similar to that of most physics textbooks used for such courses, except that the presented topics—including kinematics, statics, dynamics, thermal physics, electricity and magnetism, optics, and radioactivity—are supplemented with illustrative examples from the biological and medical sciences. The primary goal of this book is to provide the physics student with unique examples and applications to the life sciences as well as to simplify and enlighten the biology student in these sometimes difficult physical concepts and related principles.

Although a tremendous amount of painstaking effort was devoted to this project, there will, most probably, be errors in this publication that were overlooked throughout the editorial process and I assume full responsibility for these errors. I would greatly appreciate if these errors could be brought to my attention either by direct correspondence with me or with the editorial staff at McGraw-Hill.

GEORGE J. HADEMENOS

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Chapter 1

Mathematics Fundamentals

Physical principles and interactions encountered in physics are expressed typically in terms of qualitative reasoning and observations and rely on mathematics to translate these laws into quantitative or substantive results. Mathematics allows the student to intuitively and intellectually grasp physical concepts and to understand the effects of various factors on the particular physics problem. This chapter provides a brief description of the mathematics integral in the description and exemplification of physics as it relates to biological and medical applications.

1.1 FUNCTIONAL ANALYSIS

A function is defined as a mathematical one-to-one relationship between elements of a given set $X = \{x\}$, referred to as the *domain*, and another set $Y = \{y\}$, referred to as the *range*. A function represents a mathematical relationship between a dependent variable y and an independent variable x, which can represent any number within a specified range or interval. A function, denoted typically as $y = f(x)$, allows one to mathematically characterize a physical system in terms of variables that directly influence the system's behavior and stability.

ILLUSTRATIVE EXAMPLE 1.1. Poiseuille's Law and Blood Flow

Blood flow through a blood vessel in the human circulation can be approximated by the elementary case of fluid flow through a rigid tube. Suppose, for example, we want to determine the influence of tube radius R on the rate of fluid flow Q through the tube. Although there exist variables such as fluid density and viscosity which are embedded in the system function as constants, theory and experimental data reveal a relationship between the variable R and the system variable Q according to

$$Q = \frac{\pi \Delta P R^4}{8L\eta}$$

where Q is the volumetric flow rate, ΔP is the pressure gradient, L is tube length, and η is the fluid viscosity. The relationship is known as *Poiseuille's law*. The rate of fluid flow Q is a dependent variable since its value depends upon the value of R, which is an independent variable and can be expressed as a function

$$Q = f(R)$$

When displayed graphically on a rectangular coordinate system with the two axes representing the two variables Q and R, the function defined by $Q = f(R) = \text{constant} \times R^4$ is described by a continuous curve in two dimensions, as shown in Figure 1-1. This example illustrates the strong "power" dependence of flow on the tube radius.

Solved Problem 1.1. Identify the following mathematical statements as either functions or relations:

(*a*) $A = \pi R^2$

(*b*) $x + 5y = 15$

(*c*) $F = \{\text{human fingerprints}\}$, $P = \{\text{humans}\}$

(*d*) $x^2 + y^2 = 16$

(*e*) $f(x) = 7(-\infty < x < \infty)$

(*f*) $b(r) = 3r^2$

(*g*) $f(x) = \sqrt{x}$

(*h*) $x = \frac{1}{2}at^2$

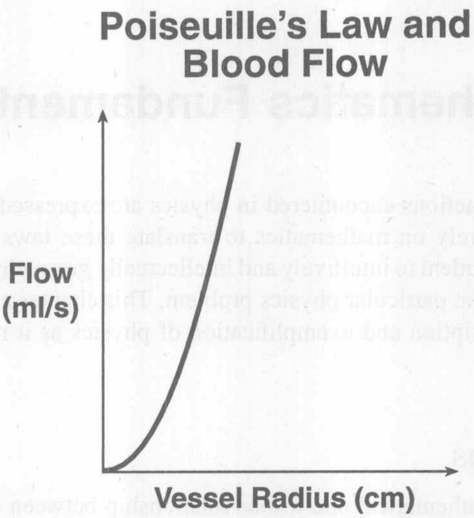

Fig. 1-1

Solution

(*a*) Function, $A = A(r)$ where π is a fixed constant.

(*b*) Function, $y = 3 - x/5$.

(*c*) Function, there is a one-to-one relationship between humans and their fingerprints.

(*d*) Relation, $y^2 = 25 - x^2$ is not a function since for a single value of x, y can be either positive or negative.

(*e*) Relation, not a function since different x values are one-to-one related to the same element, 7, of the range.

(*f*) Function, since one value of r corresponds to a single value of $b(r)$.

(*g*) Relation, depending on the domain. This is a function only for positive real x, and the square root means the positive square root.

(*h*) Function, for reasons similar to (*f*) in that one value of t corresponds to a unique value of x.

1.1.1 Slope and y Intercept

Consider the function describing a line:

$$y = mx + b$$

Two important features of a function presented by the above equation are the y intercept b and the slope of the function or curve m. These features are illustrated in Figure 1-2. Ideal functions originate at the origin (0, 0) of the coordinate system. Most functions, however, either originate from or pass through a point along the y axis other than the origin (0, 0). The value along the y axis, known as the y intercept, is given by the parameter b. The *slope* defines the rate of change of the curve in the y axis with respect to the corresponding change in the x direction and is given mathematically as

$$\text{Slope} = m = \frac{\Delta y}{\Delta x}$$

The above relation is applicable only to linear functions.

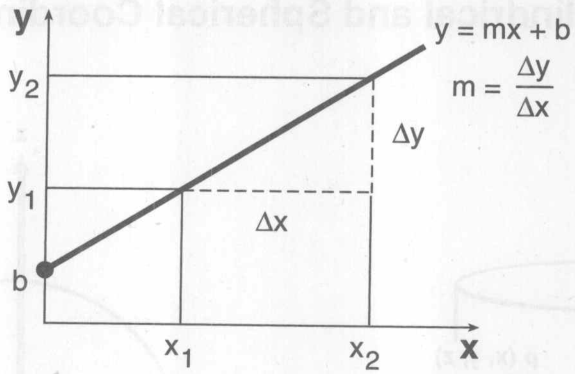

Fig. 1-2

ILLUSTRATIVE EXAMPLE 1.2. Poiseuille's Law and Blood Flow Revisited

As mentioned previously, Poiseuille's law for fluid flow is a power function described by

$$y = cx^n \Rightarrow Q = \frac{\pi \Delta P}{8\eta L} R^4$$

where c is a constant and n is any real number. The power function presented by Poiseuille's law serves as a unique variation of the above discussion. As can be seen from Figure 1-1, the curve describing fluid flow is not linear, and thus the above expression for slope cannot be applied directly. It is possible, however, to transform the power function to a linear one by taking the logarithm of both sides:

$$\log y = n \log x + \log c$$
$$y = mx + b$$

By comparison, the slope for a power function is given by

$$n = \frac{\Delta(\log y)}{\Delta(\log x)}$$

Application of Poiseuille's law for fluid flow yields

$$\log Q = 4 \log R + \log \frac{\pi \Delta P}{8\eta L}$$

Thus, the slope of Poiseuille's law is 4, implying a 4-fold increase in flow with respect to a change in tube radius. To put this in perspective, when applied to the human circulation, doubling the radius of a blood vessel increases blood flow by a factor of 16 whereas halving the radius reduces blood flow by a factor of $\frac{1}{16}$.

1.1.2 Coordinate Systems

Almost as important as the function itself are the geometric boundaries within which the function is defined. This can be understood by the following illustrative example. Consider a point in space $p(x, y, z)$ bounded by a rectangular coordinate system given by $\mathbf{x} = x$, $\mathbf{y} = y$, and $\mathbf{z} = z$. However, if that same point is now defined within a different geometry such as a cylinder or sphere, it is a cumbersome, although possible, task to define the point in rectangular coordinates. It thus becomes a matter of convenience to denote any point within a sphere or cylinder in terms of the variables that more precisely define its geometry in space through coordinate transformations between different geometries.

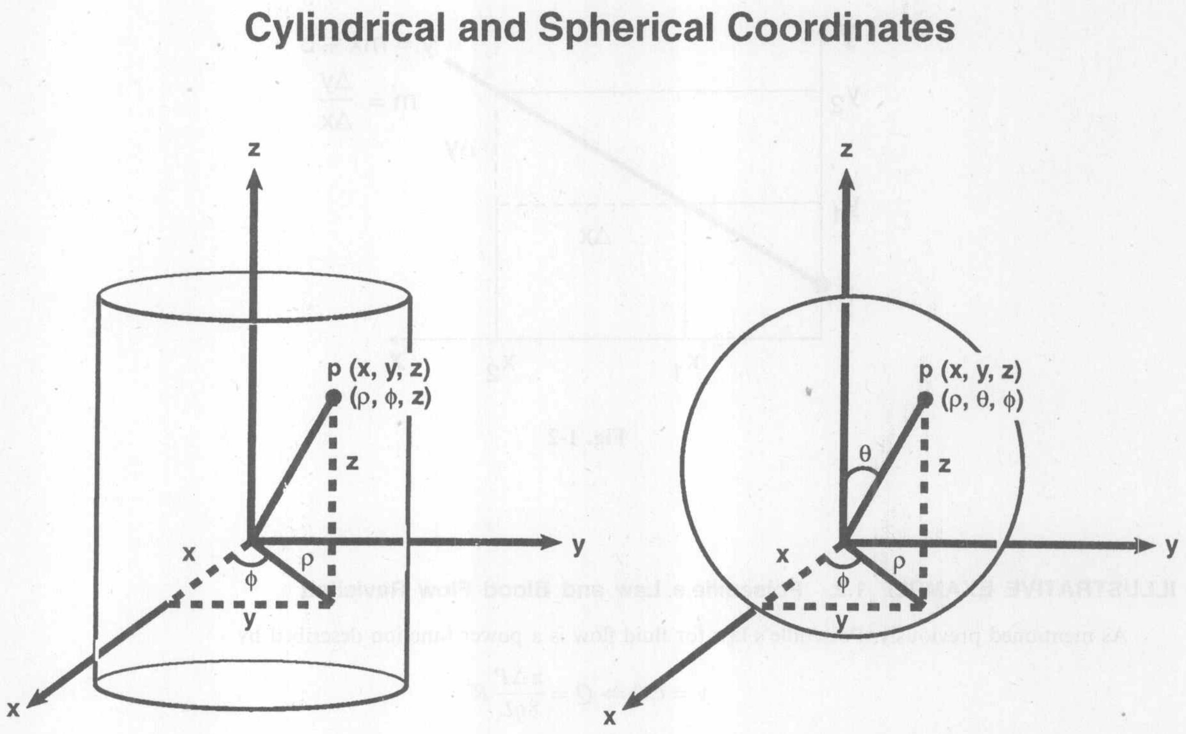

Fig. 1-3

Given the geometry of the cylinder and sphere depicted in Figure 1-3, the three-dimensional coordinates of a point in space which were defined originally as x, y, and z, in the rectangular coordinate system, are now redefined for the cylinder in cylindrical coordinates (ρ, ϕ, z) as

$$x = \rho \cos \phi$$
$$y = \rho \sin \phi$$
$$z = z$$

where $\rho \geq 0$, $0 \leq \phi < 2\pi$, $-\infty < z < \infty$; and for the sphere in spherical coordinates (ρ, θ, ϕ) as

$$x = \rho \sin \theta \cos \phi$$
$$y = \rho \sin \theta \sin \phi$$
$$z = \rho \cos \theta$$

where $\rho \geq 0$, $0 \leq \theta \leq \pi$, $0 \leq \phi < 2\pi$.

1.2 TYPES OF FUNCTIONS

Although numerous mathematical statements meet the criteria of a function, there are five general classifications of functions, described below.

1.2.1 Polynomial Functions

Polynomial functions are the most general of the five types of functions and of the form

$$y = f(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \cdots + a_n x^n$$

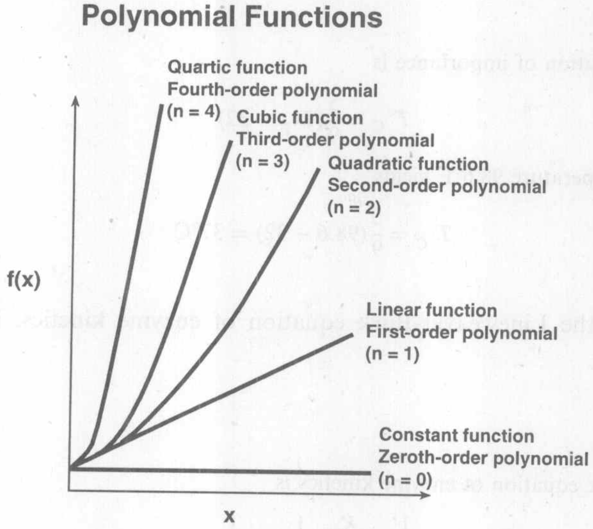

Fig. 1-4

where a_0, a_1, a_3, a_n are coefficients (constants) and n is an integer which describes the degree or order of the polynomial. The most general polynomial function is the first-order polynomial function given by

$$y = f(x) = a_0 + a_1 x \qquad a_1 \neq 0$$

which is a linear function (compare with Section 1.1.1). In the linear function, a_1 corresponds to the slope m. Figure 1-4 displays graphically the more common polynomial functions.

ILLUSTRATIVE EXAMPLE 1.3. Applications of Polynomial Functions

Polynomial functions represent a wide range of mathematical functions and can be found in numerous physical applications as they pertain to biological sciences, including:

(1) *Ohm's law of electricity.* The voltage V applied across a wire is related to the current flowing through the wire I, multiplied by the resistance R of the wire, or

$$V = IR$$

(2) *Temperature conversion.* The Celsius temperature scale (°C) and the Fahrenheit scale (°F) are linearly related by

$$T_{°C} = \frac{5}{9}(T_{°F} - 32)$$

(3) *Lineweaver-Burk plot of enzyme kinetics.* The influence of an enzyme on the speed of a chemical reaction can be observed through the relationship between the substrate concentration $[S]$ of the enzyme and the velocity of the reaction v by

$$\frac{1}{v} = \frac{K_m}{V_{max}}\frac{1}{[S]} + \frac{1}{V_{max}}$$

where V_{max} is the maximum velocity of the chemical reaction and K_m is a constant.

Solved Problem 1.2. Normal human body temperature is approximately 98.6°F. Calculate this temperature in the Celsius scale.

Solution

The mathematical relation of importance is

$$T_{°C} = \frac{5}{9}(T_{°F} - 32)$$

Substituting the body temperature 98.6°F yields

$$T_{°C} = \frac{5}{9}(98.6 - 32) = 37°C$$

Solved Problem 1.3. For the Lineweaver-Burk equation of enzyme kinetics, identify the slope and y intercept.

Solution

The Lineweaver-Burk equation of enzyme kinetics is

$$\frac{1}{v} = \frac{K_m}{V_{max}} \frac{1}{[S]} + \frac{1}{V_{max}}$$

Since it is a linear function, the above equation follows the general form of

$$y = mx + b$$

By an elementary comparison, the slope m is

$$\text{Slope} = \frac{K_m}{V_{max}}$$

and the y intercept b is

$$y \text{ intercept} = \frac{1}{V_{max}}$$

Solved Problem 1.4. The absorption of ethyl alcohol into the bloodstream in the human body is one of the few known kinetic processes that is zeroth-order. Assume that the process may be represented as

$$\text{Ethyl alcohol} \rightarrow \text{bloodstream}$$

Derive the integrated rate law for the biochemical process, and show that this is a linear function.

Solution

Assuming that ethyl alcohol can be represented by $[B]$, the reaction for the process can be mathematically characterized by

$$-\frac{dB}{dt} = k$$
$$-dB = k\,dt$$

Integrating both sides of the equation yields

$$\int_{B_0}^{B} dB = -k \int_0^t dt$$
$$B - B_0 = -kt$$
$$B = B_0 - kt$$

Integration is covered in greater detail in Section 1.4. By comparison, it can be seen that this rate law is a linear function, where $-k$ is the slope and B_0 is the y intercept.

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