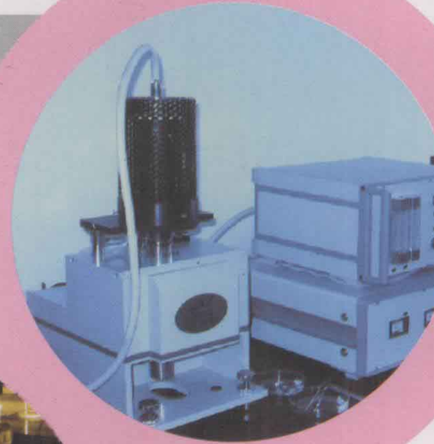
西南交通大学323实验室工程系列教材

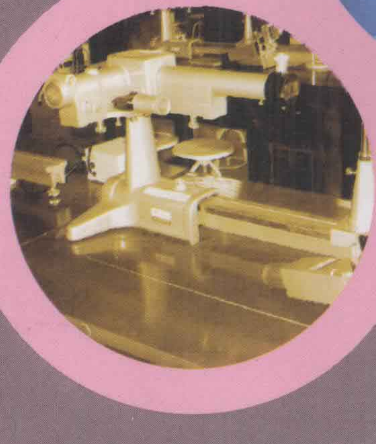
大学物理实验
双语教程

主编 邱春蓉 黄整

主审 姜向东
西南交通大学实验室及设备管理处

Bilingual Course for University Physics Experiments





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前　言

大学物理实验课程是理工科学生重要的基础实验课程之一，是必修的一门系统全面、独立设置的实践性基础实验课，同时也是通过实践学习物理知识的一个过程。随着国际交流日益频繁，培养既精通专业业务，又能熟练运用英语交流的综合性科技人才显得相当紧迫，外语教育直接关系到我国的综合国力、国际竞争力的提高以及“社会生产力跨越式发展”的战略目标的实现。不仅如此，学生从事科研工作、获取信息、出国深造都离不开高超的英语水平，所以，精通英语已经成为学生未来发展的重要素质。近几年，国内各大高校大力提倡双语教学，但是物理实验的双语教材并不多见，我们为此编写了这本能满足物理实验教学需要的教材。

本书主要分为两大部分：第一部分为理论，包括误差理论、常用仪器简介和数据处理，介绍了误差理论、测量结果的评定、不确定度的概念及计算，常用物理实验仪器和基本数据处理的方法；第二部分为具体实验介绍部分，共编入 19 个实验，包括基础实验、设计性实验和综合性实验，涉及力学、热学、光学和电学。

本书是在物理实验中心建设和实验教学经验积累的基础上完成的，汇集了集体的智慧和劳动。本书的编写离不开物理实验中心广大教师的大力支持，也参考了国内外高校的许多大学物理实验教材，并由姜向东教授、西南交通大学实验室及设备管理处审核全书。

本书是西南交通大学物理实验国家示范中心建设支持项目之一，得到了学校教务处“双语教学研究基金”和教材建设研究基金的大力支持。在本书的编写过程中，编者得到了盛克敏、靳藩、杨儒贵教授和陈桔高工的许多建设性意见和帮助，还得到姜向东、冯振勇、陈汉军、朱宏娜等老师的大力支持，在此表示感谢！

本书由西南交通大学物理实验中心邱春蓉老师和黄整老师编写。由于编者水平有限，书中难免有错漏、不妥之处，恳请读者不吝赐教。

编　者

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Part Ⅱ Experiments

PART I

ERROR THEORY AND DATA PROCESS

1 Fundament of Error Theory

1.1 Basic Concept of Measurement

Measurement plays a fundamental role in our modern world. In commerce, goods are priced by volume, mass, or something length or area; services such as transportation are billed according to quantity of material as well as according to the distance it is transported. In commercial transactions, errors in measurement have a direct bearing on profits and costs.

In the engineering technologies, every project begins and ends with measurements. The design of a highway or skyscraper starts with a survey; the design of a power transformer starts with measurement of the electrical and magnetic properties of the wire, the insulation, and the magnet core. The final product must then be tested to see if it actually measures up to its theoretical performance.

Mathematics is a scheme for dealing with numbers and with functions, or sets of numbers. This scheme tells us how to operate on numbers to get new numbers, and how to operate on functions to get new functions. But mathematics itself does not tell us what these numbers or functions mean, as far as anything physical is concerned.

Numbers and mathematical functions acquire physical meaning only when engineers and scientists become involved. Their job is to find ways of expressing properties of the real world in numerical form. Only then does mathematics become a practical tool.

Measurement is a process of comparison. Measurement is determination of the magnitude of a quantity by comparison with a standard for that quantity. Quantities frequently measured include time, length, area, volume, pressure, mass, force, and energy. To express a measurement, there must be a basic unit of the quantity involved, e.g., the inch (1 in = 2.54 cm) or second, and a standard of measurement (instrument) calibrated in such units, e.g., a ruler or clock. Had we compared the radio tower's height to something we call a "yard", the result of the measurement would have been 99 instead of 297. Had we compared it to something we call a "meter", the result would have been 90.5. Had we use inch, the measurement's numerical result would have been 3 560.

According to the differences of the measurement methods, measurement can be divided into measurement directly and indirectly. Generally, measurement directly is a process of determination of the magnitude of a quantity by comparison with a standard, for example, measure length with rule, measure time with time stop, measure current with ammeter. Measurement indirectly is a process of determination of the magnitude of a quantity through calculating with formula, for example, measure a volume of a ball with known its diameter, measure a resistor value with known current and voltage.

According to the differences of the measurement conditions, measurement can be divided into measurement with formal and uniform precision. If each measurement was done with the same measurement condition, the measurement is called formal precision measurement. If one or part of measurement conditions is changed in a set of measurement trials, it is uniform precision measurement. Generally, uniform precision measurement should be avoided.

Obviously, it is just as important to specify the thing we are comparing with as it is to quote the number itself. This is why we say that the numbers by themselves are meaningless. In the technologies, it is absolutely essential that we have a **unit** associated with each number we use. You will notice that units are specified for all numbers through this book.

We will use many different kinds of units: for example, units of distance (inches, centimeters, feet, yards, meters, kilometers, miles, and so on) and units of time (milliseconds, seconds, minutes, hours, days, years, etc.). In addition, we use combinations of units, or compound units, for some quantities: speed, for instance, may be expressed in feet per second, kilometers per hour, miles per hour, or any of a number of other combinations. And every time we make a measurement, we are comparing the known size of one of these units with the size of the quantity we are measuring. Even if a comparison must be made indirectly, it is still a comparison. It is important to keep this point in mind whenever undertaking measurements.

In 1960, 36 nations signed a treaty and created an international system of units. The entire system is officially called "Le système International d'Unités" (SI), and is called the **International System** in English-speaking countries. The SI is essentially the same as what we have come to know as the **metric system**.

Table Ⅰ.1.1 lists the seven **SI base units**. The SI base units are the official international units for the seven different kinds of physical quantities that can be measured. We can measure length, which includes width, height, thickness, distance, and so on. We can measure time, which is fundamentally different. We can measure mass, electric current, temperature, luminous intensity, and amount of substance. We can measure quantities that are combinations of some of these fundamental seven, but no one has ever encountered a measurement that cannot be referred to these seven fundamental quantities and their base units.

Table Ⅰ.1.1 The SI Base Units

Quantity	Unit
length	meter (m)
time	second (s)
mass	kilogram (kg)
electric current	ampere (A)
temperature	kelvin (K)
luminous intensity	candela (cd)
amount of substance	mole (mol)

Of course, we use many units other than the base units listed in Table I .1.1. There are many other such **defined units**. Defined units are not part of the International System. Rather they have been related to the corresponding SI units through numerical definitions.

Units that can be expressed as combinations of the SI base units are called compound units or derived units. **Compound**, or **derived units** are units for all quantities other than length, time, mass, electric current, temperature, luminous intensity, and amount of substance. In the International System (SI), all such units can be expressed as a combination of some of the base units. The derived units of the International System are listed in Appendix Table I .

1.2 Basic Concept of Measurement Error

What we have to do is examine how wrong we can allow them to be. And instead of calling them wrong, we will talk about the **measurement error** (测量误差), and how big this error is likely to be.

Measurement error is the difference between a computed or measured value and a true value (真值).

Notice that we are now using the word "error" in a very special, technical sense. In the sciences and technologies, an error is not the same thing as a mistake. Mistakes can be avoided, or at least corrected. But errors in measurement can never be eliminated completely. The best we can do is to try to keep the errors small enough that the result can still be used for its intended purposes.

First, we have to understand "true value" of an object in nature.

True value is consistent with the definition of a given particular quantity. The value would be obtained by a perfect measurement or by nature indeterminate. Since we can never know the value of any physical quantity unless we measure it, and since no measurement is absolutely accurate, it follows that we can never know the "true value" of any physical quantity. This is why "true value" is enclosed in quotation marks. When we make a measurement, we usually assume that there is such a thing as a true value, yet at the same time we recognize that we will never know exactly what this "true value" is. This severely limits the usefulness of our definition of measurement error, for it means we can never calculate exactly what our measurement error is. So, we can substitute "true value" with "conventional true value". A **conventional true value** (约定真值) is the value attributed to a particular quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose. Conventional true value is sometimes called "assigned value" or "target value". In measurement, theoretically value, empirical value(经验值) and average measurement value would be taken as conventional true value. Accordingly, the difference between a computed or measured value and a conventional true value is called as bias (偏差).

We can now make a distinction between two basic types of measurement errors—systematic error (系统误差) and random error (随机误差). We need to make this distinction because these errors are handled in different ways. A systematic error remains the same change throughout a set of measurement trials. A random error varies from trial to trial and is equally likely to be positive or negative.

Of the two types, systematic errors are usually the more difficult to detect and account for. Systematic errors generally originate in one of two ways:

(1) Errors of calibration. If the measuring instrument is not brought into precise agreement with a standard, or if the standard itself is not a faithful reproduction of a primary standard, then all readings from the instrument will be affected in the same way, giving rise to a systematic error. For instance, any measurement of a time interval on a clock that gains time will be too large.

(2) Errors of use. If the instrument is not used under conditions identical to those prevailing when it was calibrated, that change of conditions may affect the way the instrument responds to the quantity being measured. Again, all the measurements in a set of trials will be affected in the same way, and the error is systematic. For instance, if a steel tape measure was calibrated at temperature of 20 °C but is being used at a temperature of -10 °C, thermal contraction causes all the measurements to come out slightly too high.

Once we know that a systematic error exists in a measurement, we can often figure how to eliminate it, or at least how to make it small enough to neglect. Of course, discovering a systematic error is not always easy, so it is wise to be on guard against them constantly.

What can be done to minimize systematic errors? First, it's important to fully understand the instrument and the physics of its operation. We should know how the instrument's accuracy is likely to be affected by temperature, humidity, and barometric pressure. We should know exactly how to calibrate the instrument, and how often the instrument usually needs to be recalibrated. If the instrument was last calibrated under conditions different from those that currently prevail, we may have to perform a recalibration on the spot. If a recalibration is not practical, we may have to correct our readings mathematically.

Since the range of instruments is so enormous, it is often necessary to evaluate systematic errors on many instruments we have never encountered in formal training. To do so, we have to rely on the manufacturer's operating manuals. We also need to have a reasonable understanding of basic physics, or else we can never judge which factors are likely to affect the equipment's operation.

With systematic errors, we can sometimes (but not always) make a correction to the measurement based on this estimate. The following example shows one way to do so.

Example: Thermal contraction of a tape measure A 30-metre steel tape measure is designed for use at a temperature of 20.0 °C. Suppose that we need to use the tape outdoors when the temperature is only -9.0 °C. Since the steel tape will contract in the cold, we expect a systematic error to result. And because the scale divisions are getting closer together, we expect the measured results to be too high.

How much contraction is there? The handbooks tell us that steel contracts by 11 millionths of its length for each 1 °C drop in temperature. We have a total temperature drop of 29 °C, so the total fractional contraction is

$$(29)(11\times10^{-6})=319\times10^{-6}$$

where the notation 10^{-6} represents one one-millionth.

We can now calculate the total contraction in centimeters:

$$(319\times10^{-6})(30\ \text{m})\left(\frac{100\ \text{cm}}{1\ \text{m}}\right)=0.96\ \text{cm}$$

This would be the systematic error for each 30-metre measurement, if we neglected the contraction due to temperature.

If we have reason to believe that this is the only systematic error, we can easily correct our measurements by subtracting this 0.96 centimeters for each measured 30 meters. In other words, once we have taken the time to figure out how large our systematic error is, we no longer need to have the error.

Correction for systematic error is an essential part of many measurement procedures. The following story is a good illustration. An engineer who was working on carburetor improvements used a dynamometer to measure an engine's power output. He then removed the carburetor, made some changes at the machine shop, then a few days later reinstalled the carburetor and repeated the power measurement. To his horror, he found that the power output had dropped by 10 horsepower. The measurement, however, was susceptible to systematic error due to changes in atmospheric conditions, mainly barometric pressure. When the engineer corrected mathematically for these effects, he found that the engine's power output had actually increased by some 25 horsepower, if he had not made the correction, he would have concluded that his carburetor alteration had hurt the engine's power rather than helped it.

Random errors, however, are another story. We classify errors that are not deterministic and that may affect each data point in the experiment in a different way as random errors. These may result from finite instrument precision and from intrinsic or external "noise". Errors of this type may be reduced by optimizing the experimental setup or averaging large number of repeated measurements, but can never be completely eliminated. Although their origin may also be very subtle, we at least have ways of dealing with them mathematically. In most measurements, only random errors will contribute to estimates of probable error.

Random errors arise because of either uncontrolled variables or specimen variations.

(1) Uncontrolled variables. These variables are minor fluctuations in environmental or operating conditions that cause the instrument to respond differently from one measurement trial to the next.

(2) Specimen variations. If the measurement trial are being made on a number of presumably "identical" samples, minor differences in chemistry, physical structure, optical properties, etc., between one measurement specimen and another, will give rise to random errors.

Earlier it was suggested that random errors lead to a limit in the precision of a measurement. It was also mentioned that the effects of random errors may be reduced by repeating an experiment many tomes and averaging the results. Understanding how this happens requires some discussion of "Gaussian distribution of errors".

The Galton board, also known as a quincunx or beam machine, is a device for statistical experiments named after English scientist Sir Francis Galton (see Figure I .1.1). It consists of an upright board with evenly spaced nails (or pegs) driven into its upper half, where the nails are arranged in staggered order, and a lower half divided into a number of evenly-spaced rectangular slots. The front of the device is covered with a glass cover to allow viewing of both nails and slots. In the middle of the upper edge, there is a funnel into which balls can be poured, where the diameter of the balls must be much smaller than the distance between the nails. The funnel is located precisely above the central nail of the second row so that each ball, if perfectly centered, would fall vertically and directly onto the uppermost point of this nail's surface. The figure above shows a variant of the board in which only the nails that can potentially be hit by a ball dropped from the funnel are included, leading to a triangular array instead of a rectangular one.

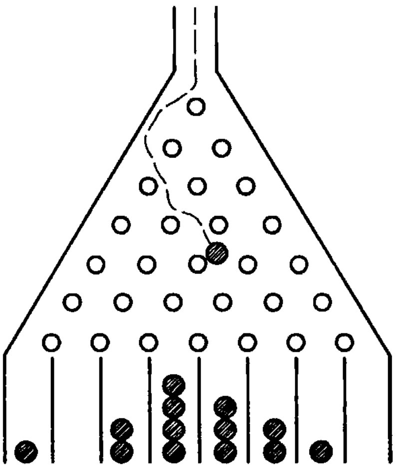

Figure I .1.1 Galton Board Experiment

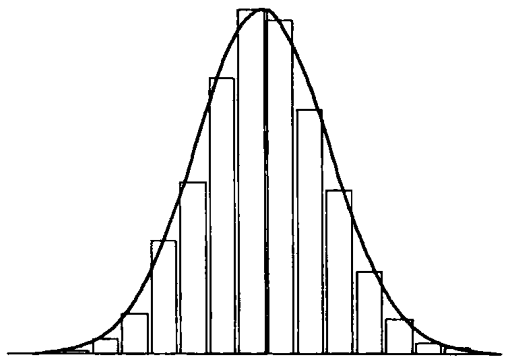

Figure I .1.2 Normal Distribution

If the number of balls is sufficiently large, then the distribution of the heights of the ball heaps will approximate a normal distribution.

A normal distribution in a variant x with the mean $\bar{x}$ and the standard deviation σ is a statistic distribution with probability density function.

$$P(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} \qquad (\text{I}.1.1)$$

on the domain $x\in(-\infty, \infty)$ (see Figure I .1.2). While statisticians and mathematicians uniformly use the term "normal distribution" for this distribution, physicists sometimes call it a Gaussian distribution. The Gaussian distribution usually arises because of many smaller effects coming together to form one overall error distribution.

From Figure I .1.3, we can know the properties of the normal distribution. ① The curve is bell shape, which has perfect bilateral symmetry — the left balances exactly with the right. ② It is the mean because it is the arithmetic average of all the data. The expected value is the mean. ③ The area under the curve is equal to 1, in other words, the sum of the probabilities of all events is 1. ④ The standard deviation tells one how the data are spread out and therefore the fatness or skinniness of the bell. ⑤ the probability within 1 standard deviation of the mean is 68.3% ; the probability within 2 standard deviation of the mean is 95.4%; the probability within 3 standard deviation of the mean is 99.7%.

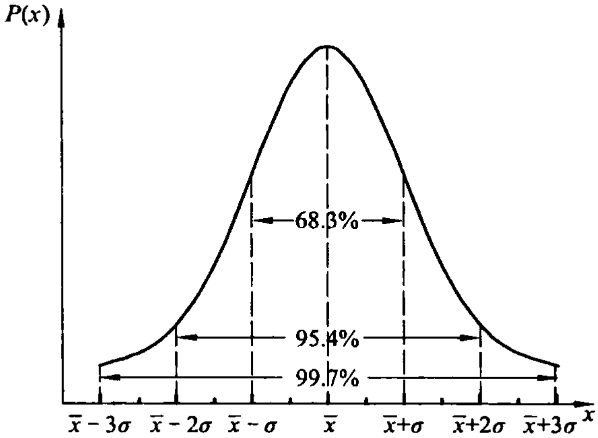

Figure I .1.3 Normal Distribution and Properties

It is customary to assign the error associated with a single measurement to be $\pm\sigma$ with a probability of 68.3%. If you make N measurements then you may say:

$$\text{Mean or average: } \bar{x}=\frac{1}{N}\sum_{i=1}^{N}x_i \qquad (\text{I .1.2})$$

$$\text{Standard deviation: } \sigma=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i-\bar{x})^2} \qquad (\text{I .1.3})$$

$$\text{Standard deviation of the mean: } \frac{\sigma}{\sqrt{N}} \qquad (\text{I .1.4})$$

Example: we are measuring the boiling point of a certain liquid. We properly calibrate our instruments, then make a series of temperature readings. As shown in table I .1.2, the measurements actually vary from one trial to the next despite all our care and accuracy.

Table I .1.2 Results of a Boiling Point Measurement Affected by Small Fluctuations in Uncontrolled Variables

Trial	Boiling Point/°C
1	317.51
2	317.72
3	317.22
4	317.93
5	317.02
6	317.83

The mean or average value was

$$\bar{T}=\frac{1}{N}\sum_{i=1}^{N}T_i=\frac{1\,905.23}{6}=317.538$$

The sum of the algebraic differences between the mean $\bar{T}$ and each T_i are of course zero by definition of the mean. The standard deviation was

$$\sigma=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(T_i-\bar{T})^2}=\sqrt{\frac{0.642\ 3}{5}}=0.358\ 4$$

1.3 Instrument Error

Instrument error refers to the combined accuracy and precision of a measuring instrument, or the difference between the actual value and the value indicated by the instrument (error). Measuring instruments are usually calibrated on some regular frequency against a standard. The most rigorous standard is one maintained by a standards organization such as NIST in the United States, or the ISO in European countries. However, in physics—precision, accuracy, and error are computed based upon the instrument and the measurement data. Precision is to 1/2 of the granularity of the instrument's measurement capability. Precision is limited to the number of significant digits of measuring capability of the coarsest instrument or constant in a sequence of measurements and computations. Error is +/− the granularity of the instrument's measurement capability. Error magnitudes are also added together when making multiple measurements for calculating a certain quantity. When making a calculation from a measurement to a specific number of significant digits, rounding (if needed) must be done properly. Accuracy might be determined by making multiple measurements of the same thing with the same instrument, and then calculating the result with a certain type of math function, or it might mean for example, a five pound weight could be measured on a scale and then the difference between five pounds and the measured weight could be the accuracy. The second definition makes accuracy related to calibration, while the first definition does not.

1. *Instruments of Measuring Length*

General tools used to measure length include rule, caliper, micrometer screw gauge, tape, and so on. Main parameters and the greatest possible errors of the tools are shown in Table Ⅰ.1.3.

Table Ⅰ.1.3 Main Parameters and the Greatest Possible Errors of the Measuring Length Tools

Instrument	Scale	Division	The Greatest Possible Error
Rule	150 mm	1 mm	±0.10 mm
	500 mm	1 mm	±0.15 mm
	1 000 mm	1 mm	±0.20 mm
Tape	1 m	1 mm	±0.8 mm
	2 m	1 mm	±1.2 mm
Caliper	125 mm	0.02 mm	±0.02 mm
		0.05 mm	±0.05 mm
Micrometer Screw Gauge	0～5 mm	0.01 mm	±0.000 4 mm

2. *Balance* (Table Ⅰ.1.4 and Ⅰ.1.5)

Table Ⅰ.1.4 Precision and the Greatest Possible Errors of the Balance

Precision	1	2	3	4	5
The Greatest Possible Errors	1×10^{-7}	2×10^{-7}	5×10^{-7}	1×10^{-6}	2×10^{-6}
Precision	6	7	8	9	10
The Greatest Possible Errors	5×10^{-6}	1×10^{-5}	2×10^{-5}	5×10^{-5}	1×10^{-4}

Table Ⅰ.1.5 Main Parameters and the Greatest Possible Errors of the Balance

Instrument	Scale	Division	The Greatest Possible Error
4 ~ 10 Balance	500 g	0.05 g	0.08 g for scale
			0.06 g for 1/2 scale
			0.04 g for 1/3 scale
1 ~ 3 Balance	200 g	0.1 mg	1.3 mg for scale
			1.0 mg for 1/2 scale
			0.7 mg for 1/3 scale

3. *Instruments of Measuring Time*

Mechanical stop watch, quartz electric watch and digit millisecond watch are often used to record time. In physic experiment, the maximum permitted errors of the stop watch and quartz electric watch are always 0.01 s. The maximum permitted errors of the digit millisecond watch is 1 ms.

4. *Instruments of Measuring Temperature*

General instruments of measuring temperature in laboratory have mercury thermometer, thermocouple and resistance thermometer. Main parameters and the greatest possible errors of the instruments are shown in Table Ⅰ.1.6.

Table Ⅰ.1.6 Main Parameters and the Greatest Possible Errors of the Instruments of Measuring Temperature

Instrument	Scale	The Greatest Possible Error
Laboratory Mercury Thermometer	− 30 ~ 300 °C	0.05 °C
Standard Mercury Thermometer	0 ~ 100 °C	0.01 °C
Industry Mercury Thermometer	0 ~ 150 °C	0.5 °C
Standard PtRh-Pt Thermocouple	600 ~ 1 300 °C	0.1 °C
Industry PtRh-Pt Thermocouple	600 ~ 1 300 °C	0.3% ± Temperature