Instructions
Read this document (including the attached excerpt from *Thinking Like an Engineer*) and complete the associated quiz on Carmen before coming to class.

Learning Objectives
After completing this preparation and the in-class activities for this topic, the successful student will be able to:

- Understand the importance of collecting high-quality data
- Recognize when a data set contains errors
- Define accuracy, precision, and resolution
- Define systematic variation and random variation
- Identify how systematic variation and random variation might influence data collection
- Choose an appropriate system attribute to measure when given a specific problem statement
- Choose an appropriate measurement tool for the type of measurement that will be collected

Collecting Measured Data
Engineers collect and use measurement data to analyze, create or verify the design of products and processes. The quality of the data that an engineer collects is directly tied to the outcome of his or her project. Because of this, correctly collecting and analyzing measured data are both critical skills for engineers of all disciplines. As engineering students, it is important for you to understand the importance of collecting high quality data and also to understand that there are many possible pitfalls in dealing with measured data. A good engineer should know how to avoid errors in data collection, but errors do happen, so he or she should be able to recognize when measured data has errors or variation.

With any engineering experiment or project, it is important to determine what needs to be measured before taking any measurements. Engineering problems may require careful thought to determine which characteristic is the most important to measure. If an engineer does a really good job measuring a specific system attribute, but it turns out to be the wrong attribute, that data won’t be useful. Typically in engineering projects, multiple measurements are collected because a single measurement rarely provides enough information for the engineers.
**Example: Collecting Measured Data**

A coffee shop chain has received complaints at a number of their stores that their coffee has inconsistent temperature. The manager decides to hire an engineering consultant to determine what is causing this temperature variation. An engineer goes to several stores to take measurements.

Because the engineer is a smart graduate of The Ohio State University, she knows that just one temperature measurement would not be sufficient to perform a proper analysis; in order to fully understand the problem, she must measure the temperatures of many cups of coffee throughout the day.

After collecting the temperature data and creating a graph (below), the engineer notices that during peak selling times the measured temperature is much lower than other times during the day. By collecting multiple measurements throughout the day, the engineer is able to focus attention on the real problem: The machines are not broken, but instead the problem is that the customer demand is too great for the number of machines present.

![Coffee Temperature Data](image.png)

*Figure 1 Coffee Temperature Data*
Measurement Systems

Measured data is collected by people using some type of equipment (like the engineer using a thermometer to measure the temperature of coffee). This combination of humans and instrumentation can be described as a measurement system. Both components are equally important to the measurement system, and in studying measured data it is important to understand both components of the measurement system and their individual effects on the quality of the data that is collected.

When measuring data, there are two important aspects to consider: The expected value and the variation. Thinking of the previous coffee example, this would be coffee machine’s desired temperature vs. the actual temperature that was measured. Even under ideal circumstances when the coffee machine is working correctly, the measured coffee temperature will likely vary slightly from the desired coffee temperature.

Understanding Variation

To understand what creates variation in measured data, we need to understand several terms that relate to variation.

Accuracy

*The extent to which a given measurement agrees with the standard value for that measurement.* [dictionary.com]

Repeatability or Precision

*The extent to which a given set of measurement of the same sample agree with their mean.* [dictionary.com]

![Figure 2: Visual Representation of Accuracy vs. Repeatability](image-url)
Instrument Resolution
The resolution of an instrument is the smallest increment the tool can reliably measure or display. [Important Note: some electronic instruments will display values that are beyond their measurement capability. For example, a cheap bathroom scale may display your weight to the tenth of a pound, but because the scale is cheap it is not built with high-quality instrumentation so it cannot reliably measure to that small of an increment.)

Random Variation
The variability of a process (or measurement) caused by many irregular and erratic fluctuations or chance factors that cannot be anticipated, detected, identified or eliminated. [businessdictionary.com] Random variation can result from using measurement instruments near the limits of their resolution.

Systematic Variation
Systematic Variation usually occurs because there is something wrong with the instrument or its data measurement system, or because the instrument is wrongly used by the experimenter. [www.physics.umd.edu]

Figure 3 Random Variation
Figure 4 Systematic Variation
Engineering Measurements and Estimations

Chapter Objectives

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

- Determine the number of significant digits in a measurement
- Perform numerical calculations with measured quantities and express the answer with the appropriate number of significant digits
- Define accuracy and precision in measurements
- Define systematic and random errors and explain how they occur in measurements
- Solve problems involving approximations in the required data
- Develop and present problem solutions, involving finding or estimating the necessary data, that enable others to understand your method of solution and to determine the validity of the numerical work

4.1 Introduction

The nineteenth-century physicist Lord Kelvin stated that knowledge and understanding are not of high quality unless the information can be expressed in numbers. Numbers are the operating medium for most engineering functions. In order to perform analysis and design, engineers must be able to measure physical quantities and express these measurements in numerical form. Furthermore, engineers must have confidence that the measurements and subsequent calculations and decisions made based on the measurements are reasonable.

In this chapter, we will describe how to properly use measurements (numbers) in engineering calculations. In your specific engineering discipline you will gain experience in selecting the correct measuring device for a particular situation.

4.2 Numbers and Significant Digits

Numbers used for calculation purposes in engineering design and analysis may be integers (exact) or real (exact or approximate). For example, six one-dozen cartons of eggs include a countable number of eggs, exactly 72. There are 2.54 centimeters in one inch, an example of an exact real number. Thus if the
conversion of inches to centimeters is required in a calculation, 2.54 is not a contributing factor to the precision of the result of the calculation. The ratio of the circumference of a circle to its diameter, \( \pi \), is an approximate real number that may be written as 3.14, 3.142, 3.14159, \ldots, depending on the precision required in a numerical calculation.

Any physical measurement that is not a countable number will be approximate. Errors are likely to be present regardless of the precautions used when making the measurement. Let us look at measuring the length of the metal bar in Fig. 4.1 with a scale graduated in tenths of inches. At first glance it is obvious that the bar is between 2 and 3 inches in length. We could write down that the bar is 2.5 ± 0.5 inches. Upon closer inspection we note the bar is between 2.6 and 2.7 inches in length, or 2.65 ± 0.05 inches. What value would we use in a computation? 2.64? 2.65? 2.66? We might select 2.64 as the “best” measurement, realizing that the third digit in our answer is doubtful and therefore our measurement must be considered approximate.

It is clear that a method of expressing results and measurements is needed that will convey how “good” these numbers are. The use of significant digits gives us this capability without resorting to the more rigorous approach of computing an estimated percentage error to be specified with each numerical result or measurement. Before we introduce significant digits, it is necessary to discuss the presentation of numerical values in formats that leave no doubts in interpretation.

The following are accepted conventions for the presentation of numbers in engineering work:

1. For numbers less than one, a zero is written in front of the decimal point to omit any possible errors due to copy processes or careless reading. Therefore, we write 0.345 and not .345.
2. A space, not a comma, is used to divide numbers of three orders of magnitude or more. We write 4,567.8 instead of 4,567.8 and 0.678,91 instead of 0.678,91.
3. For very large or very small numbers we use scientific notation to reduce the unwieldy nature of these numbers. For example, supercomputer calculating rates are compared by using the Linpack benchmark performance criteria. Recently a test on an IBM/DOE supercomputer named BlueGene/L, installed at the Lawrence Livermore National Laboratory in California, was benchmarked at 136,800,000,000 flops/s. The unit
Table 4.1 Decimal Multiples

<table>
<thead>
<tr>
<th>Multiplier</th>
<th>Prefix name</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{18}$</td>
<td>exa</td>
<td>E</td>
</tr>
<tr>
<td>$10^{15}$</td>
<td>peta</td>
<td>P</td>
</tr>
<tr>
<td>$10^{12}$</td>
<td>tera</td>
<td>T</td>
</tr>
<tr>
<td>$10^9$</td>
<td>giga</td>
<td>G</td>
</tr>
<tr>
<td>$10^6$</td>
<td>*mega</td>
<td>M</td>
</tr>
<tr>
<td>$10^3$</td>
<td>*kilo</td>
<td>k</td>
</tr>
<tr>
<td>$10^2$</td>
<td>hecto</td>
<td>h</td>
</tr>
<tr>
<td>$10^1$</td>
<td>deka</td>
<td>da</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>deci</td>
<td>d</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>centi</td>
<td>c</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>*milli</td>
<td>m</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>micro</td>
<td>μ</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>nano</td>
<td>n</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>pico</td>
<td>p</td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>femto</td>
<td>f</td>
</tr>
<tr>
<td>$10^{-18}$</td>
<td>atto</td>
<td>a</td>
</tr>
</tbody>
</table>

*Most often used.

flops/s stands for floating-point operations per second, which is computer terminology for calculations using real numbers. In scientific notation this number would be $136.8 \times 10^{12}$, an obviously more compact representation. We will see that scientific notation is of great assistance in the representation of significant digits.

Another convenient method of representing measurements is with prefix names that denote multipliers by factors of 10. Table 4.1 illustrates decimal multipliers and their corresponding prefixes and symbols. Thus our BlueGene/L computer performance could also be represented as $136.8$ teraflops/s, or $136.8$ Tflops/s. The use of prefixes enables us to express any measurement as a number between 0.1 and 1 000 with a corresponding prefix applied to the unit. For example, it is clearer to the reader if the distance between two cities is expressed as 35 kilometers (35 km) rather than 35 000 meters (35 000 m). More on prefixes may be found in the Chapter 5 discussion of the International System of Units (SI).

A significant digit, or significant figure, is defined as any digit used in writing a number, except those zeros that are used only for location of the decimal point or those zeros that do not have any nonzero digit on their left. When you read the number 0.001 5, only the digits 1 and 5 are significant, since the three zeros have no nonzero digit to their left. We would say this number has two significant figures. If the number is written 0.001 50, it contains three significant figures; the rightmost zero is significant.

Numbers 10 or larger that are not written in scientific notation and that are not counts (exact values) can cause difficulties in interpretation when zeros are present. For example, 2000 could contain one, two, three, or four significant digits; it is not clear which. If you write the number in scientific notation as $2.000 \times 10^3$, then clearly four significant digits are intended. If you want to
show only two significant digits, you would write $2.0 \times 10^3$. It is our recommendation that if uncertainty results from using standard decimal notation, you switch to scientific notation so your reader can clearly understand your intent. Figure 4.2 shows the number of significant figures for several quantities.

You may find yourself as the user of measurements where the writer was not careful to properly show significant figures. What should you do? Assuming that the number is not a count or a known exact value, about all you can do is establish a reasonable number of significant figures based on the context of the measurement and on your experience. Once you have decided on a reasonable number of significant digits, you can then use that number in any calculations that are required (as long as you clearly define for others what significance you have assigned).

When an instrument, such as an engineer’s scale, analog thermometer, or fuel gauge, is read, the last digit will normally be an estimate. That is, the instrument is read by estimating between the smallest graduations on the scale to get the final digit. In Fig. 4.3a, the reading is between 1.2 and 1.3, or 1.25 ± 0.05. For calculation purposes we might select 1.27 as a best value, with the 7 being a doubtful digit of the three significant figures. It is standard practice to
count one doubtful digit as significant, thus the 1.27 reading has three significant figures. Similarly, the thermometer in Fig. 4.3b is noted as $52.5^\circ \pm 0.5$, and we estimate a best value of $52.8^\circ$ with the 8 being doubtful.

In Fig. 4.3c, the graduations create a more difficult task for reading a fuel level. Each graduation is one-sixth of a full tank. The reading is between $1/6$ and $2/6$ full, or $3/12 \pm 1/12$. How many significant figures are there? If we convert the reading to $0.25 \pm 0.0833$, a “best” estimate might be 0.30. In any case you cannot justify more than one significant figure and the answer would be expressed as 0.3. The difficulty in this example is not the significant figures but the scale of the fuel gauge. It is meant to convey a general impression of the fuel level and not a numerically significant value. Therefore, the selection of the instrument is an important factor in physical measurements.

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. This is true no matter how many significant digits an input value or calculated value should have. Therefore, you will need to exercise care in reporting values from a calculator display or from a computer output (a spreadsheet for example). Calculators and most high-level computer languages allow you to control the number of digits that are to be displayed or printed. If a computer output is to be a part of your final presentation, you will need to carefully control the output form. If the output is only an intermediate step, you can round the results to a reasonable number of significant figures in your presentation.

As you perform arithmetic operations, it is important that you not lose the significance of your measurements or, conversely, imply precision that does not exist. Rules for determining the number of significant figures that should be reported following computations have been developed by engineering associations. The following rules customarily apply.

1. **Rounding.** In rounding a value to the proper number of significant figures, increase the last digit retained by 1 if the first figure dropped is 5 or greater. This is the rule normally built into a calculator display control or a control language.

   **Examples**
   
   a. $23.650 \text{ rounds to } 23.7 \text{ for three significant figures.}$
   
   b. $0.0143 \text{ rounds to } 0.014 \text{ for two significant figures.}$
   
   c. $827.48 \text{ rounds to } 827.5 \text{ or } 827 \text{ for four and three significant digits, respectively.}$
   
   *(Note: You must decide the number of significant figures before you round. For example, rounding 827.48 to three significant figures yields 827. However, if you first round to four figures, obtaining 827.5, and then round that number to three figures, the result would be 828—which is not correct.)*

2. **Multiplication and Division.** The product or quotient should contain the same number of significant digits as are contained in the number with the fewest significant digits.

   **Examples**
   
   a. $(2.43)(17.675) = 42.95025$
   
   If each number in the product is exact, the answer should be reported as 42.950 25. If the numbers are not exact, as is normally the case, 2.43 has three
significant figures and 17.675 has five. Applying the rule, the answer should contain three significant figures and be reported as 43.0 or $4.30 \times 10^1$.

b. \( (2.479 \text{ h}) \cdot (60 \text{ min/h}) = 148.74 \text{ min} \)

In this case, the conversion factor is exact (a definition) and could be thought of as having an infinite number of significant figures. Thus, 2.479, which has four significant figures, controls the precision, and the answer is 148.7 min, or $1.487 \times 10^2$ min.

c. \( (4.00 \times 10^2 \text{ kg}) / (2.204 6 \text{ lbm/kg}) = 881.84 \text{ lbm} \)

Here, the conversion factor is not exact, but you should not let the conversion factor dictate the precision of the answer if it can be avoided. You should attempt to maintain the precision of the value being converted; you cannot improve its precision. If you need to maintain precision greater than what is available in the conversion factor, we recommend that you locate or calculate the conversion factor to one or two more significant figures than the value you are converting. For example, the conversion factors given in the appendix of this text contain five significant figures. If you require more for a calculation, you would need to locate a more precise conversion factor from another source or derive the conversion factor and calculate it to the desired number of significant figures. For example (c), three significant figures should be reported, yielding 882 lbm.

d. \( 589.62 / 1.246 = 473.210 27 \)
The answer, to four significant figures, is 473.2.

3. **Addition and Subtraction.** The answer should show significant digits only as far to the right as is seen in the least precise number in the calculation. Remember that the last number recorded is doubtful, that is, an estimate.

**Example**

\[
\begin{array}{c}
1 725.463 \\
- 189.2 \\
\hline
1 931.393 \\
\end{array}
\]

The least precise number in this group is 189.2 because the (2) is an estimate, so, according to the rule, the answer should be reported as 1 931.4. Using alternative reasoning, suppose these numbers are instrument readings, which means the last reported digit in each is a doubtful digit. A column addition that contains a doubtful digit will result in a doubtful digit in the sum. So all three digits to the right of the decimal in the answer are doubtful. We keep just one doubtful digit in the answer; thus the answer is 1 931.4 after rounding.

\[
\begin{array}{c}
897.0 \\
-0.092 2 \\
\hline
896.907 8 \\
\end{array}
\]

Application of the rule results in an answer of 896.9.

4. **Combined Operations.** If products or quotients are to be added or subtracted, perform the multiplication or division first, establish the correct number of significant figures in the subanswer, then perform the addition or subtraction, and round to proper significant figures. Note, however, that in calculator or computer applications 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.

If results from additions or subtractions are to be multiplied or divided, an intermediate determination of significant figures can be made when the calculations are performed manually. For calculator or computer answers, use the suggestion already mentioned.

Subtractions that occur in the denominator of a quotient can be a particular problem when the numbers to be subtracted are very nearly the same. For example, 39.7/(772.3 - 772.26) gives 992.5 if intermediate roundoff is not done. If, however, the subtraction in the denominator is reported with one digit to the right of the decimal, the denominator becomes zero and the result becomes undefined. Commonsense application of the rules is necessary to avoid problems.

### 4.3 Accuracy and Precision

In measurements, “accuracy” and “precision” have different meanings and cannot be used interchangeably. **Accuracy** is a measure of the nearness of a value to the correct or true value. **Precision** refers to the repeatability of a measurement, that is how close successive measurements are to each other. Figure 4.4 illustrates accuracy and precision of the results of four dart throwers.

**Figure 4.4**

Illustration of the difference between accuracy and precision in physical measurements.
Thrower (a) is both inaccurate and imprecise because the results are away from the bull’s-eye (accuracy) and widely scattered (precision). Thrower (b) is accurate because the throws are evenly distributed about the desired result but imprecise because of the wide scatter. Thrower (c) is precise with the tight cluster of throws but inaccurate because the results are away from the desired bull’s-eye. Finally, thrower (d) demonstrates accuracy and precision with tight cluster of throws around the center of the target. Throwers (a), (b), and (c) can improve their performance by analyzing the causes for the errors. Body position, arm motion, and release point could cause deviation from the desired result.

Engineers making physical measurements encounter two types of errors, systematic and random. These will be discussed in the next section.

4.4 Errors

To measure is to err! Any time a measurement is taken, the result is being compared to a true value, which itself may not be known exactly. When we measure the dimensions of a room, why doesn’t a repeat of the measurements yield the same results? Did the same person make all measurements? Was the same measuring instrument used? Were readings all made from exactly the same location? Was the measuring instrument correctly graduated? It is obvious that errors will occur in each measurement. We must try to identify the errors if we can and correct them in our results. If we can’t identify the error, we must provide some conclusions as to the resulting accuracy and precision of our measurements.

Identifiable and correctable errors are classified as systematic; accidental or other nonidentifiable errors are classified as random.

4.4.1 Systematic Errors

Our task is to measure the distance between two fixed points. Assume that the distance is about 1200 m and that we are experienced and competent and have equipment of high quality to do the measurement. Some of the errors that occur will always have the same sign (+ or –) and are said to be systematic. Assume that a 25 m steel tape is to be used, one that has been compared with the standard at the U.S. Bureau of Standards in Washington, D.C. If the tape is not exactly 25.000 m long, then there will be a systematic error each of the 48 times that we use the tape to measure out the 1200 m.

However, the error can be removed by applying a correction. A second source of error can stem from a difference between the temperature at the time of use and at the time when the tape was compared with the standard. Such an error can be removed if we measure the temperature of the tape and apply a mathematical correction. The coefficient of thermal expansion for steel is 11.7 × 10⁻⁶ per kelvin. The accuracy of such a correction depends on the accuracy of the thermometer and on our ability to measure the temperature of the tape instead of the temperature of the surrounding air. Another source of systematic error can be found in the difference in the tension applied to the tape while in
use and the tension employed during standardization. Again, scales can be used but, as before, their accuracy will be suspect. In all probability, the tape was standardized by laying it on a smooth surface and supporting it throughout. But such surfaces are seldom available in the field. The tape is suspended at times, at least partially. But, knowing the weight of the tape, the tension that is applied, and the length of the suspended tape, we can calculate a correction and apply it.

The sources of systematic error just discussed are not all the possible sources, but they illustrate an important problem even encountered in taking comparatively simple measurements. Similar problems occur in all types of measurements: mechanical quantities, electrical quantities, mass, sound, odors, and so forth. We must be aware of the presence of systematic errors, eliminate those that we can, and quantify and correct for those remaining.

4.4.2 Random Errors

In reading the previous section, you may have realized that even if it had been possible to eliminate all the systematic errors, the measurement is still not exact. To elaborate on this point, we will continue with the example of the task of measuring a 1200 m distance. Several random errors can creep in, as follows. When measuring the temperature of the tape, we must estimate the thermometer reading when the indicator falls between graduations. Moreover, it may appear that the reading is exactly on a graduation when it is actually slightly above or below the graduation. Furthermore, the thermometer may not be accurately measuring the tape temperature but may be influenced instead by the temperature of the ambient air. These errors can thus produce measurements that are either too large or too small. Regarding sign and magnitude, the error is therefore random.

Errors can also result from our correcting for the sag in a suspended tape. In such a correction, it is necessary to determine the weight of the tape, its cross-sectional area, its modulus of elasticity, and the applied tension. In all such cases, the construction of the instruments used for acquiring these quantities can be a source of both systematic and random errors.

The major difficulty we encounter with respect to random errors is that although their presence is obvious by the scatter in the data, it is impossible to predict the magnitude and sign of the accidental error that is present in any one measurement. Repeating measurements and averaging the results will reduce the random error in the average. However, repeating measurements will not reduce the systematic error in the average result.

Refinement of the apparatus and care in its use can reduce the magnitude of the error; indeed, many engineers have devoted their careers to this task.

Likewise, awareness of the problem, knowledge about the degree of precision of the equipment, skill with measurement procedures, and proficiency in the use of statistics allow us to estimate the magnitude of the error remaining in measurements. This knowledge, in turn, allows us to accept the error or develop different apparatus or methods for our work. It is beyond the scope of this text to discuss quantifying accidental errors. However, Chapter 6 includes a brief discussion of central tendency and standard deviation, which are part of the analysis of random errors.
4.5 Approximations

Engineers strive for a high level of precision in their work. However, it is also important to be aware of an acceptable precision and the time and cost of attaining it. There are many instances where an engineer is expected to make an approximation to an answer, that is, to estimate the result with reasonable accuracy but under tight time and cost constraints. To do this engineers rely on their basic understanding of the problem under discussion coupled with their previous experience. This knowledge and experience is what distinguishes an "approximation" from a "guess." If greater accuracy is needed, the initial approximation can be refined when time, funds, and the necessary additional data for refining the result are available.

In the area of our highest competency, we are expected to be able to make rough estimates to provide figures that can be used for tentative decisions. These estimates may be in error by perhaps 10 to 20% or even more. The accuracy of these estimates depends strongly on what reference materials we have available, how much time is allotted for the estimate, and, of course, how experienced we are with similar problems. The first example we present will attempt to illustrate what an engineer might be called upon to do in a few minutes with little in the way of references.

Example Problem 4.1 An aerospace engineer is asked to sit in on a meeting of executives of an airline considering the purchase of the new Boeing 787 Dreamliner. The engineer is asked if she could give the group a quick estimate of the average cruise fuel consumption of the 787 on a per-mile basis. The executives can use the result to compare the 787 with competitive aircraft as they proceed toward a purchase decision.

Discussion The engineer has reviewed preliminary specifications published by Boeing to prospective buyers of the 787. The base model of the aircraft (787-8) has an estimated range of 8 000 to 8 500 nautical miles (nmi), or 9 200 to 9 775 miles, and a cruise Mach number of \( M = 0.85 \). Mach number is the ratio of the speed of the aircraft to the speed of sound at the flight altitude. The fuel capacity is about 33 000 gallons or about 220 000 lb. Assuming that 10% of the fuel is used during taxi, takeoff, climb to cruise altitude, descent, and final taxi and a 10% reserve is required upon arrival, and using the high end of the mileage range, the engineer quickly estimates cruise fuel consumption per mile as \( 26 \text{ 400}/9 \text{ 775} = 2.7 \text{ gal/mi} \) or \( 176 \text{ 000}/9 \text{ 775} = 18 \text{ lb/mi} \). From this quick estimate, the executives can estimate a fuel cost per mile at current fuel prices and the overall fuel cost for any flight leg. This problem does not require specialized knowledge in any particular engineering discipline, but does require an ability to understand the problem and put together the available data to obtain a solution. Experience in the aerospace discipline speeds the understanding of the problem and enables the quick estimate to be done. Some additional data and estimation problems involving the 787 are presented in the chapter problems.
The Boeing 787 Dreamliner

The latest commercial aircraft being designed, developed, and manufactured by the Boeing Company is the 787 Dreamliner. This aircraft is in response to preferences expressed by airlines around the world for a superefficient airplane. The 787 is the ninth airplane in the Boeing 7x7 commercial fleet, which began in the 1950s with the 707 and continued with the 727, 737, 747, 757, 767, 777, and now the 787, due to go into service in 2008.

The 787 family will consist of three models. The 787-8 will carry 210–250 passengers on routes of 8 000 to 8 500 nautical miles (nm), or 14 800 to 15 700 kilometers (km). The 787-8 will be test-flown in 2007 and then delivered to customers beginning in 2008. The second member of the family, the 787-3, will fly shorter routes, 3 000 to 3 500 nm (5 500 to 6 500 km) and accommodate 290–330 passengers. It will be delivered to customers beginning in mid-2010. The third family member, to be delivered in late 2010, is the 787-9. This Dreamliner will carry 250–290 passengers on routes of 8 600 to 8 800 nm (15 900 to 16 300 km). Each of the family members is specifically optimized for its design range, passenger capacity, and cargo capacity.

Advancing technologies, design procedures, and manufacturing improvements have led to an aircraft of unprecedented efficiency. The primary structure of the aircraft will be 50% composites and 20% aluminum, compared with 11% composites and 70% aluminum on the 777, which went into service in 1995. The great increase in composites will eliminate 1 500 aluminum sheets and 40 000 to 50 000 fasteners per fuselage section, thus saving assembly time, material handling, and weight. The empty weight of the 787 will run 40 000 to 50 000 lb less than other aircraft in its class, giving airlines added cargo revenue. Maximum takeoff weight consists of empty aircraft plus fuel weight plus cargo (passengers and freight). If the empty weight can be reduced, cargo can increase correspondingly for the same takeoff weight, generating increased revenue.

The Rolls-Royce Trent 1000 and the General Electric GEnx engines, each rated at 74 000 lb of thrust have been selected for installation on the 787. Advances in engine technology will create an 8% increase in efficiency and the engines will use 20% less fuel for comparable routes than any other aircraft of similar size. Engine emissions are therefore reduced by an equivalent amount. The engines will propel the aircraft at speeds equivalent to current large jets, Mach 0.85.

Another major area of improvement is the replacement of pneumatic systems with electrical systems to run auxiliary devices. In previous aircraft, bleed air was taken from the engine compressor to, among other uses, power the pneumatic systems for cabin pressure. Now the engines will drive electric generators that will in turn provide the power for the auxiliary devices. This results in a 35% drop in the power extracted from the engines.

Passengers will experience improved conditions for flights. The Dreamliner’s windows are 65% larger than those in competitive aircraft. Climate control in the cabin will include higher humidity and improved air handling. Seats are ergonomically designed to provide improved comfort and convenience.

The 787 Dreamliner is truly an international effort. The Boeing Commercial Airplanes in the Seattle, Washington, area will handle 787 development integration, final assembly, and program leadership. Major components of the aircraft will be manufactured in 26 foreign countries, including Japan (wing box and main landing gear well), France (landing gear structure and electric brakes), the United Kingdom (landing gear actuation and control system and Rolls-Royce engines), Korea (raked wing tips), Sweden (cargo and access doors), and Germany (main cabin lighting and metal tubing and ducting). Other contributing companies in the United States include Boeing subsidiaries in Washington and Kansas, Rockwell Collins in Iowa, Honeywell in Arizona, Goodrich in North Carolina, General Electric in Ohio (engine), Moog Inc. in New York, and Hamilton Sundstrand in Connecticut.
Example Problem 4.2 is an illustration of a problem you might be assigned. You have the necessary experience to perform the estimation without special knowledge. Not counting the final written presentation, you should be able to do a similar problem in one-half to 1 hour.

Example Problem 4.2 Suppose your instructor assigns the following problem: Estimate the height of two different flagpoles on your campus. This will be done on a cloudy day so no shadow is present. The poles are in the ground (not on top of a building) and the bases of the poles are accessible. One of the poles is on level ground and you have available a carpenter's level, straight edge, protractor, and masking tape. The other pole is on ground that slopes away from the base and you have available a carpenter’s level, straight edge, protractor, and a 12-ft. tape. See Fig. 4.5 for the response of one student (whom we will call Dave).

Discussion To estimate the height of the flagpole on level ground, Dave recognizes that he does not have a normal distance measuring device but that he must know some distance in order to use trigonometry to solve the problem. He knows that he is 6’1” tall, and he can mark that height on the pole with masking tape, which he can see from a location several feet from the pole. He can use the level, protractor, and straight edge to estimate angles from the horizontal. The distance away from the pole for measuring the angles is arbitrary, but he chooses a distance that will provide angles that are neither too large nor too small, both of which would be difficult to estimate. Then from this point on the ground he estimates the angles to his 6’1” masking tape mark and to the top of the pole. Note that Dave has kept all of the significant figures through the calculations and rounded only at the end, reasoning that he does not want intermediate rounding to affect his answer. Based on the method used for estimation, he believes his answer is not closer than the nearest foot so he rounds to that value.

When estimating the height of the pole on sloping ground, Dave had a tape available so it was not necessary to mark his height on the pole. Again, Dave kept all significant figures through the calculation procedure and rounded only the final result.

Example Problem 4.3 A homeowner has asked you to estimate the number of gallons of paint required to prime and finish coat her new garage. You are told that paint is applied about 0.004 in. thick on smooth surfaces. The siding is to be gray and the roof overhang and trim are to be white. See Fig. 4.6 for one approach done by Laura.

Discussion From experience, Laura knew that one coat of primer would be needed and that two coats of finish paint would be required for a lasting outcome. She also noted that the garage doors were painted by the manufacturer before installation and therefore would not need further paint. She decided to neglect the effect of windows in the garage because of their small size. She observed that the siding was a rough vertical wood type and that the soffit
PROBLEM 4.2

ESTIMATE THE HEIGHT OF 2 FLAGPOLES ON YOUR CAMPUS. ASSUME THE SUN IS NOT SHINING AND THAT THE BASES OF THE POLES ARE AT GROUND LEVEL (NOT ON TOP OF A BUILDING) AND THAT THE BASES ARE ACCESSIBLE.

A. DO THE ESTIMATE FOR POLE 1 WHERE YOU HAVE AVAILABLE A CARPENTER’S LEVEL, STRAIGHT EDGE, PROTRACTOR AND MASKING TAPE. POLE 1 SITS ON LEVEL GROUND.

B. FOR POLE 2, YOU HAVE A CARPENTER’S LEVEL, STRAIGHT EDGE, PROTRACTOR AND A 12’ TAPE. THE GROUND AROUND POLE 2 SLOPES AWAY FROM THE BASE.

PART A.

ASSUMPTIONS
1. GROUND APPROXIMATELY LEVEL AROUND FLAGPOLE BASE

PROCEDURE
- PLACE A PIECE OF MASKING TAPE AT MY HEIGHT ON THE FLAGPOLE.
- CHOOSE POSITION ABOUT FLAGPOLE HEIGHT AWAY FROM THE BASE AND MEASURE ELEVATION ANGLES TO TOP OF POLE (β) AND TO TAPE (α). SEE FIG. 1.

DATA
1. MY HEIGHT KNOWN TO BE 6’ 1”.
2. LEVEL, STRAIGHT EDGE, AND PROTRACTOR CAN SERVE AS A SYSTEM FOR MEASURING ELEVATION ANGLES (FIG. 2)
3. α = 7.5°, β = 48°

SOLUTION
\[
\begin{align*}
\tan \alpha &= \frac{6’ 1”}{d} = \tan 7.5° \\
\tan \beta &= \frac{h}{d} = \tan 48°
\end{align*}
\]

4. \[ h = d \cdot (\tan 48°) = \left( \tan 7.5° \right) \cdot (\tan 48°) \approx 51.319 \text{ FT} \]

APPROXIMATE \( h = 51’ \)
PART B

ASSUMPTIONS
1. GROUND HAS CONSTANT SLOPE FROM BASE TO MEASURING POINT.

PROCEDURES
• CHOOSE POINT ABOUT FLAGPOLE HEIGHT AWAY FROM BASE AND MEASURE ELEVATION ANGLES TO TOP(\(\gamma\)) AND TO BASE(\(\Delta\))
• MEASURE DISTANCE (\(d\)) FROM CHosen point to BASE. FIG. 3.

DATA
1. \(\Delta = 3.5^\circ\)
2. \(\gamma = 44^\circ\)
3. \(d = 93.4''\)

SOLUTION
\[
\sin \Delta = \frac{b}{d}
\]
\[
b = d \sin \Delta = (93.4') \sin 3.5^\circ = 5.6979'
\]
\[
\tan \Delta = \frac{b}{d_h}
\]
\[
d_h = \frac{b}{\tan \Delta} = \frac{5.6979}{\tan 3.5^\circ} = 93.1598'
\]
\[
\tan \gamma = \frac{h+b}{d_h}
\]
\[
h = d_h \tan \gamma - b = (93.1598') \tan 44^\circ - 5.6979
\]
\[
= 84.265'
\]

APPROXIMATE \(h = 84\)
Figure 4.6a

PROBLEM 5.3

A HOMEOWNER HAS ASKED FOR AN ESTIMATE OF THE NUMBER OF GALLONS OF PAINT REQUIRED TO PRIME AND FINISH COAT HER NEW GARAGE. PAINT SHOULD BE APPLIED ABOUT 0.004 IN. THICK ON SMOOTH SURFACES. THE SIDING IS TO BE GRAY AND THE TRIM WHITE.

ASSUMPTIONS

1. 1 COAT OF PRIMER, 2 FINISH COATS
2. GARAGE DOORS ARE NOT PAINTED.
3. NEGLECT AREA OF SMALL WINDOWS IN GARAGE.

PROCEDURE

MEASURE GARAGE SURFACES TO OBTAIN TOTAL AREA TO BE PAINTED. OBSERVE "SMOOTHNESS" OF SIDING TO ESTIMATE PAINT COVERAGE. COMPUTE AMOUNT OF EACH TYPE OF PAINT.

COLLECTED DATA

1. SINCE 1 GAL = 231 IN³, PAINT THICKNESS OF 0.004 IN RESULTS IN 1 GAL COVERING = 400 FT² OF SMOOTH SURFACE.
2. OVERHANGS ARE 18 IN.
3. SIDING IS OBSERVED TO BE ROUGH WOOD/VERTICAL, SOFFIT IS SMOOTH PLYWOOD.
4. LOCAL PAINT STORE REPRESENTATIVE SUGGESTED THAT PRIMER ON ROUGH WOOD SIDING COVERS ONLY 1/3 NORMAL AREA AND THAT TOP COAT COVERS ABOUT 3/4 NORMAL AREA.

SOLUTION

NORTH SIDE AREA = (9)(50) - (7)(8) - (7)(16) - (7)(3) = 261 FT²
SOUTH SIDE AREA = (9)(50) = 450 FT²
EAST/WEST END AREA = 9(24) + \frac{1}{2}(24)(5) = 276 FT² / END
OVERHANG AREA = (53)(1.5)(2) + 2 \left[ (13.5)^2 + \left( \frac{5}{12} \right)(13.5) \right]^{1/2} = 159 + 29.25 = 188 FT²
TOTAL AREA OF SIDING = 261 + 450 + 2(276) = 1263 FT²

TOTAL OVERHANG AREA = 188 FT²

PRIMER NEEDED FOR SIDING = \left(\frac{1263}{400}\right) 3 = 9.47 GAL

PRIMER NEEDED FOR OVERHANG = \frac{188}{400} = 0.47 GAL

TOTAL PRIMER NEEDED = 9.47 + 0.47 = 9.94 GAL

GRAY FINISH COAT FOR SIDING = (2) \left(\frac{1263}{400} \times \frac{4}{3}\right) = 8.42 GAL

WHITE FINISH COAT FOR OVERHANG/TRIM = (2) \left(\frac{188}{400}\right) = 0.94 GAL

RECOMMENDED PURCHASE:

PRIMER: 10 GAL
GRAY TOP COAT: 9 GAL
WHITE TOP COAT: 1 GAL
(underside of the roof overhang) was smooth plywood. Since she had limited experience with rough siding, she contacted a local paint retailer and learned that rough siding would take approximately three times as much primer as smooth siding and that because of the siding roughness the finish paint would cover only about 3/4 of the normal area. She carefully documented this fact in her presentation.

Laura took all necessary measurements and computed the areas that must be painted. She determined that the paint film thickness of 0.004 in. corresponds to approximately 400 ft²/gal coverage. Like Dave in the previous example, Laura retained extra significant figures until finally rounding at the end of the estimate. In this case, she correctly rounded up rather than to the nearest gallon, as the paint would be purchased in whole gallons.

**Example Problem 4.4** Estimate the cost of the concrete that is in the roadbed of Interstate 17 running from Flagstaff, Arizona, to Interstate 10 near the Phoenix airport. Consider only the actual roadbed and not stopping lanes or interchanges. Keep track of the time to develop a solution and perform the write-up.

**Discussion** Figure 4.7 is a write-up on a word processor of the solution performed. The assumptions are listed and simplify the data collection process considerably. Two telephone calls were made to obtain information on interstate highway construction and the cost of concrete. Thus the resulting estimate is based on current design practice and costs. A similar estimation problem relaxing some of the assumptions is provided in Problem 4.31.

**Problems**

4.1 How many significant digits are contained in each of the following quantities?
   
   (a) 72.470  
   (b) 7.2470   
   (c) 0.0031   
   (d) 24,000,000  
   (e) $0.1 \times 10^8$  
   (f) 0.32000  
   (g) 200.07   
   (h) $1.320 \times 10^{-3}$  
   (i) 2,000,000,000  
   (j) $3.0267 \times 10^2$

4.2 How many significant digits are contained in each of the following quantities?
   
   (a) 2.345  
   (b) 0.1003   
   (c) 0.000023  
   (d) 2,204.6 kg/lbm  
   (e) 300.0030   
   (f) 2.54 cm/in.  
   (g) 1.0002   
   (h) $1.000 \times 10^8$  
   (i) 60 s/min  
   (j) $4 \times 10^{12}$

4.3 Perform the computations below and report with the answer rounded to the proper number of significant digits.
   
   (a) $56.3 \times 372.05$  
   (b) $3.735 - 1.4300$  
   (c) $(6.231 \times 827)(4.23 \times 10^7)$  
   (d) $0.25 \div 0.50$  
   (e) $31.05 \div 2.0$  
   (f) $(1.45 \times 10^9)(1.0003 \times 10^{-3})$  
   (g) $1.784.57 \times 700.025$  
   (h) $17.54678 \div 0.02435$  
   (i) $4.300240 \div 784$  
   (j) $(4500.3 + 372 - 1121) \div 86.00$
Estimate the cost of concrete in the roadbed of the entire length of Interstate Highway 17 (I-17), from its beginning at Flagstaff, Arizona to its terminus at Interstate Highway 10 (I-10) in Phoenix near the Phoenix airport. In the presentation, specify the approximate amount of time spent on the solution.

**ASSUMPTIONS**

1. Four lanes (two lanes each direction) from Flagstaff to Loop 101 in Phoenix
2. Eight lanes in Phoenix
3. Assume entire roadbed is concrete
4. Neglect on and off ramps, bridge supports and railings, and emergency stop lanes

**COLLECTED DATA**

1. Concrete costs $75 per cubic yard delivered to site (estimate from contractor)
2. Average depth of roadbed is 12 inches (Department of Transportation)
3. Lane width is 12 feet (Department of Transportation)
4. Unit relationships: 1 mi = 5280 ft
   \[1 \text{ yd} = 3 \text{ ft}\]
   \[1 \text{ ft} = 12 \text{ in}\]
5. Data from 2004 State Farm Road Atlas

<table>
<thead>
<tr>
<th></th>
<th>miles</th>
<th>lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Flagstaff to Phoenix Loop 101</td>
<td>124</td>
<td>4</td>
</tr>
<tr>
<td>b. Loop 101</td>
<td>21</td>
<td>8</td>
</tr>
</tbody>
</table>

**CALCULATIONS**

Volume \((V)\) = Length \((L)\) \times Width \((W)\) \times Depth \((D)\)

Cost \((C)\) = Volume \((V)\) \times (cost/cubic yard)

\[V_a = (124 \text{ mi})(5280 \text{ ft/mi})(4)(12 \text{ ft})(12 \text{ in})(1 \text{ ft/12 in})(1 \text{ yd}^3/27 \text{ ft}^3) = 1.164 \times 10^6 \text{ yd}^3\]

\[V_b = (21 \text{ mi})(5280 \text{ ft/mi})(8)(12 \text{ ft})(12 \text{ in})(1 \text{ ft/12 in})(1 \text{ yd}^3/27 \text{ ft}^3) = 0.3942 \times 10^6 \text{ yd}^3\]

\[V = 1.558 \times 10^6 \text{ yd}^3\]

\[C = (1.558 \times 10^6 \text{ yd}^3)(\$75/\text{yd}^3) = \$117,000,000\]

Time estimate: 40 min (obtaining data and calculations) + 30 min (write-up) = 70 min

Student presentation, produced on a word processor for Example Problem 4.4
4.4 Using the conversion factors given in each problem, perform the calculations below using exact conversions or with enough significant digits that it does not affect the accuracy of the answer.
(a) 762 feet to miles
    \[1 \text{ mi} = 5.280 \text{ ft}\]
(b) \(8 \times 10^{20}\) atoms to moles
    \[1 \text{ mole} = 6.022 \times 10^{23} \times \text{atoms}\]
(c) 653.5 kg to pound mass
    \[1 \text{ kg} = 2.204 \text{ lbm}\]
(d) 7.358 centimeters to inches
    \[1 \text{ in.} = 2.54 \text{ cm}\]
(e) 7.62 cubic meters to cubic feet
    \[1 \text{ m} = 3.280 \text{ ft}\]
(f) 12.5 weeks to seconds
    \[1 \text{ day} = 86400 \text{ s}\]

4.5 Solve the following problems and give the answers rounded to the proper number of significant digits.
(a) \(v = 2.14t^2 + 36.35t + 2.25\) 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) \(V = \frac{1}{3} \pi r^2 h = \text{? cm}^3\) (volume of a cone)
(e) \(325.03 - 527.897 + 615 = \)
(f) \$32\text{ per part} \times 45 \text{ 250 parts} = \$

4.6 A pressure gauge on an air tank reads 210 pounds per square inch (psi). The face of the gauge says \( \pm 5\% \) at 180 psi.
(a) What is the range of air pressure in the tank when the gauge reads 210 psi?
(b) What is the range of air pressure in the tank when the gauge reads 87 psi?

4.7 A vacuum gauge reads 86 kPa. The face of the gauge says \( \pm 0.1 \text{ kPa at 75 kPa.}\)
(a) What is the actual range of vacuum?
(b) What is the range when the gauge reads 110 kPa?

4.8 What is the percent of error if you use a pair of calipers on a 6-in. precision gauge block and get a reading of 5.998?

For problems 4.9 to 4.34, develop and present a solution in a manner demonstrated in Example Problems 4.2, 4.3, or 4.4. Your solutions should indicate the amount of time required for developing and preparing the solution.

4.9 Estimate the cost of soft drinks that the students taking this class purchase in a week.

4.10 Estimate the number of quarters that will fit in a box 16 inches by 10 inches by 12 inches. (Time limit of 20 minutes.)

4.11 Estimate the number of square feet of windows in the building this class is held in.

4.12 Estimate the area in square feet of the running track on your campus.

4.13 Estimate the volume (capacity) in cubic feet of the water tower closest to or on your campus.

4.14 Estimate the amount of rainfall, in gallons, that must be carried away from your campus in a typical year.

4.15 Estimate the weight of the newspapers delivered daily in the city of New York.

4.16 Estimate the cubic feet of natural gas that a specified engineering building on your campus will consume for heating next winter.

4.17 Estimate the volume of water used to take showers by the members of this class in one academic year.

4.18 Estimate the number of regular M&M's that can fit in a two-liter bottle.

4.19 Estimate the amount of total time spent by the members of this class studying for this class this week.

4.20 Estimate the cost of the gasoline the students in this class use in their vehicles in a typical week. (A brief survey of a representative segment of the class is recommended.)

4.21 Estimate the amount of time during a typical class day that you spend walking. Also estimate the number of steps you take during this time.
4.22 Estimate the weight, in pounds, of cars in the parking lot closest to the building where this class is held. Assume all parking spots are occupied.

4.23 Estimate the number of minutes students in your class spend on their cell phones in a typical week. (A brief survey of a representative segment of the class is recommended.)

4.24 Estimate the cost of lighting the building where this class is held.

4.25 Estimate the number of hours that you spend watching television in a typical week during the academic semester.

4.26 Estimate the average number of CDs and DVDs owned by the students in your major. Also estimate the average amount each student has invested in a CD/DVD collection.

4.27 Estimate the amount and cost of paint to change the color of the paint in all the classrooms in the building where this class is held.

4.28 Estimate the number of soccer balls that can be stored in a railroad box car.

4.29 Estimate the number of square yards of carpet in the Student Union on your campus.

4.30 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. (This will require significant research and time to gather the necessary data. Allow appropriate time for your effort.)

4.31 Select a segment of interstate highway (or have your instructor designate a segment) in your area and estimate the cost of roadbed materials. Be sure to include rural and city components in your segment. Include estimates for emergency stopping lanes and interchanges on the selected segment. Find data on reinforcing rods used in the construction and include this in the cost estimate. This problem may be best worked by teams of students with two or three students on a team. Include the amount of time the team used to complete the roadbed material cost.

The following are general specifications for the Boeing 787-8 Dreamliner. Use the data to perform the estimations required in problems 4.32–4.34.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum takeoff weight</td>
<td>476,000 lb (215,910 kg)</td>
</tr>
<tr>
<td>Empty weight</td>
<td>223,100 lb (106,499 kg)</td>
</tr>
<tr>
<td>Maximum fuel capacity</td>
<td>32,340 gal (124,691 L)</td>
</tr>
<tr>
<td>Passengers</td>
<td>224*</td>
</tr>
<tr>
<td>Range</td>
<td>8000–8500 nmi</td>
</tr>
<tr>
<td>Cruise speed (Mach number)</td>
<td>$M = 0.85$</td>
</tr>
</tbody>
</table>

*Occupancy ranges from 210 to 250, depending upon the configuration for first, business, and tourist classes.

4.32 Estimate the weight of the crew, passengers, cargo, and fuel for a sold-out flight.

4.33 Using the information in Example Problem 4.1, estimate the flight time and fuel consumed on a flight from Tokyo to San Francisco. Assume the speed of sound at cruising altitude is 975 feet per second (fps).

4.34 Estimate the fuel consumption on a per-hour basis for a maximum range flight at an altitude where the speed of sound is 975 fps.