Schaum's
题解精萃

# 现代物理

# MODERN PHYSICS

影印版

Ronald Gautreau William Savin

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## 内容简介

Schaum's 丛书是由麦格劳－希尔(McGraw－Hill)国际出版公司出版的著名的系列教学辅助用书,涵盖了高等教育各类各门学科和课程。每本书都汇集了该门学科课程中的精髓内容,并对基本理论和基本概念作了简明精炼的归纳和总结,还提供了由美国众多经验丰富的资深教师和学者推荐、讲解透彻的精选例题和形式多样的各类习题。

本书根据 Schaum's 系列丛书中《现代物理》第二版原文影印出版。可供在校本科生、研究生以及社会各类科技人员参考使用。

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# 出版说明

随着我国高等教育改革形势的发展，高等教育的人才培养模式及教学形式和教学方法正在发生重大变化，一个拓宽专业口径，实行弹性学习制度，允许分阶段完成学业，横向沟通、纵向衔接的教育体制正在逐步构建形成。为了促进高等教育的改革，活跃高等学校的教学工作，扩大学生的眼界，我们组织出版了这套"Schaum's题解精萃"。

"Schaum's丛书"是由麦格劳－希尔(McGraw－Hill)国际出版公司出版的著名的系列教学辅助用书，目前已出版了约700多个品种，涵盖了高等教育各类各门学科和课程。本套丛书的特点是：每本书都汇集了该门学科课程中的精髓内容，并对基本理论和基本概念作了简明精炼的归纳和总结；同时，还提供了由美国众多经验丰富的资深教师和学者推荐、讲解透彻的精选例题和形式多样的各类习题约2000—4000个。本套书在美国高等学校中颇具权威性，多年来持续畅销，目前在世界范围销售超过3000万册。

我们从"Schaum's丛书"中经精心挑选，组合成"Schaum's题解精萃"，以原版影印的形式介绍到国内，意在使学生在使用本书的同时，了解、熟悉相关学科和课程的英语专业词汇，提高英语专业阅读的速度和水平，锻炼使用英语学习、解题的能力。因为，当今时代，熟练掌握英语已成为21世纪人才必备的基本素质和能力。"Schaum's题解精萃"第一批影印书内容涉及理工科各基础学科，今后我们将陆续影印出版该系列其他学科的图书。

本套书可供高等学校的理工科学生在学习各学科课程的同时，进行辅助学习和各类习题训练，有助于提高学生巩固学科基本知识和解题的综合能力，同时也可适用于各科教师在教学和辅导中参考。本套书同时还可作为在校本科生、研究生以及社会各类科技人员参加各类国际资格证书考试、国外留学考试(如GRE)等的适用参考书。

我们相信，本套书的出版，将会对我国高等院校的学生、教师们提供丰富多彩、形式多样、卓有成效的参考资料。

出版者

2000年4月

# PREFACE

The area of modern physics embraces topics that have evolved since roughly the turn of the twentieth century. These developments can be mind-boggling, as with the effects on time predicted by Einstein's Special Theory of Relativity, or quite practical, like the many devices based upon semiconductors, whose explanation lies in the band theory of solids.

The scope of the present book may be gauged from the Table of Contents. Each chapter consists of a succinct presentation of the principles and "meat" of a particular subject, followed by a large number of completely solved problems that naturally develop the subject and illustrate the principles. It is the authors' conviction that these solved problems are a valuable learning tool. The solved problems have been made short and to the point, and have been ordered in terms of difficulty. They are followed by unsolved supplementary problems, with answers, which allow the reader to check his or her grasp of the material.

It has been assumed that the reader has had the standard introductory courses in general physics, and the book is geared primarily at the sophomore or junior level, although we have also included problems of a more advanced nature. While it will certainly serve as a supplement to any standard modern physics text, this book is sufficiently comprehensive and self-contained to be used by itself to learn the principles of modern physics.

We extend special thanks to David Beckwith for meticulous editing of the first edition and for input that improved the final version of the book. Any mistakes are ours, of course, and we would appreciate having these pointed out to us. Finally, we are indebted to our families for their enormous patience with us throughout the long preparation of this work.

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PART I

# The Special Theory of Relativity

CHAPTER 1

# Galilean Transformations

## 1.1 EVENTS AND COORDINATES

We begin by considering the concept of a physical event. The event might be the striking of a tree by a lightning bolt or the collision of two particles, and happens at a point in space and at an instant in time. The particular event is specified by an observer by assigning to it four coordinates: the three position coordinates $x$, $y$, $z$ that measure the distance from the origin of a coordinate system where the observer is located, and the time coordinate $t$ that the observer records with his clock.

Consider now two observers, $O$ and $O'$, where $O'$ travels with a constant velocity $v$ with respect to $O$ along their common $x-x'$ axis (Fig. 1-1). Both observers are equipped with metersticks and clocks so that they can measure coordinates of events. Further, suppose that both observers adjust their clocks so that when they pass each other at $x = x' = 0$, the clocks read $t = t' = 0$. Any given event $P$ will have eight numbers associated with it, the four coordinates $(x, y, z, t)$ assigned by $O$ and the four coordinates $(x', y', z', t')$ assigned (to the same event) by $O'$.

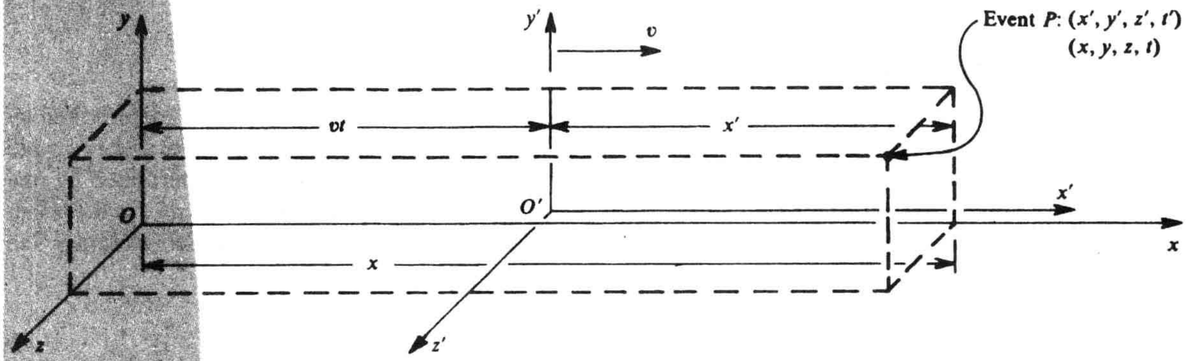


Fig. 1-1

## 1.2 GALILEAN COORDINATE TRANSFORMATIONS

The relationship between the measurements $(x, y, z, t)$ of $O$ and the measurements $(x', y', z', t')$ of $O'$ for a particular event is obtained by examining Fig. 1-1:

$$x' = x - vt \qquad y' = y \qquad z' = z$$

In addition, in classical physics it is implicitly assumed that

$$t' = t$$

These four equations are called the *Galilean coordinate transformations*.

## 1.3 GALILEAN VELOCITY TRANSFORMATIONS

In addition to the coordinates of an event, the velocity of a particle is of interest. Observers $O$ and $O'$ will describe the particle's velocity by assigning three components to it, with $(u_x, u_y, u_z)$ being the velocity components as measured by $O$, and $(u'_x, u'_y, u'_z)$ being the velocity components as measured by $O'$.

The relationship between $(u_x, u_y, u_z)$ and $(u'_x, u'_y, u'_z)$ is obtained from the time differentiation of the Galilean coordinate transformations. Thus, from $x' = x - vt$,

$$u'_x = \frac{dx'}{dt'} = \frac{d}{dt}(x - vt)\frac{dt}{dt'} = \left(\frac{dx}{dt} - v\right)(1) = u_x - v$$

Altogether, the *Galilean velocity transformations* are

$$u'_x = u_x - v \qquad u'_y = u_y \qquad u'_z = u_z$$

## 1.4 GALILEAN ACCELERATION TRANSFORMATIONS

The acceleration of a particle is the time derivative of its velocity, i.e., $a_x = du_x/dt$, etc. To find the *Galilean acceleration transformations* we differentiate the velocity transformations and use the facts that $t' = t$ and $v =$ constant to obtain

$$a'_x = a_x \qquad a_y = a_y \qquad a'_z = a_z$$

Thus the measured acceleration components are the same for all observers moving with uniform relative velocity.

## 1.5 INVARIANCE OF AN EQUATION

By *invariance* of an equation it is meant that the equation will have the same form when determined by two observers. In classical theory it is assumed that space and time measurements of two observers are related by the Galilean transformations. Thus, when a particular form of an equation is determined by one observer, the Galilean transformations can be applied to this form to determine the form for the other observer. If both forms are the same, the equation is invariant under the Galilean transformations. See Problems 1.11 and 1.12.

# Solved Problems

**1.1.** A passenger in a train moving at 30 m/s passes a man standing on a station platform at $t = t' = 0$. Twenty seconds after the train passes him, the man on the platform determines that a bird flying along the tracks in the same direction as the train is 800 m away. What are the coordinates of the bird as determined by the passenger?

*Ans.* The coordinates assigned to the bird by the man on the station platform are

$$(x, y, z, t) = (800\,\text{m}, 0, 0, 20\,\text{s})$$

The passenger measures the distance $x'$ to the bird as

$$x' = x - vt = 800\,\text{m} - (30\,\text{m/s})(20\,\text{s}) = 200\,\text{m}$$

Therefore the bird's coordinates as determined by the passenger are

$$(x', y', z', t') = (200\,\text{m}, 0, 0, 20\,\text{s})$$

**1.2.** Refer to Problem 1.1. Five seconds after making the first coordinate measurement, the man on the platform determines that the bird is 850 m away. From these data find the velocity of the bird (assumed constant) as determined by the man on the platform and by the passenger on the train.

*Ans.* The coordinates assigned to the bird at the second position by the man on the platform are

$$(x_2, y_2, z_2, t_2) = (850\,\text{m}, 0, 0, 25\,\text{s})$$

Hence, the velocity $u_x$ of the bird as measured by the man on the platform is

$$u_x = \frac{x_2 - x_1}{t_2 - t_1} = \frac{850\,\text{m} - 800\,\text{m}}{25\,\text{s} - 20\,\text{s}} = +10\,\text{m/s}$$

The positive sign indicates the bird is flying in the positive $x$-direction. The passenger finds that at the second position the distance $x_2'$ to the bird is

$$x_2' = x_2 - vt_2 = 850\,\text{m} - (30\,\text{m/s})(25\,\text{s}) = 100\,\text{m}$$

Thus, $(x_2', y_2', z_2', t_2') = (100\,\text{m}, 0, 0, 25\,\text{s})$, and the velocity $u_x'$ of the bird as measured by the passenger on the train is

$$u_x' = \frac{x_2' - x_1'}{t_2' - t_1'} = \frac{100\,\text{m} - 200\,\text{m}}{25\,\text{s} - 20\,\text{s}} = -20\,\text{m/s}$$

so that, as measured by the passenger, the bird is moving in the negative $x'$-direction. Note that this result is consistent with that obtained from the Galilean velocity transformation:

$$u_x' = u_x - v = 10\,\text{m/s} - 30\,\text{m/s} = -20\,\text{m/s}$$

**1.3.** A sample of radioactive material, at rest in the laboratory, ejects two electrons in opposite directions. One of the electrons has a speed of $0.6c$ and the other has a speed of $0.7c$, as measured by a laboratory observer. According to classical velocity transformations, what will be the speed of one electron as measured from the other?

*Ans.* Let observer $O$ be at rest with respect to the laboratory and let observer $O'$ be at rest with respect to the particle moving with speed $0.6c$ (taken in the positive direction). Then, from the Galilean velocity transformation,

$$u_x' = u_x - v = -0.7c - 0.6c = -1.3c$$

This problem demonstrates that velocities greater than the speed of light are possible with the Galilean transformations, a result that is inconsistent with Special Relativity.

**1.4.** A train moving with a velocity of 60 mi/hr passes through a railroad station at 12:00. Twenty seconds later a bolt of lightning strikes the railroad tracks one mile from the station in the same direction that the train is moving. Find the coordinates of the lightning flash as measured by an observer at the station and by the engineer of the train.

*Ans.* Both observers measure the time coordinate as

$$t = t' = (20\,\text{s})\left(\frac{1\,\text{hr}}{3600\,\text{s}}\right) = \frac{1}{180}\,\text{hr}$$

The observer at the station measures the spatial coordinate to be $x = 1$ mi. The spatial coordinate as determined by the engineer of the train is

$$x' = x - vt = 1\text{ mi} - (60\text{ mi/hr})\left(\frac{1}{180}\text{ hr}\right) = \frac{2}{3}\text{ mi}$$

**1.5.** A hunter on the ground fires a bullet in the northeast direction which strikes a deer 0.25 miles from the hunter. The bullet travels with a speed of 1800 mi/hr. At the instant when the bullet is fired, an airplane is directly over the hunter at an altitude h of one mile and is traveling due east with a velocity of 600 mi/hr. When the bullet strikes the deer, what are the coordinates as determined by an observer in the airplane?

*Ans.* Using the Galilean transformations,

$$t' = t = \frac{0.25\text{ mi}}{1800/\text{hr}} = 1.39 \times 10^{-4}\text{ hr}$$
$$x' = x - vt = (0.25\text{ mi})\cos 45^\circ - (600\text{ mi/hr})(1.39 \times 10^{-4}\text{ hr}) = 0.094\text{ mi}$$
$$y' = y = (0.25\text{ mi})\sin 45^\circ = 0.177\text{ mi}$$
$$z' = z - h = 0 - 1\text{ mi} = -1\text{ mi}$$

**1.6.** An observer, at rest with respect to the ground, observes the following collision. A particle of mass $m_1 = 3$ kg moving with velocity $u_1 = 4$ m/s along the $x$-axis approaches a second particle of mass $m_2 = 1$ kg moving with velocity $u_2 = -3$ m/s along the $x$-axis. After a head-on collision the ground observer finds that $m_2$ has velocity $u_2^* = 3$ m/s along the $x$-axis. Find the velocity $u_1^*$ of $m_1$ after the collision.

*Ans.*

$$\text{Initial momentum} = \text{final momentum}$$
$$m_1u_1 + m_2u_2 = m_1u_1^* + m_2u_2^*$$
$$(3\text{ kg})(4\text{ m/s}) + (1\text{ kg})(-3\text{ m/s}) = (3\text{ kg})u_1^* + (1\text{ kg})(3\text{ m/s})$$
$$9\text{ kg}\cdot\text{m/s} = (3\text{ kg})u_1^* + 3\text{ kg}\cdot\text{m/s}$$

Solving, $u_1^* = 2$ m/s.

**1.7.** A second observer, $O'$, who is walking with a velocity of 2 m/s relative to the ground along the $x$-axis observes the collision described in Problem 1.6. What are the system momenta before and after the collision as determined by him?

*Ans.* Using the Galilean velocity transformations,

$$u_1' = u_1 - v = 4\text{ m/s} - 2\text{ m/s} = 2\text{ m/s}$$
$$u_2' = u_2 - v = -3\text{ m/s} - 2\text{ m/s} = -5\text{ m/s}$$
$$u_1^{*\prime} = u_1^* - v = 2\text{ m/s} - 2\text{ m/s} = 0$$
$$u_2^{*\prime} = u_2^* - v = 3\text{ m/s} - 2\text{ m/s} = 1\text{ m/s}$$
$$(\text{initial momentum})' = m_1u_1' + m_2u_2' = (3\text{ kg})(2\text{ m/s}) + (1\text{ kg})(-5\text{ m/s}) = 1\text{ kg}\cdot\text{m/s}$$
$$(\text{final momentum})' = m_1u_1^{*\prime} + m_2m_2^{*\prime} = (3\text{ kg})(0) + (1\text{ kg})(1\text{ m/s}) = 1\text{ kg}\cdot\text{m/s}$$

Thus, as a result of the Galilean transformations, $O'$ also determines that momentum is conserved (but at a different value from that found by $O$).

**1.8.** An open car traveling at 100 ft/s has a boy in it who throws a ball upward with a velocity of 20 ft/s. Write the equation of motion (giving position as a function of time) for the ball as seen by (*a*) the boy, (*b*) an observer stationary on the road.

*Ans.* (*a*) For the boy in the car the ball travels straight up and down, so

$$y' = v_0 t' + \tfrac{1}{2}at'^2 = (20\,\text{ft/s})t' + \tfrac{1}{2}(-32\,\text{ft/s}^2)t'^2 = 20t' - 16t'^2$$
$$x' = z' = 0$$

(*b*) For the stationary observer, one obtains from the Galilean transformations

$$t = t'$$
$$x = x' + vt = 0 + 100t \qquad y = y' = 20t - 16t^2 \qquad z = z' = 0$$

**1.9.** Consider a mass attached to a spring and moving on a horizontal, frictionless surface. Show, from the classical transformation laws, that the equations of motion of the mass are the same as determined by an observer at rest with respect to the surface and by a second observer moving with constant velocity along the direction of the spring.

*Ans.* The equation of motion of the mass, as determined by an observer at rest with respect to the surface, is $F = ma$, or

$$-k(x - x_0) = m\frac{d^2x}{dt^2} \tag{1}$$

To determine the equation of motion as found by the second observer we use the Galilean transformations to obtain

$$x = x' + vt' \qquad x_0 = x_0' + vt' \qquad \frac{d^2x}{dt^2} = \frac{d^2x'}{dt'^2}$$

Substituting these values in (*1*) gives

$$-k(x' - x_0') = m\frac{d^2x'}{dt'^2} \tag{2}$$

Because (*1*) and (*2*) have the same form, the equation of motion is invariant under the Galilean transformations.

**1.10.** Show that the electromagnetic wave equation,

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 0$$

is not invariant under the Galilean transformations.

*Ans.* The equation will be invariant if it retains the same form when expressed in terms of the new variables $x', y', z', t'$. We first find from the Galilean transformations that

$$\frac{\partial x'}{\partial x} = 1 \qquad \frac{\partial x'}{\partial t} = -v \qquad \frac{\partial t'}{\partial t} = \frac{\partial y'}{\partial y} = \frac{\partial z'}{\partial z} = 1$$
$$\frac{\partial x'}{\partial y} = \frac{\partial x'}{\partial z} = \frac{\partial y'}{\partial x} = \frac{\partial t'}{\partial x} = \cdots = 0$$

From the chain rule and using the above results we have

$$\frac{\partial\phi}{\partial x} = \frac{\partial\phi}{\partial x'}\frac{\partial x'}{\partial x} + \frac{\partial\phi}{\partial y'}\frac{\partial y'}{\partial x} + \frac{\partial\phi}{\partial z'}\frac{\partial z'}{\partial x} + \frac{\partial\phi}{\partial t'}\frac{\partial t'}{\partial x} = \frac{\partial\phi}{\partial x'} \qquad \text{and} \qquad \frac{\partial^2\phi}{\partial x^2} = \frac{\partial^2\phi}{\partial x'^2}$$

Similarly,

$$\frac{\partial^2\phi}{\partial y^2} = \frac{\partial^2\phi}{\partial y'^2} \qquad \frac{\partial^2\phi}{\partial z^2} = \frac{\partial^2\phi}{\partial z'^2}$$