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时代教育·国外高校优秀教材精选

21 世纪普通高等教育基础课规划教材

双语教学专用教材

西尔斯当代大学物理

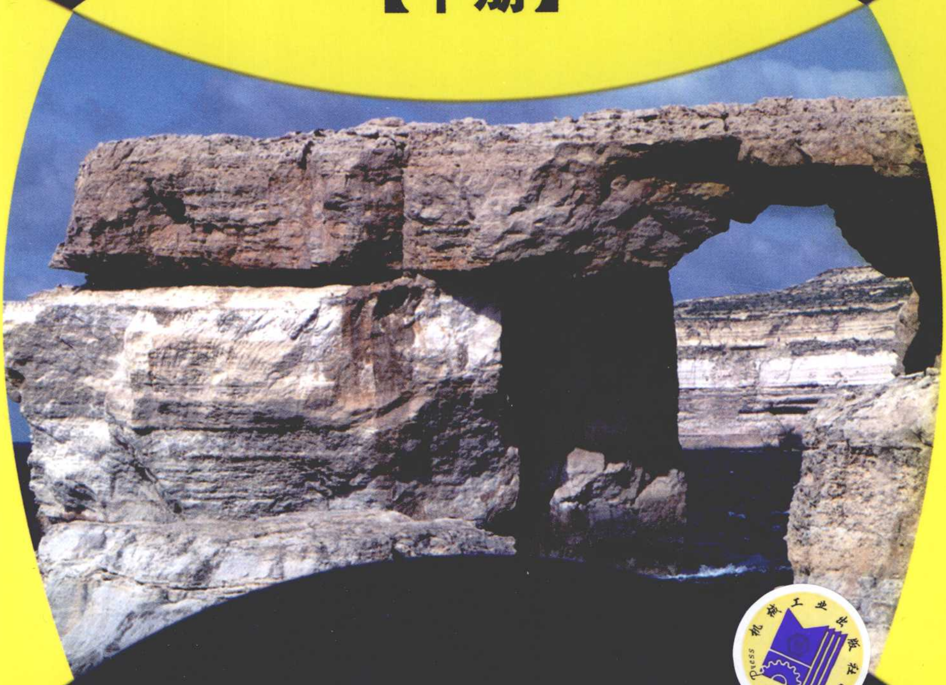
英文改编版（原书第11版）

Sears and Zemansky's
UNIVERSITY PHYSICS with Modern physics (11th Ed.)

（美）HUGH D. YOUNG & ROGER A. FREEDMAN 著

邓铁如 徐元英 孟大敏 等改编

【下册】



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改编自美国的《Sears and Zemansky's UNIVERSITY PHYSICS with Modern Physics》(11th Ed.)
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本英文改编教材的原书——《西尔斯物理学》是几代编著者长达半个多世纪物理教育探索与创新的产物，其许多可圈可点的特色在美国乃至世界其他国家，影响了一代又一代的大学师生，是当今世界发行量最大的主流教材之一。

本教材分上下两册。本书是下册，主要内容有电磁学、波动光学、近代物理学等。

本书既充分体现了原书的特色，又在适合我国国情方面有了新的特点，主要表现在：对原书取舍得当，篇幅适当，教材内容覆盖了教育部最新教学基本要求建议的75个A类知识点和部分B类知识点；教材95%以上是原书的文字，体现了原书教学理念的精华，整个教材体系具有更好的系统性和完整性；内容生动、丰富，图文并茂，举例鲜活，趣味性强，联系实际密切，强调概念理解，注重能力培养；每章的问题引入法、正文探索式的叙述法以及每节的思考题检测法等多种教学方法并用，将有效调动学生学习的积极性，提高学生学习的效能；所有例题都采用四步解题法：审题（Identify）、破题（Set up）、求解（Excute）和讨论（Evaluate），这种规范、科学的解题方式十分有利于学生形成思维清晰、表述准确、方法明确的解题习惯，并能逐步获得较强的解决实际问题的能力；英语行文规范、流畅，原汁原味，代表了当前科技英语文献的风格，是我国学生学习英文科技写作的极好范本。

本教材为高等学校理工科各专业学生的大学物理双语教学专用教材。由于与国内教材有很强的相关对应性，故对于希望了解物理知识英文表述的非双语教学的师生及其他科技工作者，本书也是一本十分有益的参考书。

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Preface

1. 关于原书、原作者

本书改编自培生教育出版公司（Pearson Education, Inc.）于2004年推出的西尔斯大学物理第11版（Sears and Zemansky's UNIVERSITY PHYSICS with modern physics, 11th edition，以下简称西书）。

西书是美国几代物理教育专家长达半个多世纪探索与改革的产物。初版由美国物理教育界领军人物F. W. Sears和M. W. Zemansky于1949年推出。西书作者提倡站在学生的角度探究式地展开讨论，强调讲透概念、原理与培养学生解题能力并重，在版面设计上作出有针对性的安排。这些探索成果对促进学生自主学习产生了较大反响。西书第11版的主要作者H. D. Young自1973年始成为Sears和Zemansky的合作者，参加第5版编写。前两位作者相继去世后，Young从第8版起单独署名。他继承与完善了西书的导学式理念，使西书不仅在美国，而且在其他国家影响了一代又一代的大学师生，至今仍是发行量最大的主流教材之一。另两位作者R. A. Freedman与A. L. Ford分别自第10版、第11版参加编写工作。

西书曾于20世纪50年代以《西尔斯物理学》之名被翻译成中文在中国出版。当时该书受到我国大学物理教师的关注并作为教学参考书。至今我国物理教材中的一些讲法和习题都渊源于该书。机械工业出版社2003年影印出版了西书第10版。由于特色鲜明、角度新颖、讲解详尽、讨论深入，加之行文流畅，代表了当前英语科技文献流行风格，该影印版被一些高校选作物理双语课本，获得好评。

西书第11版的刚体力学、振动与波、热学、电磁学、波动光学、狭义相对论与量子物理基础等6部分（覆盖大学物理课程教学内容9成以上）涵盖的知识点、调用的数学知识以及达到的难度与深度，同国内流行教材吻合度很高，适合选作非物理类尤其是工科专业的大学物理双语教材。

西书第11版每章由一个开篇问题（Opening question）引导，每节由一道理解检测题（Test your understanding question）收尾、以便学生阅读时自测，引导学生深入思考、探究。其答案都列于每章之末，以供核对。在课文适当处以Caution为标志点出学生常犯的通病和易产生的误解，警醒读者规避。这些编排有助于提升学生读书的效果。

西书第11版另一特点是注重传授解题技巧。除配有大量例题之外，西书编者将解题的思路与步骤概括为审题（identify）、破题（set up）、求解（execute）与评价（evaluate）四个环节。首先审定该问题涉及的物理原理、概念，确定待求的目标变量；其次列出相应的方程或方程组，明确哪些是已知量、哪些是待求的未知量；再次完成数学运算，得出结果；最后根据物理背景要求，评价结果的合理性、有效性。其亮点在于，全书将各种物理问题分门别类，以Problem-Solving Strategy为标志列出某一类问题的审题思路、破题入口，求解的步骤及技巧，并在其后附以该类问题的若干示范例题，供学生揣摩、领会。课文中每则解题技巧与每道例题都按上述四个环节逐步讨论（改编版自第6章始），并借用首字母缩略词将这种解题方略称为

ISEE 方法。H. D. Young 认为持之以恒地按 ISEE 训练，有利于学生养成思维清晰、条理分明、表述规范的良好解题习惯，能使学生从面对习题不知所措过渡为训练有素，按部就班解题，从而减少失误，树立信心。ISEE 受到使用西书师生的欢迎，得到物理教学法研究人员的好评，值得我们借鉴。

那么，这样优秀的教材为什么还要改编呢？

2. 改编初衷

改革开放以来，尤其是在倡导双语教学的21世纪，国内引进出版的英文物理类教材可称汗牛充栋。虽然它们对我国教材建设、教学改革以及促进双语教学功不可没，但是，由于国情和教学理念的差异，探索双语教学的同仁们逐渐认识到：即使是优秀的国外一流教材，直接用作双语课本也未必是最适合的。笔者自20世纪80年代末，在合肥工业大学探索物理双语教学已历20载，深感直接选用外国优秀教材存在许多不尽人意之处。

首先是质点力学起点过低、展开太细、与中学重复甚多，所有英文原版物理教材概莫能外。以西书11版为例，洋洋洒洒8章326页，仍明显未达国内现行大学物理质点力学的深度与难度。教育部最新颁布的《理工科大学物理课程教学基本要求》（以下简称“基本要求”）指出，力学中除角动量、刚体外，“绝大多数概念学生在中学阶段已有接触，故教学中展开应适度，以避免重复感”。显然，目前的任何一本原版物理教材都与此精神不符。虽然“基本要求”对质点力学的建议学时仅8~10学时，不到课程总学时的10%，但由于该部分排在大学物理教材之首，位居学生接受双语教学和接触原版教材之初，低水平的重复容易破坏学生的学习兴趣，成为教学中的拦路虎。笔者每轮教学至此都颇费周章，相信业内同仁亦有同感。20世纪80年代中后期国内从事物理双语教学的许多学校就曾直接删去力学，从热学甚至电磁学开讲，笔者也曾试过，这当然是无奈之举。后来在探索中，笔者用几十页自撰讲义取代原书相应部分，化解了这一难题。

按“基本要求”精神，质点力学起点应定位于我国高中毕业生已达之水平。突出矢量运算与微积分思想方法的应用，提纲挈领地回顾运动学、动力学、功与能、动量与冲量、机械能与动量守恒定律等知识，并让学生通过解答涉及变加速度、变力等非用微积分不可的问题，深化认识。这一教案不难移植到双语教学中，难的是无法在原教材中挑出适用的章节甚至段落来呼应。作为替代，笔者将全英文的教案写得尽可能详细，以多媒体方式在讲课中展示，同时印发给学生作为讲义。这一教法能达到与国内教材持平的深度。自撰讲义虽列为5章，篇幅只几十页，但与建议学时相适应，体现了“展开应适度”的精神。讲义维持了体系的完整，实现了与后续内容的衔接，使大刀阔斧地删减前8章成为可能。由于采用这一教法，合肥工业大学物理双语教学近5年效果良好。这便是我们提出“有删有补”改编方案的缘起。

此外，原版教材篇幅浩大、扩展内容过多，也应在改编中一并解决。

3. 改编的具体构想

“基本要求”列出75个A类知识点，它们构成大学物理课程教学内容的基本框架，是核心内容。国内从事物理双语教学的同仁迫切希望有一本既保留引进教材长处和特色，又覆盖上述A类知识点、篇幅适当的英文物理教材。回应这一需求，国内曾出过自主撰写的英文教材，但难以传递原汁原味的行文风格；国内也出过缩编版，但因受原出版商“只删不补”的制约，为维持内容体系完整，删减力度不大，力学困惑依旧。

我们认为，最适用的双语教材应主体选自国外优秀一流教材，应以“基本要求”列出的A类知识点为改编删留的依据。对难以删留的质点力学，不妨以自撰讲义替代。

西书11版的刚体力学（第9，10两章，指原书序号，下同）、振动与波（第13，15两章）、热学（第17，18，19，20共4章）、电磁学（第21，22，23，24，25，27，28，29，30共9章）、波动光学（第32，33，35，36共4章）、近代物理（第37，38，39，40共4章）总计25章，它们与国内传统教材贴近，难度与数学要求相当，可全部保留，只需删去与中学重复的4小节（热膨胀、电容串并联、电功率、全反射）以及属于扩展内容的9小节（横波波速、物质相变、内燃机、直流电动机、电磁驻波、色散、光散射、全息、电磁波多普勒效应）。这25章是教学内容的主体，占改编版90%以上篇幅，保留这25章，便保证了原书特色、长处的承传及原汁原味文风的传递。

除删去质点力学8章之外，整章删除的还有不属于本课程内容的3章：静力学（第11章）、直流电路（第26章）、交流电（第31章）；属于扩展内容的8章：万有引力（第12章）、流体力学（第14章）、声音与听力（第16章）、几何光学与光学仪器（第34章）、原子结构（第41章）、凝聚态（第42章）、核物理（第43章）、粒子物理与宇宙学（第44章）。共计删除19章。

扩展内容比重大是国外教材的一大特色。适当讲授这些内容或供学生课外阅读固然可以深化理解，扩展眼界，起到开启新“知识窗口”、预留“知识接口”之功效，国内面向21世纪推出的教材不少都借鉴了这一特色，有的扩展内容近半。然而，在实际教学中，多数学生只浏览其中一部分，倒是教师研读得仔细。前述删去的扩展内容，作为中文教材，或者供教师参考用的原版教材都宜保留，而作为学生双语课本，则可另作别论，因为学生英文阅读量已十分浩大（平均每次2学时覆盖教材12页以上）。绝大多数学生无暇阅读扩展内容。再者，能在浏览中挑出感兴趣内容来阅读，对多数低年级学生来说力不从心。

保留的25章中仍有少数A类知识点未能覆盖或覆盖不足，这些欠缺可自删除的篇幅中挑出相关内容补齐。例如第16章第7节“拍”与第8节“多普勒效应”，分别改作第15章的第8、9两节；第41章第1节“氢原子”、第3节“电子自旋”和第4节“多电子原子与不相容原理”，分别改作第40章的第6、7、8节。第13章的第2节引入了相矢量，但未讲透，而补充的段落又在第31章交流电中被删去，需要将此段落挖出适当改动，然后补充到13章第2节中。

所有章节的删留都存在一个衔接整合问题，有大量案头工作要做。除此之外，我们还作了以下删减。

习题量大是国外教材又一特色。作为参考书固然多多益善，但作为课本，考虑到学生的浏览能力有限，我们按“基本要求”作了筛选，依建议学时的4~5倍选留习题，同时删去每章的小结、书末的照片出处及索引，并用中文的改编前言代替原书目录之前的附页。改编版将原书篇幅由1780页缩至800页，覆盖了“基本要求”列出的全部75个A类知识点，同时至少涉及14个B类知识点。

尽管自撰稿能化解质点力学的难题，但笔者深知自撰文字无法与原书风格衔接，只能退而求其次，按详细教案自撰讲义。用自撰讲义替代原书前8章实属不得已之举，为使自撰稿尽可能规范，笔者尽量从删去的8章中选出适用的段落与句子，尽量套用原书及其他优秀原版教材中的英语表述方式，使纯粹自撰的句子压缩到20页之内，只占改编版的3%，而原汁原味的英

文表述占到97%以上。何况这20页自撰稿中，公式图表还占了相当比重，使文字不地道的负面影响尽可能减小。

4. 鸣谢

有删有补的改编构想得到了机械工业出版社的大力支持。经多方争取，获得了国外原出版商的改编授权，使我们的构想得以施行。在改编方案拟订之初，机械工业出版社李永联编辑帮助笔者广泛征求了国内物理双语教学同行的意见，许多专家、学者热情鼓励，不吝赐教，笔者深受感动。昆明理工大学王安安教授、北京交通大学滕小瑛副教授、成都电子科技大学王慧教授、湖南大学张智教授、浙江大学吴泽华教授、重庆邮电大学梁斌教授等，都根据自己双语教学的经验和体会给出了很好的建议。西安交通大学吴百诗教授在百忙中审阅了本书的改编方案与说明，并提出了中肯的意见。美国马里兰大学巴尔的摩分校的Lily博士悉心审订了自撰讲义稿。

笔者在探索双语教学的20年中，始终得到合肥工业大学分管教学的校领导、教务处、理学院及大学物理教研室领导的鼓励与支持，他们对本书的改编也极为关注。

中国科学技术大学井思聪教授担任本书主审，对全书的框架结构、删留取舍的合理性等进行了审查，并从更适应教学规律的角度提出了有益的建议和意见。

全体改编者愿在此对上述专家、学者及领导表示衷心的感谢！

5. 结语

我们希望提供一本反映美国最新主流教材特色，保持活泼生动、流畅规范、原汁原味语言风格的英文物理教材；希望该教材能覆盖教育部最新“教学基本要求”提出的全部核心内容，达到国内主流教材已达到的深度，同时满足篇幅适当、成本价格与国内教材相当的要求，供开展物理双语教学师生选用。

本书改编分工如下：邓铁如教授（现退休后兼职于宁波大红鹰学院）担任主编，负责改编方案的制定、前5章的撰稿以及全书的统稿；副主编孟大敏老师负责第6~13章的改编与多媒体课件设计；副主编徐元英老师负责第14~20章的改编及自撰讲义配图；宋逢泉老师负责第21~25章的改编及配套网络制作；景佳老师负责第26~30章的改编及多媒体课件制作。

限于水平，自撰稿失误在所难免，改编中取舍也有不周之处，欢迎业内同仁们及广大师生批评指正。

全体改编者
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MAGNETIC FIELD AND MAGNETIC FORCES

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Charged particles ejected from the sun are steered by the earth's magnetic field toward our planet's north and south poles. When these particles strike gas molecules in the upper atmosphere, the molecules are set aglow. The result is the brilliant light show called the aurora australis (at far southern latitudes) or aurora borealis (at far northern latitudes, as in this photograph from Alaska).

? Why do charged solar particles move predominantly toward the earth's poles rather than the equator?

Everybody uses magnetic forces. They are at the heart of electric motors, TV picture tubes, microwave ovens, loudspeakers, computer printers, and disk drives. The most familiar aspects of magnetism are those associated with permanent magnets, which attract unmagnetized iron objects and can also attract or repel other magnets. A compass needle aligning itself with the earth's magnetism is an example of this interaction. But the *fundamental* nature of magnetism is the interaction of moving electric charges. Unlike electric forces, which act on electric charges whether they are moving or not, magnetic forces act only on *moving* charges.

Although electric and magnetic forces are very different from each other, we use the idea of a *field* to describe both kinds of force. We saw in Chapter 14 that the electric force arises in two stages: (1) a charge produces an electric field in the space around it, and (2) a second charge responds to this field. Magnetic forces also arise in two stages. First, a *moving* charge or a collection of moving charges (that is, an electric current) produces a *magnetic* field. Next, a second current or moving charge responds to this magnetic field, and so experiences a magnetic force.

In this chapter we study the second stage in the magnetic interaction—that is, how moving charges and currents *respond* to magnetic fields. In particular, we will see how to calculate magnetic forces and torques, and we will discover why magnets can pick up iron objects like paper clips. In Chapter 20 we will complete our picture of the magnetic interaction by examining how moving charges and currents *produce* magnetic fields.

19.1 | Magnetism

Magnetic phenomena were first observed at least 2500 years ago in fragments of magnetized iron ore found near the ancient city of Magnesia (now Manisa, in western Turkey). These fragments were examples of what are now called **permanent magnets**; you probably have several permanent magnets on your refrigerator door at home. Permanent magnets were found to exert forces on each other as well as on pieces of iron that were not magnetized. It was discovered that when an iron rod is brought in contact with a natural magnet, the rod also becomes magnetized. When such a rod is floated on water or suspended by a string from its center, it tends to line itself up in a north-south direction. The needle of an ordinary compass is just such a piece of magnetized iron.

Before the relation of magnetic interactions to moving charges was understood, the interactions of permanent magnets and compass needles were described in terms of *magnetic poles.* If a bar-shaped permanent magnet, or *bar magnet,* is free to rotate, one end points north. This end is called a *north pole* or *N-pole*; the other end is a *south pole* or *S-pole.* Opposite poles attract each other, and like poles repel each other (Fig.19.1). An object that contains iron but is not itself magnetized (that is, it shows no tendency to point north or south) is attracted by *either* pole of a permanent magnet (Fig.19.2). This is the attraction that acts between a magnet and the unmagnetized steel door of a refrigerator. By analogy to electric interactions, we describe the interactions in Figs.19.1 and 19.2 by saying that a bar magnet sets up a *magnetic field* in the space around it and a second body responds to that field. A compass needle tends to align with the magnetic field at the needle's position.

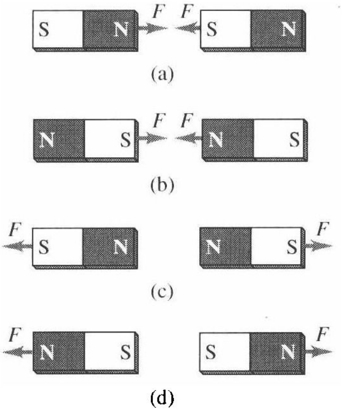


Fig.19.1 (a), (b) Two bar magnets attract when opposite poles (N and S, or S and N) are next to each other. (c), (d) The bar magnets repel when like poles (N and N, or S and S) are next to each other.

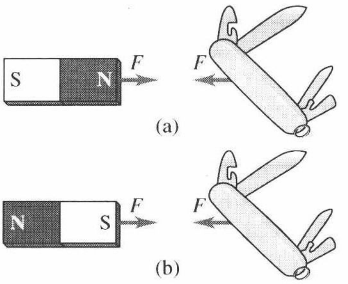


Fig.19.2 (a), (b) Either pole of a bar magnet attracts an unmagnetized object that contains iron.

The earth itself is a magnet. Its north geographical pole is close to a magnetic *south* pole, which is why the north pole of a compass needle points north. The earth's magnetic axis is not quite parallel to its geographic axis (the axis of rotation), so a compass reading deviates somewhat from geographic north. This deviation, which varies with location, is called *magnetic declination* or *magnetic variation.* Also, the magnetic field is not horizontal at most points on the earth's surface; its angle up or down is called *magnetic inclination.* At the magnetic poles the magnetic field is vertical.

Figure 19.3 is a sketch of the earth's magnetic field. The lines, called *magnetic field lines,* show the direction that a compass would point at each location; they are discussed in detail in Section

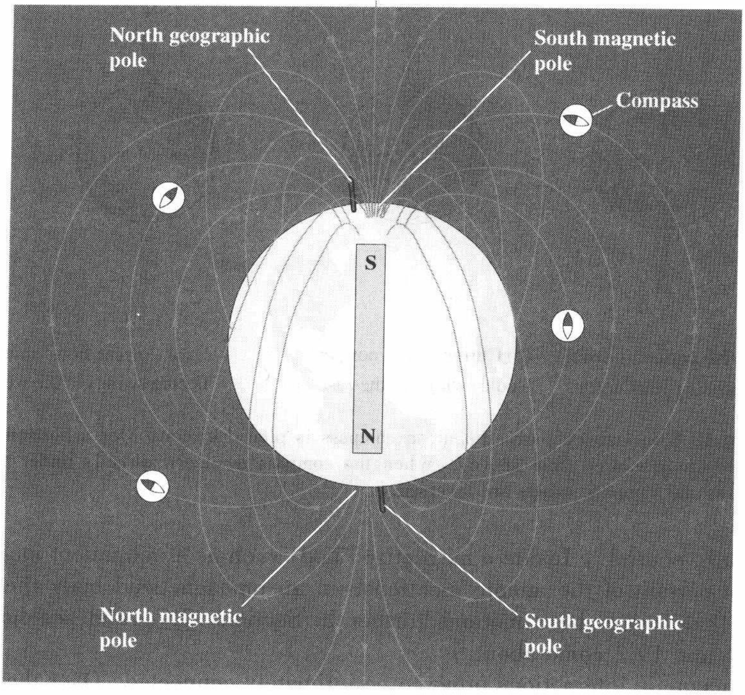


Fig.19.3 A compass placed at any location in the earth's magnetic field points in the direction of the field line at that location. Representing the earth's field as that of a tilted bar magnet is only a crude approximation of its fairly complex configuration. The field, which is caused by currents in the earth's molten core, changes with time; geologic evidence shows that it reverses direction entirely at irregular intervals of about a half million years.

19.3. The direction of the field at any point can be defined as the direction of the force that the field would exert on a magnetic north pole. In Section 19.2 we'll describe a more fundamental way to define the direction and magnitude of a magnetic field.

The concept of magnetic poles may appear similar to that of electric charge, and north and south poles may seem analogous to positive and negative charge. But the analogy can be misleading. While isolated positive and negative charges exist, there is *no* experimental evidence that a single isolated magnetic pole exists; poles always appear in pairs. If a bar magnet is broken in two, each broken end becomes a pole (Fig.19.4). The existence of an isolated magnetic pole, or **magnetic monopole**, would have sweeping implications for theoretical physics. Extensive searches for magnetic monopoles have been carried out, but so far without success.

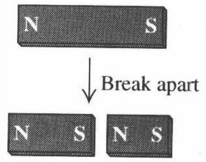
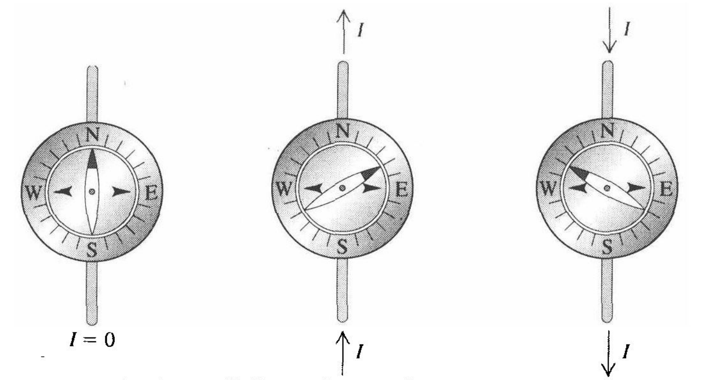


Fig.19.4 Breaking a bar magnet. Each piece has a north and south pole, even if the pieces are different sizes. (The smaller the piece, the weaker its magnetism.)

The first evidence of the relationship of magnetism to moving charges was discovered in 1819 by the Danish scientist Hans Christian Oersted. He found that a compass needle was deflected by a current-carrying wire, as shown in Fig.19.5. Similar investigations were carried out in France by André Ampère. A few years later, Michael Faraday in England and Joseph Henry in the United States discovered that moving a magnet near a conducting loop can cause a current in the loop. We now know that the magnetic forces between two bodies shown in Figs.19.1 and 19.2 are fundamentally due to interactions between moving electrons in the atoms of the bodies. (There are also *electric* interactions between the two bodies, but these are far weaker than the magnetic interactions because the two



(a) No current in wire: needle points north (b) Current flows north: needle swings to the east (c) Current flows south: needle swings to the west

Fig.19.5 In Oersted's experiment, a compass is placed directly over a horizontal wire (here viewed from above). When the compass is placed directly under the wire, the compass swings are reversed.

bodies are electrically neutral.) Inside a magnetized body such as a permanent magnet, there is a *coordinated* motion of certain of the atomic electrons; in an unmagnetized body these motions are not coordinated. (We'll describe these motions further in Section 19.7, and see how the interactions shown in Figs.19.1 and 19.2 come about.)

Electric and magnetic interactions prove to be intimately connected. Over the next several chapters we will develop the unifying principles of electromagnetism, culminating in the expression of these principles in *Maxwell's equations.* These equations represent the synthesis of electromagnetism, just as Newton's laws of motion are the synthesis of mechanics, and like Newton's laws they represent a towering achievement of the human intellect.

Test Your Understanding

Suppose you cut off the part of the compass needle shown in Fig.19.5a that is painted white. You discard this part, drill a hole in the remaining red part, and place the red part on the pivot at the center of the compass. Will the red part still swing east and west when a current is applied as in Figs.19.5b and 19.5c?

19.2 | Magnetic Field

To introduce the concept of magnetic field properly, let's review our formulation of *electric* interactions in Chapter 14, where we introduced the concept of *electric* field. We represented electric interactions in two steps:

1. A distribution of electric charge at rest creates an electric field $\vec{E}$ in the surrounding space.
2. The electric field exerts a force $\vec{F} = q\vec{E}$ on any other charge q that is present in the field.

We can describe magnetic interactions in a similar way:

1. A moving charge or a current creates a **magnetic field** in the surrounding space (in addition to its *electric* field).
2. The magnetic field exerts a force $\vec{F}$ on any other moving charge or current that is present in

the field.

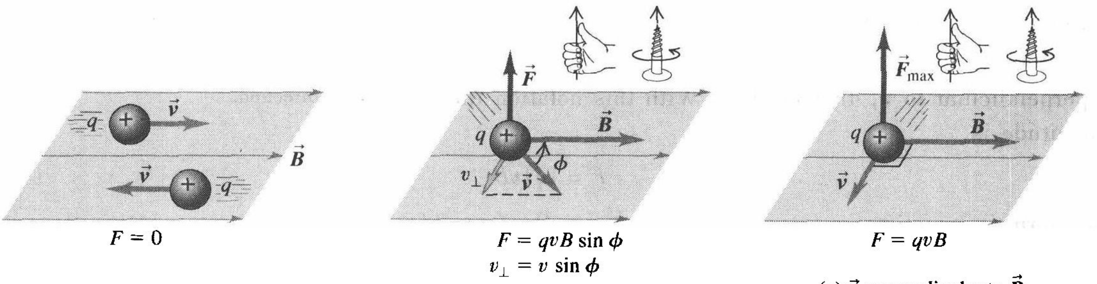
In this chapter we'll concentrate on the *second* aspect of the interaction: Given the presence of a magnetic field, what force does it exert on a moving charge or a current? In Chapter 20 we will come back to the problem of how magnetic fields are *created* by moving charges and currents.

Like electric field, magnetic field is a *vector field*—that is, a vector quantity associated with each point in space. We will use the symbol $\vec{B}$ for magnetic field. At any position the direction of $\vec{B}$ is defined as that in which the north pole of a compass needle tends to point. The arrows in Fig. 19.3 suggest the direction of the earth's magnetic field; for any magnet, $\vec{B}$ points out of its north pole and into its south pole.

What are the characteristics of the magnetic force on a moving charge? First, its magnitude is proportional to the magnitude of the charge. If a 1-μC charge and a 2-μC charge move through a given magnetic field with the same velocity, experiments show that the force on the 2-μC charge is twice as great as that on the 1-μC charge. The magnitude of the force is also proportional to the magnitude, or "strength," of the field; if we double the magnitude of the field (for example, by using two identical bar magnets instead of one) without changing the charge or its velocity, the force doubles.

The magnetic force also depends on the particle's velocity. This is quite different from the electric-field force, which is the same whether the charge is moving or not. A charged particle at rest experiences *no* magnetic force. Furthermore, we find by experiment that the magnetic force $\vec{F}$ *does not* have the same direction as the magnetic field $\vec{B}$ but instead is always *perpendicular* to both $\vec{B}$ and the velocity $\vec{v}$. The magnitude F of the force is found to be proportional to the component of $\vec{v}$ perpendicular to the field; when that component is zero (that is, when $\vec{v}$ and $\vec{B}$ are parallel or antiparallel), the force is zero.

Figure 19.6 shows these relationships. The direction of $\vec{F}$ is always perpendicular to the plane containing $\vec{v}$ and $\vec{B}$. Its magnitude is given by



$F = 0$

(a) Velocity $\vec{v}$ parallel or antiparallel to magnetic field $\vec{B}$: magnetic force is zero

$F = qvB\sin\phi$
$v_\perp = v\sin\phi$

(b) $\vec{v}$ at an angle ϕ to $\vec{B}$: magnetic force has magnitude $F = qvB\sin\phi$

$F = qvB$

(c) $\vec{v}$ perpendicular to $\vec{B}$: magnetic force has magnitude $F = qvB$

Fig.19.6 The magnetic force $\vec{F}$ acting on a positive charge q moving with velocity $\vec{v}$ is perpendicular to both $\vec{v}$ and the magnetic field $\vec{B}$. For given values of the speed v and magnetic field strength B, the force is greatest when $\vec{v}$ and $\vec{B}$ are perpendicular.

$$F = |q|v_\perp B = |q|vB\sin\phi \tag{19.1}$$

where $|q|$ is the magnitude of the charge and ϕ is the angle measured from the direction of $\vec{v}$ to the direction of $\vec{B}$, as shown in the figure.

This description does not specify the direction of $\vec{F}$ completely; there are always two directions, opposite to each other, that are both perpendicular to the plane of $\vec{v}$ and $\vec{B}$. To complete the description, we use the same right-hand rule that we used to define the vector product in Section 1.6. (It would be a good idea to review that section before you go on.) Draw the vectors $\vec{v}$ and $\vec{B}$ with their tails together, as in Fig.19.6b. Imagine turning $\vec{v}$ until it points in the direction of $\vec{B}$(turning through ϕ, the smaller of the two possible angles). Wrap the fingers of your right hand around the line perpendicular to the plane of $\vec{v}$ and $\vec{B}$ so that they curl around with the sense of rotation from $\vec{v}$ to $\vec{B}$. Your thumb then points in the direction of the force $\vec{F}$ on a *positive* charge. (Alternatively, the direction of the force $\vec{F}$ on a positive charge is the direction in which a right-hand-thread screw would advance if turned the same way.)

This discussion shows that the force on a charge q moving with velocity $\vec{v}$ in a magnetic field $\vec{B}$ is given, both in magnitude and in direction, by

$$\vec{F} = q\vec{v} \times \vec{B} \qquad \text{(magnetic force on a moving charged particle)} \qquad (19.2)$$

This is the first of several vector products we will encounter in our study of magnetic-field relationships. It's important to note that Eq.(19.2) was *not* deduced theoretically; it is an observation based on *experiment.*

Equation (19.2) is valid for both positive and negative charges. When q is negative, the direction of the force $\vec{F}$ is opposite to that of $\vec{v} \times \vec{B}$. If two charges with equal magnitude and opposite sign move in the same $\vec{B}$ field with the same velocity (Fig.19.7), the forces have equal magnitude and opposite direction. Figures 19.6 and 19.7 show several examples of the relationships of the directions of $\vec{F}$, $\vec{v}$, and $\vec{B}$ for both positive and negative charges. Be sure you understand the relationships shown in these figures.

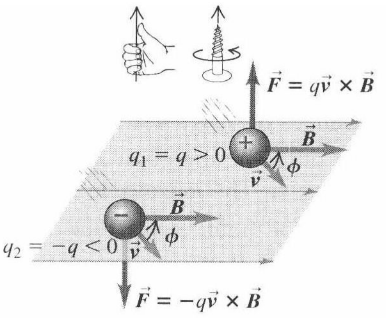


Fig.19.7 Two charges of the same magnitude but opposite sign moving with the same velocity in the same magnetic field. The magnetic forces on the charges are equal in magnitude but opposite in direction.

Equation (19.1) gives the magnitude of the magnetic force $\vec{F}$ in Eq.(19.2). We can express this magnitude in a different but equivalent way. Since ϕ is the angle between the directions of vectors $\vec{v}$ and $\vec{B}$, we may interpret $B\sin\phi$ as the component of $\vec{B}$ perpendicular to $\vec{v}$, that is, $B_\perp$. With this notation the force magnitude is

$$F = |q|vB_\perp \qquad (19.3)$$

This form is sometimes more convenient, especially in problems involving *currents* rather than individual particles. We will discuss forces on currents later in this chapter.

From Eq.(19.1) the *units* of B must be the same as the units of F/qv. Therefore the SI unit of B is equivalent to $1\,\mathrm{N \cdot s/C \cdot m}$, or, since one ampere is one coulomb per second ($1\mathrm{A} = 1\mathrm{C/s}$), $1\,\mathrm{N/A \cdot m}$. This unit is called the **tesla** (abbreviated T), in honor of Nikola Tesla (1857—1943), the prominent Serbian-American scientist and inventor:

$$1\,\text{tesla} = 1\,\mathrm{T} = 1\,\mathrm{N/A \cdot m}$$

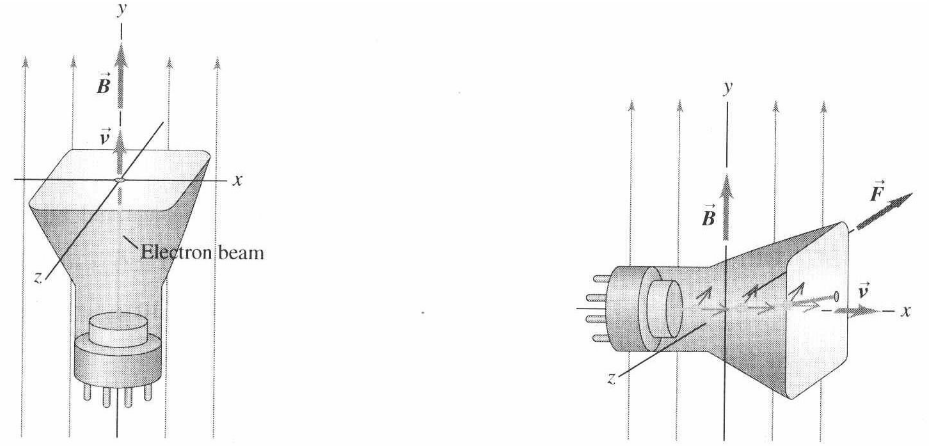
Another unit of B, the **gauss** ($1\mathrm{G} = 10^{-4}\mathrm{T}$), is also in common use. Instruments for measuring magnetic field are sometimes called *gaussmeters.*

The magnetic field of the earth is of the order of 10^{-4}T or 1G. Magnetic fields of the order of 10T occur in the interior of atoms and are important in the analysis of atomic spectra. The largest steady magnetic field that can be produced at present in the laboratory is about 45T. Some pulsed-current electromagnets can produce fields of the order of 120T for short time intervals of the order of a millisecond. The magnetic field at the surface of a neutron star is believed to be of the order of 10^8T.

To explore an unknown magnetic field, we can measure the magnitude and direction of the force on a *moving* test charge, then use Eq.(19.2) to determine $\vec{B}$. The electron beam in a cathode-ray tube, such as that used in a television set, is a convenient device for making such measurements. The electron gun shoots out a narrow beam of electrons at a known speed. If there is no force to deflect the beam, it strikes the center of the screen.

If a magnetic field is present, in general the electron beam is deflected. But if the beam is parallel or antiparallel to the field, then $\phi = 0$ or π in Eq.(19.1) and $F = 0$; there is no force, and hence no deflection. If we find that the electron beam is not deflected when its direction is parallel to a certain axis as in Fig.19.8a, the $\vec{B}$ vector must point either up or down along that axis.

If we then turn the tube 90° (Fig.19.8b), $\phi = \pi/2$ in Eq.(19.1) and the magnetic force is maximum; the beam is deflected in a direction perpendicular to the plane of $\vec{B}$ and $\vec{v}$. The direction and magnitude of the deflection determine the direction and magnitude of $\vec{B}$. We can perform additional experiments in which the angle between $\vec{B}$ and $\vec{v}$ is between zero and 90° to confirm Eq.(19.1) or (19.3) and the accompanying discussion. We note that the electron has a negative charge; the force in Fig.19.8 is opposite in direction to the force on a positive charge.



(a) If tube axis is parallel to the y-axis, beam is undeflected: hence $\vec{B}$ is in either $+y$ or $-y$ direction

(b) If tube axis is parallel to the x-axis, beam is deflected in $-z$ direction: hence $\vec{B}$ is in $+y$ direction

Fig.19.8 Determining the direction of a magnetic field using a cathode-ray tube. Because electrons have a negative charge, the magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ in part (b) points in the direction opposite to the rule in Fig.19.6.

When a charged particle moves through a region of space where *both* electric and magnetic fields are present, both fields exert forces on the particle. The total force $\vec{F}$ is the vector sum of the electric and magnetic forces:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{19.4}$$

Problem-Solving Strategy

Magnetic Forces

IDENTIFY *the relevant concepts*: The right-hand rule allows you to determine the magnetic force on a moving charged particle.

SET UP *the problem using the following steps*:

1. Draw the velocity vector $\vec{v}$ and magnetic field $\vec{B}$ with their tails together so that you can visualize the plane in which these two vectors lie.
2. Identify the angle ϕ between the two vectors.