世界优秀教材中国版

理科类系列教材

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改编版

Fundamentals of Physics (7th Edition) (Extended Edition)

基础物理学（第7版）

□ David Halliday Robert Resnick Jearl Walker 原著

□ 李学潜 方哲宇 改编

高等教育出版社
Higher Education Press

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内容简介：

本书是哈里德等人编写的 Fundamentals of physics（7th Edition）的改编版。

哈里德一书是一套典型的美国教材，在我国也有很高的知名度。原书物理原理阐述通俗易懂，图文并茂内容丰富。编者在改编时保持了原作的风格和特色，根据国内高校教学的基本特点，系统地阐述了力学、热学、光学、电磁学等基本规律和基本概念，并初步介绍了相对论原理、原子物理、半导体物理等近现代物理内容。删掉与中学物理重复的部分，使整体内容紧凑合理，并在每章末尾安排了较多的思考题和习题，使本书在理工科教学中更具有实用性，普适性。本书可作为高等学校物理专业基础课双语教材，也可供其他理工科类专业有关教师、学生参考。

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出版者的话

为适应当前我国高等学校各类创新人才培养的需要，大力推进教育部倡导的双语教学，配合教育部实施的“高等学校教学质量与教学改革工程”和“精品课程”建设的需要，国内一些出版社都陆续原版引进了不少海外优秀教材。海外优秀教材的立体化配套、多种教学资源的整合，以及为课程提供的整体教学解决方案，都有不少值得我们学习借鉴之处。但一个不容忽视的问题是，外文原版教材与我国现行的课程内容、教学体系、教学习惯等存在着巨大的差异性。譬如，重点课程的原版教材通常很厚，内容很多，容量是国内自编教材的好几倍。国外的情况是，老师未必会都讲，剩下大量的内容留给学生自学；而国内的情况不尽相同。受国内教学学时所限，完全照搬是不合时宜的。教材的国际化必须与本民族的文化教育传统相融合，在原有的基础上吸收国外优秀教材的长处，这使得我们需要对外文原版教材进行适当的改编。改编不是简单地使内容减少，而是结合国内教学特点，引进国外先进的教学模式及思想，在教学内容和方式上更中国化，使之更符合国内的课程设置及教学环境。

2004年伊始，高等教育出版社有计划、大规模地开展了海外优秀理科系列教材的引进及改编工作。在引进改编海外优秀教材的过程中，我们坚持了两条原则：（1）精选版本，打造精品系列；（2）慎选改编者，保证品质。

首先，我们和 Pearson Education，John Wiley & Sons，McGraw-Hill 以及 Thomson Learning 等国外出版公司进行了广泛接触，经推荐并在国内专家的协助下，提交引进版权总数200余种，学科专业领域涉及数学、物理、化学化工、地理、环境等。收到样书后，我们聘请了国内高校一线教师、专家学者参与这些原版教材的评介工作，从中遴选出了一批优秀教材进行改编，并组织出版。这批教材普遍具有以下特点：（1）基本上是近几年出版的，在国际上被广泛使用，在同类教材中具有相当的权威性；（2）高版次，历经多年教学实践检验，内容翔实准确，反映时代要求；（3）各种教学资源配套整齐，为师生提供了极大的便利；（4）插图精美，丰富，图文并茂，与正文相辅相成；（5）语言简练，流畅，可读性强，比较适合非英语国家的学生阅读。

其次，慎选改编者。原版教材确定后，随之碰到的问题是寻找合适的改编者。要改编一本教材，必须要从头到尾吃透它，有这样的精力自编一本教材都绰绰有余了。我们与国内众多高等院校的专家学者进行了广泛的接触和细致的协商，几经酝酿，最终确定下来改编者。大多数改编者都是有国外留学背景的中青年学者，他们既有相当高的学术水平，又热爱教学，长期工作在教学第一线。他们了解引进版教材的知识结构、表达方式和写作方法，最重要的是他们有时间，有精力，有热情，有的甚至付出了比写一本新教材更多的劳动。我们向他们表示最真诚的敬意。

在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作，这套引进改编的教材体现了一定的权威性、系统性、先进性和经济性等特点。

这套教材出版后，我们将结合各高校的双语教学计划，开展大规模的宣传和培训工作，及时地将本套丛书推荐给各高校使用。在使用过程中，我们衷心希望广大教师和学生提出宝贵的意见和建议。如有好的教材值得引进，也请与高等教育出版社物理分社联系。联系电话：010-58556216（物理）。E-mail: guoyl@hep.com.cn。

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2004年10月

前　　言

Fundamentals of Physics 是一本有启发性的教科书，美国多所大学采用它作为一年级的普通物理教材。它帮助物理专业以及相关领域的学生掌握牢固的物理知识，深刻了解重要的概念，熟悉理论推导的基本技术，熟练运用数值计算。教师可以和学生一样从本书中受益。我们采用它作为在南开大学进行普通物理双语教学的主要教科书已有若干年了，我们对它的高质量以及对自然的深刻认识是十分欣赏的。

作为普通物理的一本优化教科书，Fundamentals of Physics 告诉学生们一个物理学家是如何思考和认识这个世界的。对于一个刚刚踏进物理这个神圣而又神秘和迷人领域的一年级学生来说尤为重要。

确实我们常问自己什么是物理，做实验的目的又是什么？我们知道，物理学从本质上说是一门实验科学。理论家根据在实验中的观测建立他们的模型，然后对那些可以在实验中测量的物理量进行预言，最后新的数据会支持或否定这些模型。在物理中，任何规则和定律都有它们的适用范围，理论绝不能凭空产生。有一次我和学生讨论理论与实验的关系，我问学生们认为理论和实验哪一个更重要，哪一个起到主导作用。让我吃惊的是大部分学生认为理论更重要，这让我意识到我们的教育在哪儿出了毛病。

大部分中国高中学生靠读书学到了公式和物理定律，他们从不（或极少）自己动手做实验。同时，他们的老师也认真地讲述这些公式是如何推导，甚至只是根据观察而猜出来的。逐渐地，这些高中孩子们得到一种感觉，那些罗列在教科书中的公式就是整个物理学，是不能破坏和违背的。还有为了上好大学而产生的压力，使这些中学生只集中精力去学习用现成的公式和方法解题而不是思考相应的物理概念和自然本质。这种误导，如果不予以纠正，将会妨碍他们在未来的事业中获得真正的成功。

在大学阶段，我们尽可能地把他们引导到另一方面：介绍物理学家是如何做出重大发现的；假定我们和那些物理大家们生活在同一个时代里，想一想他们是如何进行思维的；同时指出隐藏在这些经典理论中尚未解决的问题。通过这些，我们展示给学生什么是物理学。学习物理不仅仅是掌握复杂的数学和计算技巧，更重要的是锻炼对自然的深刻洞察力。Fundamentals of Physics 就是能帮助我们得到对自然界深刻认识的一本了不起的教科书，它在一定程度上解决了我们面临的问题。

与大部分中国普通物理教科书不同，Fundamentals of Physics 不求助于复杂和冗繁的推导也不试图去包含所有相关的材料，而是聚焦在物理本质及现象的描述和理解上。例如，在第一卷中的陀螺运动和第二卷中的磁镜形成机制，都引起了学生极大的兴趣，尽管书中并没有提供详尽的数学公式。这样的内容可以大大激发学生对学习更多知识的热情，而且如果他们愿意，他们能找到相应资料去弥补教科书中省略掉的部分。有不少学生确实这样努力地做了。中文教科书更为强调逻辑和数学推导的严格性，这是建立在微积分基础上的，这样看来 Fundamentals of Physics 具有它鲜明的特色，它与现在国内大学生所使用的普通教科书有很强的互补性。在每章的开头都有一小段“什么是与本章相关的物理”，它描述了本章的要点以及它的含义，这有助于学生掌握相关物理知识的关键点和本质。本书还包含了许多精彩的照片和图表，它们生动地描述了相关的内容。附在每章结尾处的问题帮助学生加强对概念的理解。

为符合国内大学普通物理双语教学的要求，根据中国学生的特点，我们改编了 Fundamentals of Physics 一书，调整、合并以及删除了一些章节。这个工作很不容易，我们努力保持原著的风格，尽量防止由于这些改变丢失一些重要的内容。我们很高兴把本书献给热爱物理并选择物理作为终身事业的同学。感谢教育部对双语教学的指导和支持；感谢 Fundamentals of Physics 的作者允许我们改编这本精彩的教

科书并支持我们的改编方案；也感谢高等教育出版社的编辑们，帮助我们解决了许多具体问题。另外，还要对南开大学物理系的学生表达我们衷心的感谢，他们对双语教学的热情很高，并且提出了许多有价值的评论和建议。

李学潜　方哲宇

2008年2月28日于天津

Contents

Chapter 1

Measurement

1-1 What Is Physics?

Science and engineering are based on measurements and comparisons. Thus, we need rules about how things are measured and compared, and we need experiments to establish the units for those measurements and comparisons. One purpose of physics (and engineering) is to design and conduct those experiments.

For example, physicists strive to develop clocks of extreme accuracy so that any time or time interval can be precisely determined and compared. You may wonder whether such accuracy is actually needed or worth the effort. Here is one example of the worth: Without clocks of extreme accuracy, the Global Positioning System (GPS) that is now vital to worldwide navigation would be useless.

1-2 Measuring Things

We discover physics by learning how to measure the quantities involved in physics. Among these quantities are length, time, mass, temperature, pressure, and electric current.

We measure each physical quantity in its own units, by comparison with a **standard.** The **unit** is a unique name we assign to measures of that quantity—for example, meter (m) for the quantity length. The standard corresponds to exactly 1.0 unit of the quantity. As you will see, the standard for length, which corresponds to exactly 1.0 m, is the distance traveled by light in a vacuum during a certain fraction of a second. We can define a unit and its standard in any way we care to. However, the important thing is to do so in such a way that scientists around the world will agree that our definitions are both sensible and practical.

Once we have set up a standard—say, for length—we must work out procedures by which any length whatever, be it the radius of a hydrogen atom, the wheelbase of a skateboard, or the distance to a star, can be expressed in terms of the standard. Rulers, which approximate our length standard, give us one such procedure for measuring length. However, many of our comparisons must be indirect. You cannot use a ruler, for example, to measure the radius of an atom or the distance to a star.

There are so many physical quantities that it is a problem to organize them. Fortunately, they are not all independent; for example, speed is the ratio of a length to a time. Thus, what we do is pick out—by international agreement—a small number of physical quantities, such as length and time, and assign standards to them alone. We then define all other physical quantities in terms of these *base quantities* and their standards (called *base standards*). Speed, for example, is defined in terms of the base quantities length and time and their base standards.

Base standards must be both accessible and invariable. If we define the length standard as the distance between one's nose and the index finger on an outstretched arm, we certainly have an accessible standard—but it will, of course, vary from person to person. The demand for precision in science and engineering pushes us to aim first for invariability. We then exert great effort to make duplicates of the base standards that are accessible to those who need them.

1-3 The International System of Units

In 1971, the 14th General Conference on Weights and Measures picked seven quantities as base quantities, thereby forming the basis of the International System of Units, abbreviated SI from its French name and popularly known as the *metric system.* Table 1-1 shows the units for the three base quantities—length, mass, and time—that we use in the early chapters of this book. These units were defined to be on a "human scale."

TABLE 1-1 Units for Three SI Base Quantities

Quantity	Unit Name	Unit Symbol	Quantity	Unit Name	Unit Symbol
Length	meter	m	Mass	kilogram	kg
Time	second	s			

Many SI *derived units* are defined in terms of these base units. For example, the SI unit for power, called the **watt** (W), is defined in terms of the base units for mass, length, and time. Thus, as you will see in Chapter 4,

$$1 \text{ watt} = 1 \text{ W} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^3, \tag{1-1}$$

where the last collection of unit symbols is read as kilogram-meter squared per second cubed.

To express the very large and very small quantities we often run into in physics, we use *scientific notation*, which employs powers of 10. In this notation,

$$3\ 560\ 000\ 000 \text{ m} = 3.56 \times 10^9 \text{ m} \tag{1-2}$$

and

$$0.000\ 000\ 492 \text{ s} = 4.92 \times 10^{-7} \text{ s}. \tag{1-3}$$

Scientific notation on computers sometimes takes on an even briefer look, as in 3.56 E9 and 4.92 E–7, where E stands for "exponent of ten." It is briefer still on some calculators, where E is replaced with an empty space.

As a further convenience when dealing with very large or very small measurements, we use the prefixes listed in Table 1-2. As you can see, each prefix represents a certain power of 10, to be used as a multiplication factor. Attaching a prefix to an SI unit has the effect of multiplying by the associated factor. Thus, we can express a particular electric power as

$$1.27 \times 10^9 \text{ watts} = 1.27 \text{ gigawatts} = 1.27 \text{ GW} \tag{1-4}$$

or a particular time interval as

$$2.35 \times 10^{-9} \text{ s} = 2.35 \text{ nanoseconds} = 2.35 \text{ ns}. \tag{1-5}$$

Some prefixes, as used in milliliter, centimeter, kilogram, and megabyte, are probably familiar to you.

TABLE 1-2 Prefixes for SI Units

Factor	Prefix[a]	Symbol	Factor	Prefix[a]	Symbol
10^{24}	yotta-	Y	10^{-1}	deci-	d
10^{21}	zetta-	Z	$\mathbf{10^{-2}}$	**centi-**	**c**
10^{18}	exa-	E	$\mathbf{10^{-3}}$	**milli-**	**m**
10^{15}	peta-	P	$\mathbf{10^{-6}}$	**micro-**	**μ**
10^{12}	tera-	T	$\mathbf{10^{-9}}$	**nano-**	**n**
$\mathbf{10^{9}}$	**giga-**	**G**	$\mathbf{10^{-12}}$	**pico-**	**p**
$\mathbf{10^{6}}$	**mega-**	**M**	10^{-15}	femto-	f
$\mathbf{10^{3}}$	**kilo-**	**k**	10^{-18}	atto-	a
10^{2}	hecto-	h	10^{-21}	zepto-	z
10^{1}	deka-	da	10^{-24}	yocto-	y

[a]The most frequently used prefixes are shown in bold type.

1-4 Changing Units

We often need to change the units in which a physical quantity is expressed. We do so by a method called *chain-link conversion*. In this method, we multiply the original measurement by a **conversion factor** (a ratio of units that is equal to unity). For example, because 1 min and 60 s are identical time intervals, we have

$$\frac{1 \text{ min}}{60 \text{ s}} = 1 \quad \text{and} \quad \frac{60 \text{ s}}{1 \text{ min}} = 1.$$

Thus, the ratios (1 min)/(60 s) and (60 s) /(1 min) can be used as conversion factors. This is *not* the same as writing $\frac{1}{60} = 1$ or $60 = 1$; each *number* and its *unit* must be treated together.

Because multiplying any quantity by unity leaves the quantity unchanged, we can introduce conversion factors wherever we find them useful. In chain-link conversion, we use the factors to cancel unwanted units. For example, to convert 2 min to seconds, we have

$$2\text{ min} = (2\text{ min})(1) = (2\cancel{\text{min}})\left(\frac{60\text{ s}}{1\cancel{\text{min}}}\right) = 120\text{ s}. \tag{1-6}$$

If you introduce a conversion factor in such a way that unwanted units do *not* cancel, invert the factor and try again. In conversions, the units obey the same algebraic rules as variables and numbers.

Appendix D gives conversion factors between SI and other systems of units, including non-SI units still used in the United States. However, the conversion factors are written in the style of "1 min = 60 s" rather than as a ratio.

1-5 Length

In 1792, the newborn Republic of France established a new system of weights and measures. Its cornerstone was the meter, defined to be one ten-millionth of the distance from the north pole to the equator. Later, for practical reasons, this Earth standard was abandoned and the meter came to be defined as the distance between two fine lines engraved near the ends of a platinum–iridium bar, the **standard meter bar,** which was kept at the International Bureau of Weights and Measures near Paris. Accurate copies of the bar were sent to standardizing laboratories throughout the world. These **secondary standards** were used to produce other, still more accessible standards, so that ultimately every measuring device derived its authority from the standard meter bar through a complicated chain of comparisons.

Eventually, modern science and technology required a standard more precise than the distance between two fine scratches on a metal bar. In 1960, a new standard for the meter, based on the wavelength of light, was adopted. Specifically, the standard for the meter was redefined to be 1 650 763.73 wavelengths of a particular orange-red light emitted by atoms of krypton-86 (a particular isotope, or type, of krypton) in a gas discharge tube. This awkward number of wavelengths was chosen so that the new standard would be close to the old meterbar standard.

By 1983, however, the demand for higher precision had reached such a point that even the krypton-86 standard could not meet it, and in that year a bold step was taken. The meter was redefined as the distance traveled by light in a specified time interval. In the words of the 17th General Conference on Weights and Measures:

The meter is the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second.

This time interval was chosen so that the speed of light c is exactly

$$c = 299\ 792\ 458\text{ m/s}.$$

Measurements of the speed of light had become extremely precise, so it made sense to adopt the speed of light as a defined quantity and to use it to redefine the meter.

Table 1-3 shows a wide range of lengths, from that of the universe (top line) to those of some very small objects.

TABLE 1-3 Some Approximate Lengths

Measurement	Length in Meters
Distance to the first galaxies formed	2×10^{26}
Distance to the Andromeda galaxy	2×10^{22}
Distance to the nearby star Proxima Centauri	4×10^{16}
Distance to Pluto	6×10^{12}
Radius of Earth	6×10^{6}
Height of Mt. Everest	9×10^{3}
Thickness of this page	1×10^{-4}
Length of a typical virus	1×10^{-8}
Radius of a hydrogen atom	5×10^{-11}
Radius of a proton	1×10^{-15}

1-6 Time

Time has two aspects. For civil and some scientific purposes, we want to know the time of day so that we can order events in sequence. In much scientific work, we want to know how long an event lasts. Thus, any time standard must be able to answer two questions: "*When* did it happen?" and "What is its *duration*?" Table 1-4 shows some time intervals.

TABLE 1-4 Some Approximate Time Intervals

Measurement	Time Interval in Seconds
Lifetime of the proton (predicted)	3×10^{40}
Age of the universe	5×10^{17}
Age of the pyramid of Cheops	1×10^{11}
Human life expectancy	2×10^{9}
Length of a day	9×10^{4}
Time between human heartbeats	8×10^{-1}
Lifetime of the muon	2×10^{-6}
Shortest lab light pulse	1×10^{-16}
Lifetime of the most unstable particle	1×10^{-23}
The Planck time[a]	1×10^{-43}

[a]This is the earliest time after the big bang at which the laws of physics as we know them can be applied.

Any phenomenon that repeats itself is a possible time standard. Earth's rotation, which determines the length of the day, has been used in this way for centuries; Fig. 1-1 shows one novel example of a watch based on that rotation. A quartz clock, in which a quartz ring is made to vibrate continuously, can be calibrated against Earth's rotation via astronomical observations and used to measure time intervals in the laboratory. However, the calibration cannot be carried out with the accuracy called for by modern scientific and engineering technology.

To meet the need for a better time standard, atomic clocks have been developed. An atomic clock at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, is the standard for Coordinated Universal Time (UTC) in the United States. Its time signals are available by shortwave radio (stations WWV and WWVH) and by telephone (303-499-7111). Time signals (and related information) are also available from the United States Naval Observatory at Web site http://tycho.usno.navy.mil/time.html. (To set a clock extremely accurately at your particular location, you would have to account for the travel time required for these signals to reach you.)

Figure 1-2 shows variations in the length of one day on Earth over a 4-year period, as determined by comparison with a cesium (atomic) clock. Because the variation displayed by Fig. 1-2 is seasonal and

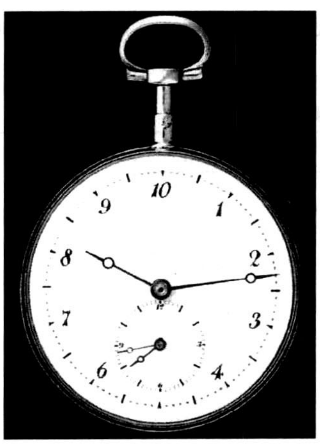

Fig. 1-1 When the metric system was proposed in 1792, the hour was redefined to provide a 10-hour day. The idea did not catch on. The maker of this 10-hour watch wisely provided a small dial that kept conventional 12-hour time. Do the two dials indicate the same time?

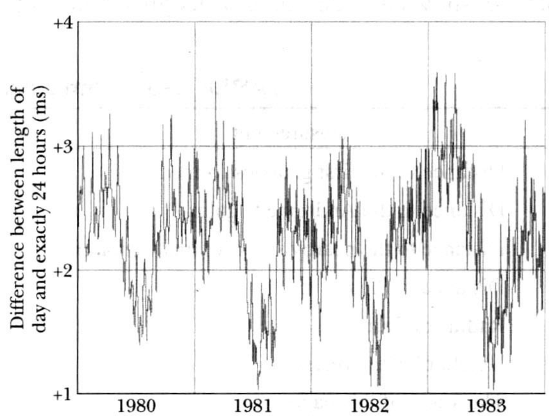

Fig. 1-2 Variations in the length of the day over a 4-year period. Note that the entire vertical scale amounts to only 3 ms (= 0.003 s).

repetitious, we suspect the rotating Earth when there is a difference between Earth and atom as timekeepers. The variation is due to tidal effects caused by the Moon and to large-scale winds.

The 13th General Conference on Weights and Measures in 1967 adopted a standard second based on the cesium clock:

One second is the time taken by 9 192 631 770 oscillations of the light (of a specified wavelength) emitted by a cesium-133 atom.

Atomic clocks are so consistent that, in principle, two cesium clocks would have to run for 6000 years before their readings would differ by more than 1 s. Even such accuracy pales in comparison with that of clocks currently being developed; their precision may be 1 part in 10^{18}—that is, 1 s in 1×10^{18} s (which is about 3×10^{10} y).

Sample Problem 1-1

The ghostly clouds in this chapter's opening photograph first appeared following the huge 1883 volcanic explosion of Krakatoa Island (near Java in the southeast Pacific). The explosion was so violent that it hurled dust to the *mesosphere*, a cool portion of the atmosphere located well above the stratosphere. There water collected and froze on the dust to form the particles that made the first of these clouds. Since then, the clouds have frequently reappeared not because of volcanic explosio ns but because of the increased production of methane by industries, rice paddies, landfills, and livestock flatulence. The methane works its way into the upper atmosphere and undergoes chemical changes, resulting in an increase of water molecules and the bits of ice needed for the formation of the mesospheric clouds, as they are now called.

The mesospheric clouds are visible after sunset because they are in the upper portion of the atmosphere that is still illuminated by sunlight. They are not visible earlier in the day in spite of their illumination because the lower atmosphere is then too brightly lit for them to be distinguished. If the clouds are spotted overhead 38 min after sunset and then quickly dim, what is their altitude H?

Solution: Figure 1-3 shows the situation for the observer, who is at point A on Earth's surface, below the mesospheric clouds at altitude H. A **Key Idea** is that at sunset, the last sunlight reaching the observer follows a path that is tangent to Earth's surface at point A. A second **Key Idea** is that the last sunlight reaching the mesospheric clouds above the observer follows a path that is tangent to Earth's surface at point B. This occurs at time $t = 38$ min after sunset.

From Fig. 1-3, the angle between these two paths is θ, the angle through which the Sun appears to move about Earth during the 38 min. During a full day, which is approximately 24 h, the Sun appears to move through an angle of 360°. Thus, in time $t = 38$ min, the Sun appears to move through an angle

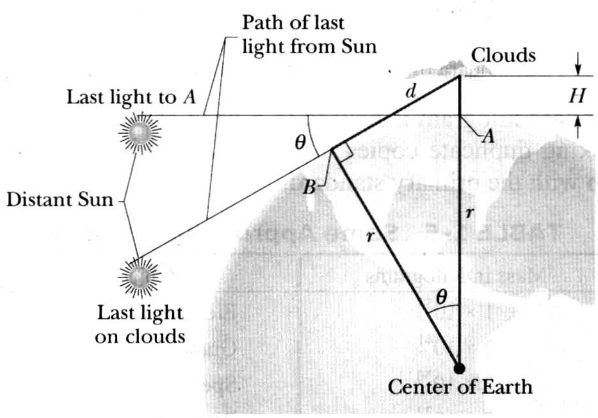

Fig. 1-3 The last sunlight reaching an observer at point A occurs at sunset. The last sunlight reaching clouds at height H above the observer occurs later, after the Sun appears to rotate through an angle θ. Height H and angle θ are exaggerated for clarity.

$$\theta = (38\text{ min})\left(\frac{1\text{ h}}{60\text{ min}}\right)\left(\frac{360^\circ}{24\text{ h}}\right) = 9.50^\circ.$$

From Fig. 1-3, this angle θ is also the angle between the Earth radii r to the two tangent points A and B. The figure shows a right triangle: one leg is r and the hypotenuse is $r + H$. Using the definition of the cosine function from trigonometry, we can write

$$\cos\theta = \frac{r}{r+H}. \qquad (1\text{-}7)$$

From Appendix C, the (mean) radius of Earth is $r = 6.37 \times 10^6$ m. Substituting this and $\theta = 9.50°$ into Eq. 1-7, we have

$$\cos 9.50^\circ = \frac{6.37\times10^6\text{ m}}{(6.37\times10^6\text{ m}) + H},$$

which gives us

$$H = 8.86 \times 10^4 \text{ m} \approx 89 \text{ km}. \quad \text{(Answer)}$$

The more frequent occurrence of the clouds in recent decades indicates that methane production on Earth's surface is changing even the mesosphere.

1-7 Mass

The Standard Kilogram

The SI standard of mass is a platinum–iridium cylinder (Fig. 1-4) kept at the International Bureau of Weights and Measures near Paris and assigned, by international agreement, a mass of 1 kilogram. Accurate copies have been sent to standardizing laboratories in other countries, and the masses of other bodies can be determined by balancing them against a copy. Table 1-5 shows some masses expressed in kilograms, ranging over about 83 orders of magnitude.

Fig.1-4 The international 1 kg standard of mass, a platinum–iridium cylinder 3.9 cm in height and in diameter.

The U.S. copy of the standard kilogram is housed in a vault at NIST. It is removed, no more than once a year, for the purpose of checking duplicate copies that are used elsewhere. Since 1889, it has been taken to France twice for recomparison with the primary standard.

TABLE 1-5 Some Approximate Masses

Object	Mass in Kilograms	Object	Mass in Kilograms
Known universe	1×10^{53}	Elephant	5×10^{3}
Our galaxy	2×10^{41}	Grape	3×10^{-3}
Sun	2×10^{30}	Speck of dust	7×10^{-10}
Moon	7×10^{22}	Penicillin molecule	5×10^{-17}
Asteroid Eros	5×10^{15}	Uranium atom	4×10^{-25}
Small mountain	1×10^{12}	Proton	2×10^{-27}
Ocean liner	7×10^{7}	Electron	9×10^{-31}

A Second Mass Standard

The masses of atoms can be compared with one another more precisely than they can be compared with the standard kilogram. For this reason, we have a second mass standard. It is the carbon-12 atom, which, by international agreement, has been assigned a mass of 12 **atomic mass units** (u). The relation between the two units is

$$1 \text{ u} = 1.66\,054\,02 \times 10^{-27} \text{ kg}, \quad (1\text{-}8)$$