



FUNDAMENTALS OF TECHNOLOGY



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 EDITION

BY CHENXU YU & THOMAS BRUMM

Fundamentals of Technology

FIRST EDITION

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FOREWORD

Generally, professors don't sit around thinking about the books they can write—textbook writing is not very lucrative. Often, there are adequate textbooks available for the classes they teach. Certainly that is the case for many subjects in engineering and technology. Yet for a fundamentals class in general technology, there was no appropriate textbook to be found. Clearly there was a need for us to create something—for teachers, as a repository of our teaching material, and for students, as reference material for the topics covered in such a class. Left with no other option, this textbook is the result of our desire to have education materials that are a bit more lasting and formal than a bunch of pdf files of our class notes from the 10+ years we have been teaching this course.

Originally intended to be comprehensive and complete, we realize that this first edition is just a start and expect revisions and improvements in later editions, especially with feedback from students. No first effort is perfect. Every effort, however, creates something that didn't previously exist, such as this textbook for teaching the fundamentals of technology. Similarly, we hope you find such satisfaction in your careers – creating something of value that didn't previously exist.

Chenxu Yu
Tom Brumm
June, 2015

1

SCIENTIFIC MEASUREMENTS AND SIGNIFICANT FIGURES

OBJECTIVES

When you complete your study of this chapter, you will be able to:

1. Define the nature of two types of numbers, and determine the number of significant figures in a scientific measurement
2. Define accuracy, precision and uncertainty in measurements
3. Define systematic and random errors, and explain how they occur in measurements
4. Perform proper rounding technique, and use scientific notation to represent numerical values
5. Perform numerical calculation with measured quantities, and express the results with the appropriate number of significant figures

1.1 Introduction

No knowledge or understanding of a given technological problem will be of much value unless it can be expressed in a quantitative manner. Quantitative description of anything requires the use of numbers. In this chapter, we will discuss several features of numbers, and computational techniques to use with numbers. We will also discuss how to properly express numerical information obtained through measurements.

1.2 Numbers and Significant Figures

Jobs in technology use two types of numbers: exact and approximate. There are only two ways to obtain an exact number, either by counting or by definition. The first is easy to understand, as counting will yield an integer, which tells the counter the exact numerical value of a quantity. For example, if a worker counted 102 parts that were manufactured in a workshop in one day, he would have exactly 102 parts. An extension to counting is ratio. Ratios are exact numbers because $\frac{2}{5}$ of a circle is exactly $\frac{2}{5}$ of a circle. However, ratios expressed as a decimal, say, $\frac{2}{3} = 0.6666667$, are approximate numbers because some ratios expressed as a decimal contain repeating digits, and rounding was used to cut off the digits at a certain point. The second way to yield an exact number, by definition, needs some explanation. Here it usually refers to unit conversion factors, or some physical and mathematical constants. For example, in converting inches to centimeters, we use a unit conversion factor of $1 \text{ in} = 2.54 \text{ cm}$, or 2.54 cm/in . Here the number 2.54 is not an integer, but it can be considered as an exact number because it arises from the definition of a unit conversion. Another example is gravitational acceleration, g . A typical standard value for g is 9.80665 m/s^2 . Although this value is obtained through scientific measurement, in most practical applications it could be treated as a physical constant, hence as an exact number. Another example is π , which is an infinite irrational number, $3.14159265\dots$. In all practical purposes, we usually use 3.14 for the value of π . Although this is an approximate value, we may treat it as an exact number since it comes from a mathematical constant.

Any number obtained by a measurement is an approximate number. The actual value of an approximate number is uncertain, because all measuring devices have a limit to their precision, and errors of measurement are likely to be present regardless of the precautions used when making the measurement. The approximate nature of a measurement is well represented in Figure 1.1, showing a measurement being conducted to determine the length of a metal bar, with a scale graduated in $\frac{1}{8}$ of an inch, or 0.125 inch. The scale hence is only accurate to the nearest $\frac{1}{8}$ inch. At the first glance it is obvious that the bar is over 2 inches in length. With a closer look, it is revealed that the length of the bar is not aligned with any of the marks on the scale. It is between $2\frac{1}{4}$ inches and $2\frac{3}{8}$ inches in length. You may record the length of the bar as a value between $2\frac{1}{4}$ and $2\frac{3}{8}$ inches. Here

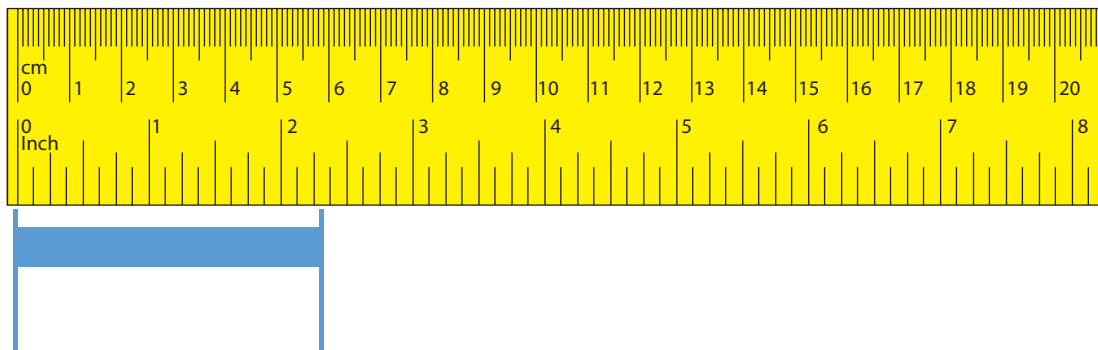


Figure 1.1: Example of an Approximate Measurement Yielding an Approximate Number

you need to use your best judgment to come up with the best estimation. Hence, our measurement must be considered approximate, and the result is an approximate number, for example, 2.32 inches.

For approximate numbers, we need a method to convey how “good” these numbers are in terms of determining how “good” the measurements are. The use of significant figures hence is introduced into science and technology to give us this capability. The significant figures are the digits in an approximate number that accurately reflect the result of a measurement. As a rule of thumb, for any measured number, as illustrated in the above example, the last digit of it is NOT accurate, as it is produced through an estimation. The number reported above, 2.32 inches, is accurate at the first digit after the decimal (i.e., 3), and the last digit, 2, is an estimation only. In an approximate number, the last significant digit is always an estimation. In the above example, the number 2.32 inches has three significant figures, or digits, and the last one of them, 2, is an estimation.

Digits can be introduced into a calculation that is not accurate (i.e., significant), and negatively impact the accuracy of the answer. This is particularly problematic when a calculator is used. Most calculators show eight or nine digits automatically, regardless of their significance. It is up to the calculator operator to determine how many digits are significant and to round accordingly.

The principle of significant figures is used to determine the number of digits that should be kept in a number after mathematical calculation. The rules for determining significant figures are different for exact numbers and for approximate numbers.

Because there is no uncertainty with exact numbers, all digits in an exact number are accurate. Besides, they do not convey or transmit any error. Hence, practically we can treat all exact numbers as having infinite significant figures. In other words, when determining significant figures for a calculation involving both exact numbers and approximate numbers, exact numbers need not be considered, because they will always have the most significant figures, and hence are not the limiting factor.

For approximate numbers, a significant figure, or significant digit, is defined as any digit used in writing a number, except those zeros that are used only for indicating location of the decimal point, or those zeros that do not have any nonzero digit on their left. For example, the number 0.0024 has only two significant figures, 2 and 4, because the three zeros do not have any nonzeros to the left, and they are location holders for the decimal point. If the number is written as 0.002400 instead, the number of significant figures will jump to 4, because now the two zeros to the right of 4 are also significant. Similarly, if the number is 1.0024, there are now five significant figures, the two zeros have a nonzero to their left, and they are significant.

Scientific notation, also called standard form, is used to express large or small numbers in a more convenient form. Scientific notation uses powers of ten to replace the nonsignificant digits of a large or small number. Scientific notation uses a whole digit, then a decimal point, and then the rest of the significant figures. For example, if the number 1,000,000 has one significant figure, it is expressed as $1. \times 10^6$; if it has two significant figures, it is expressed as 1.0×10^6 . To use the scientific notation effectively, you must understand the powers of numbers, and how they can be manipulated during mathematical computations.

Table 1.1 shows the power of tens, for both positive and negative powers.

Another convenient way of representing powers of tens is with prefix names. Table 1.2 illustrates powers of tens (as multipliers) and their corresponding prefixes and symbols. The use of prefixes

Table 1.1: A Review of the Powers of Tens

$10^0 = 1$	
$10^1 = 10$	$10^{-1} = 0.1 = 1/10$
$10^2 = 100$	$10^{-2} = 0.01 = 1/100$
$10^3 = 1000$	$10^{-3} = 0.001 = 1/1000$
$10^4 = 10000$	$10^{-4} = 0.0001 = 1/10000$
$10^5 = 100000$	$10^{-5} = 0.00001 = 1/100000$

Table 1.2: Decimal Multipliers and Prefixes

MULTIPLIERS	PREFIX NAME	SYMBOL
10^{18}	Exa	E
10^{15}	Peta	P
10^{12}	Tera	T
10^9	Giga	G
10^6	Mega	M
10^3	Kilo	k
10^2	Hecto	h
10^1	Deka	da
10^{-1}	Deci	d
10^{-2}	Centi	c
10^{-3}	Milli	m
10^{-6}	Micro	μ
10^{-9}	Nano	n
10^{-12}	Pico	p
10^{-15}	Femto	f
10^{-18}	Atto	a

Source: Engineering Fundamentals and Problem Solving, 5th edition, McGraw Hill, New York, 2006

enables us to express any measurement as a number between 0.1 and 1000, with a corresponding prefix applied to the unit. For example, it is clearer for a reader if the distance to the next exit on a highway is expressed as 12 kilometers (12 km), rather than 12,000 meters (12,000 m).

When an instrument such as a scale, an analog thermometer, or a fuel gauge is read, the last digit will normally be an estimate, because the instrument is usually read by estimating between the smallest graduations on the scale to get the final digit. It is standard practice to count the one doubtful digit as significant. Hence, it should be remembered that the last digit in an approximate number obtained by measurement is always an educated guess; it is not accurate, even if it is zero, because zero here means that your best estimate is that the reading matches with a marked graduation perfectly. Of course, there is still room for some small deviation, and that makes the zero an estimate, not an accurate measurement.

Example 1.1: How to determine the number of significant figures

3.10: 3 significant figures, the 0 is the last one

0.001010: 4 significant figures, first three 0s are not significant, they are location holders only

320: 2 significant figures, the 0 here is a location holder to tell us where the decimal point is

320.: 3 significant figures, since the decimal point is shown, the “0” becomes significant

320 tickets: the unit (i.e., ticket) implies that the number 320 is obtained through counting, hence it is an exact number, and has an infinite number of significant figures!

2.54 cm/in: a unit conversion factor is considered as an exact number, hence it has infinite number of significant figures.

Calculators and computers maintain countable numbers (integers) in exact form up to the capacity of the machine. Real numbers are kept at the precision level of the particular device, regardless of how many significant figures an input value or calculated value should have. Therefore, it is the operator’s duty to exercise care when reporting values from a calculator display, or from a computer output.

As you perform arithmetical operations, it is important that you do not lose the significance of your measurements, or, conversely, imply precision that does not exist by artificially increasing the number of significant figures in your final results beyond the justifiable limit. The following rules usually apply when determining the proper number of significant figures.

1. **Rounding:** Rounding is used to eliminate figures that are not significant. If the digits to be rounded are to the left of the decimal point, the digits are replaced by zeros. If the digits are to the right of the decimal point, just drop them. For example, if you need to round $41,580 \text{ ft}^2$ to two significant figures, the answer is $42,000 \text{ ft}^2$. If the digit being dropped is greater than 5, add one to the next digit remaining, as we did in our example. If the digit being dropped is less than 5, the first remaining digit is unchanged. If the digit being dropped is exactly 5, leave the remaining digit even. If the remaining digit is odd, add one; if it is even, leave it as is. For example, the number $41,580 \text{ ft}^2$, if rounded to one significant figure, the answer is $40,000 \text{ ft}^2$; rounded to two it is $42,000 \text{ ft}^2$; and rounded to three, it is $41,600 \text{ ft}^2$.
2. **Multiplication and Division:** The product or quotient should contain the same number of significant figures as are contained in the number with the fewest significant figures.

Example 1.2

a. $2.23 \times 14.324 = 31.94252$

If each number in the product is exact, the answer should be reported as 31.94252. If the numbers are not exact, as is normally the case, 2.23 has three significant figures, and it is less than 14.324 (which has five). Hence, the product cannot have more than three significant figures, and it can be reported as 32.0, or using scientific notation, as 3.2×10^1 .

b. $1.279 \text{ in} \times 2.54 \text{ cm/in} = 3.24866 \text{ cm}$

In this case, the conversion factor is an exact number (a definition), and has infinite significant figures. Hence, the number 1.279 in has fewer significant figures (four), and the answer should be reported as 3.249 cm.

c. $786.23/52.1 = 15.0907869$

The answer, with three significant figures, is 15.1.

3. **Addition and Subtraction:** The answer should show significant figures only, as far to the right as in the least precise number in the calculation. This is because the last digit recorded is doubtful.

Example 1.3

a. 12.6543

3.12

+ 100.1001

115.8743

The least precise number in this group is 3.12, because the 2 is an estimate. According to our rule, the answer should be reported as 115.87.

b. 87.0

-1.654

85.346

Using our rule, the answer should be reported as 85.3.

As we look at these answers, suppose the numbers are all obtained by measurements. Therefore, the last digit in each number is doubtful. The addition or subtraction involving a doubtful digit will only yield a doubtful digit as a result. Therefore, in the first example, after adding the three numbers, since the second digit after the decimal point in 3.12 is doubtful, all digits in the final answer, 115.8743, beyond 7, are all doubtful. We can only keep one doubtful digit in an approximate number. Hence, the answer should be just 115.87. The same argument can be made for the second example, too.

4. **Combined Operations:** In combined operations, when conducted manually, rounding following proper rules should usually be conducted in the intermediate steps. However, when a calculator or computer is used, usually it is not practical to perform intermediate rounding. It is normal practice to perform the entire calculation and then report a reasonable number of significant figures, which usually matches the number with the least significant figures.

Subtraction that occurs in the denominator of a quotient can be particularly problematic when the numbers to be subtracted are very nearly the same. For example, $42.3 / (22.12 - 22.1)$ gives 2115 if intermediate rounding is not done. However, if rounding is used in the intermediate step for the subtraction, the denominator becomes zero, and the result becomes undefined. Common sense must prevail in cases like this to avoid problems.

1.3 Accuracy, Precision and Uncertainty

It is important to understand that accuracy, precision, and uncertainty have different meanings in measurements, and hence they represent different characteristics of numbers obtained through measurements. Accuracy refers to the nearness of a value to the correct or true value;

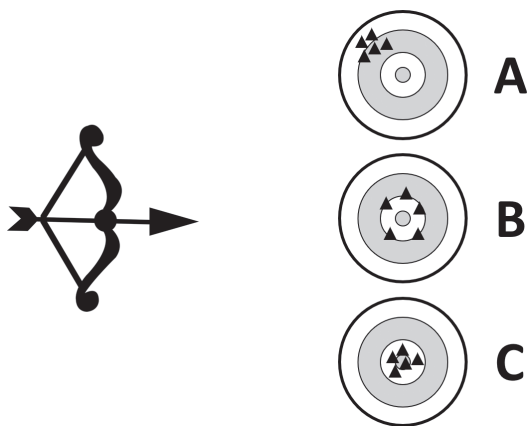


Figure 1.2: Illustration of Difference Between Accuracy and Precision in Measurements

in measurements the accuracy usually is determined by the decimal places of the number obtained. The greater the number of decimal places, the greater the accuracy. A measurement of 12.23 pounds is more accurate than a measurement of 12.2 pounds. It could be derived that an answer that has more significant figures is usually more accurate than an answer that has less.

Precision refers to the repeatability of a measurement—that is, how close successive measurements are to each other. The precision of a measurement is usually determined by the smallest size of unit of the measuring instruments, assuming the measurements are done consistently; hence artificial errors are

minimized between repeated experiments. For example, if a metal piece is being measured for its mass, and two choices of instruments are available: one is a digital scale that has the smallest unit at 0.1 g, and the other is an analytical balance that has the smallest unit at 0.0001 g. The numbers obtained using the latter will be more precise than the numbers obtained using the former.

Figure 1.2 illustrates the difference between accuracy and precision. The results in panel A are precise, because if individual results are close to each other, but they are not accurate, they are all far away from the true value (i.e., the center). The results in panel B are accurate, because each individual result is close to the true value, but they are not precise, because they are far away from each other. The results in panel C are both accurate and precise, and that is what we would want to achieve in any measurement.

Uncertainty refers to the variations in the obtained numbers through measurements. It is closely related to the precision of a measurement. If the uncertainty is not clearly stated after the number, say, 12.6 in ± 0.1 , then you may assume the uncertainty is \pm half of the smallest unit, as shown in Table 1.3.

It can be said that accuracy is dependent on the “correctness” of the instruments, and precision is dependent on the “refinement” of the instruments. Uncertainty is a measure of the precision of numbers obtained through measurements.

1.4 Errors

In any measurement, errors are inevitable no matter how good the instruments are, or how careful you conduct the measurement. There are two types of errors: systematic errors and random errors. Systematic errors can be eliminated and corrected. In contrast, random errors cannot be completely

Table 1.3: Levels of Uncertainty

NUMBER	UNCERTAINTY
25	± 0.5
15.7	± 0.05
2.567	± 0.0005

Source: Theory and Problems of Technical Mathematics. Schaum's Outline Series, McGraw Hill, New York, 1979

eliminated, but they can be minimized, and their impact on the results of measurements can be characterized.

1.4.1 Systematic Errors

Panel A in figure 1.2 displays a good example of systematic errors. All results are biased, and differ significantly from the true value of the measured attribute represented by the center. Sources of systematic error may be imperfect calibration of measurement instruments (i.e., zero error), changes in the environment that interfere with the measurement process, and flawed methods of observation to obtain the results.

For example, consider a worker measuring distance between two locations using a steel tape that is 15 m long. If the steel tape, after being compared to the standard at the U.S. Bureau of Standards in Washington D.C., is found to not be exactly 15.000 m long; rather it is 14.900 m, then there will be a systematic error (-0.100 m) each time the tape is used. Suppose the tape is used 10 times, then the distance reported to be 150 m is actually only 149 m, and that -1.00 m (-0.100 m \times 10 times) is an accumulated systematic error due to the imperfect tape.

Systematic errors may also be present in the result of an estimate based on a mathematical model or physical law. For instance, the estimated oscillation frequency of a pendulum will be systematically in error if slight movement of the support is not accounted for.

Systematic errors usually can be eliminated by applying a correction. In the previous example, if we know that a -0.100 m deviation exists between the tape's value and the true value, we can easily account for that in our measurements. After using the tape 10 times, instead of reporting a 150 m length between the two locations, we can apply the correction of -0.100 m \times 10 = 1.00 m, and hence report a final result of 149 m.

The sources of systematic errors can be many, and they occur in all types of measurements: mechanical quantities, electrical quantities, mass, sound, odors, light intensity, and so on. We must be aware of their existence, eliminate as much as we can, and quantify and correct for those that remain.

1.4.2 Random Errors

Panel B and C in figure 1.2 also showcase random errors. Random errors are errors in measurement that lead to measurable values being inconsistent when repeated measures of an attribute or quantity are taken. The word “random” indicates that they are inherently unpredictable, namely,

they are scattered about the true value. As shown in Panel B and C, the repeated measurements yield values that are different from each other, and different from the true value. The signs of these differences are also random; some of them will be larger than the true value, and some of them will be smaller than the true value. One good thing about random errors is that they tend to cancel each other out when a measurement is repeated several times with the same instrument. All measurements are prone to random error.

Random error is caused by unpredictable fluctuations in the readings of a measurement instrument, or in the experimenter's interpretation of the instrumental reading. Random errors are closely related to the concept of precision. The higher the precision of a measurement instrument, the smaller the variability of the fluctuations in its readings, which will lead to smaller random errors being generated. Random errors cannot be totally eliminated, but they can be significantly reduced by taking multiple measurements using the same instrument and then reporting the average (i.e., mathematical mean) as the measured value.

EXERCISES

1. How many significant figures are contained in each of the following quantities?

QUANTITY	SIG FIGS	QUANTITY	SIG FIGS	QUANTITY	SIG FIGS
4,930 feet		5.220×10^2		0.0030	
4.930		9.009		3,600 seconds/hr	
0.0493 seconds		0.0003		3.2203×10^5	
206.0		50,620 meters		0.00051	
5,280 ft/mile		0.09050		3.22	

2. Perform the following computations and report the answers with the proper number of significant figures.

COMPUTATION	SIG FIGS	RESULT	COMPUTATION	SIG FIGS	RESULT
$(2.05)(360)$			$185.323 + 12.3 + 99.37$		
$(26.35)/(12.03)$			$163/(0.02168 - 0.02166)$		
$[(4.91)(32.2)]/12.03$			$436.2 \text{ miles} / 1.06 \text{ hrs}$		

$$\frac{(4.5976 \times 10^2)}{(7.3 \times 10^{-1})}$$

$$0.009024 +$$

$$0.0653201$$

$$\frac{(4.01 \times 10^3 \text{ sec})}{(3600 \text{ sec/hr})}$$

$$(\$36/\text{ticket})$$

$$(23,850 \text{ tickets})$$

3. Solve the following problems and give the answers rounded to the proper number of significant figures.
 - a. $v = 2.14t^2 + 35.35t + 2.25$ for $t = 3.2$
 - b. $24.56 \text{ ft} \times 12 \text{ in/ft} = ? \text{ inches}$
 - c. $\$400 \text{ a plate} \times 20 \text{ guests} = \$?$
 - d. $V = [\pi(4.62 \text{ cm}^2)(7.53 \text{ cm})]/3 = ? \text{ cm}^3$ (volume of a cone)
 - e. $325.03 - 527.897 + 615 = ?$
 - f. $32¢ \text{ per part} \times 45 \text{ 250 parts} = \$?$
4. Estimate the volume of water used to take showers by the members of this class (67 students) in one academic year. Clearly state your assumptions.
5. Estimate the amount of water used in a one-year period by a family of four who live in a detached house. Determine the cost from local utility rates.
6. A major concern relative to global warming is the amount of carbon dioxide released into the air by transportation vehicles. Is there any truth to the statement that each car in the US emits its own weight in carbon dioxide each year?

Assumptions: The average car in the US gets 20 miles per gallon of gasoline, is driven 12,000 miles per year, and weighs 3,500 pounds. Gasoline weighs 5.9 pounds per gallon and contains 85% carbon by weight. Every 12 lbs of carbon emission is equal to 44 lbs of carbon dioxide emission.

Table and Figure Sources

1. Tbl. 1.2: Arvid Eide, Roland Jenison, Larry Northup, and Steven Mickelson, Engineering Fundamentals and Problem Solving. Copyright © 2006 by McGraw-Hill Education.
2. Fig. 1.2: Source: <https://pixabay.com/en/bow-arrow-drawn-archery-target-311747>.
3. Tbl. 1.3: Paul Calter, Theory and Problems of Technical Mathematics. Copyright © 1979 by McGraw-Hill Education.