Freshman Problem Solving and the Basics - A Question of Importance

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Introduction

Freshman engineering, what is it all about? Is it about building a universal widget, developing better modes of transportation, creating and using new composites in previously unforeseen ways, or developing the next generation computer or Internet system? I believe the answer to each of these questions is “No”. Freshman engineering is not about all the wonderful things engineers have done, are doing, or will do in the future. Freshman engineering is about the basics.

Freshman engineering students tend to arrive on campus clueless about engineering. They, like many other university students, enter a world they have yet to understand. They seldom have more than a cursory knowledge of engineering. Typical freshman engineering advisors find that most freshmen picked engineering because they were told “engineers earn good money” and/or they like the prestige associated with being called an “engineer” or attending a “College of Engineering.” Few freshman engineering students have been exposed to engineering or have a knowledge of this field. Many are unaware of the different areas of engineering and most have no knowledge of the functions within each field.

Freshman engineering students also arrive with varied levels of knowledge and skills. Many have been challenged in high school and are well prepared. Others are quickly challenged by the demands of their new engineering environment. Their standards of performance vary, as does their understanding of problem-solving basics. For example, most students have taken high school chemistry and physics. But, student understanding of the scientific problem-solving method and the ability to apply the method to solve simple problems is dependent upon the emphasis placed on the topic by high school teachers. The same is true for other basic skills, such as unit conversions and significant digits.

As a result, topics such as "the engineering profession" and "the engineering problem-solving method" are integrated into initial freshman engineering courses. Engineering colleges have also assumed responsibility for ensuring freshman engineering students are well versed in basic engineering methods and skills. The question is whether we, freshman-engineering instructors, are overlooking systematic errors in our teachings and texts.

This paper addresses some systematic problems in teaching engineering problem-solving to freshman engineering students. The objective is to examine freshman engineering textbooks and teaching practices in terms of the engineering problem-solving method. In doing so, conflicts between what is professed and what is practiced will be examined. The two major items addressed will be units and significant digits. The intent is to fully analyze the engineering problem-solving method and the responsibility of freshman engineering instructors to practice what is taught by fully integrating unit analysis and significant digit determination into daily teaching endeavors and associated text material. Recommended courses of action to eliminate the problem areas will then be provided.

As an illustration of a typical textbook problem that can unintentionally promote sloppy techniques in student work, consider the following problem statement.

> A stationary 33 foot horizontal beam with a mass of 20 kg/m is located 2000 cm above the ground. How much energy is stored in the beam? Hint: PE = mgh where PE is potential energy, m is mass, g is gravity (9.8 m/s^2), and h is height.

If the solution is to multiply the beam length by beam mass, gravitational pull, and object height, then the approach to the solution is correct and this approach is normally the focus of teaching. But, was the given information questioned? Also, if the format below was provided as the text's solution to the problem or if this was a student's solution to the problem, is the solution correct?

$$\begin{aligned} PE &= (33)(1/3.2808)(20)(9.8)(2000)(1/100) \\ &= 39\ 000 \text{ J} \end{aligned}$$

(Please see the end of this article for possible solutions.) The above problem depicts two systematic errors in present teaching techniques and texts. These errors are associated with unit conversions and significant digits.

Engineering Problem-Solving Presentation

To ensure a complete analysis of these two systematic errors, it is important to trace their role throughout the engineering problem-solving process. This means looking at an engineering problem-solving presentation method from problem statement to final solution. In doing so, a better understanding of the role and the effects of poor teaching practices and poor textual material will become apparent. By understanding the way these systematic errors are unknowingly fostered, corrective action can be facilitated to serve students better.

Many engineering problem-solving presentation forms are used throughout the engineering community. However, the variations are similar in sequencing and content. The main differences occur in the number of steps, specific step definitions, and individual interpretations or explanations of step activities. Eide's six-step engineering problem-solving presentation approach will be used as a basis for analyzing errors in unit conversions and significant digits.

Eide's six-step engineering problem-solving presentation includes: problem statement, diagram, theory, assumptions, solution steps, and identify results & verify accuracy. [1] In an academic environment, the "problem statement" is provided by a text or instructor. The statement refers to a clear description of an event, which requires resolution based upon given information.

"Diagram" refers to a visual depiction of the problem statement along with given and required information. "Theory" refers to the identification of relationships or equations necessary to solve the problem. "Assumptions" refers to the documentation of suppositions or presumptions deemed necessary to clarify the problem statement. "Solution Steps" refers to the methodical sequence of steps taken to determine a solution. Finally, "Identify Results and Verify Accuracy" refers to clearly displaying a solution and checking to ensure the solution is meaningful and reasonable.

Units and significant digits play a major role in Eide's first and second steps. The problem statement and diagram steps set the problem's stage from which all other deductions are made and the solution is derived.. Although the identification of units is not a common problem, the two steps reflect a consistent oversight in significant digit accountability. If the problem statement and diagram do not clearly define the given situation, the student must rely upon assumptions, step #4, to clarify the problem definition. For example, note the following example problem from a college engineering textbook: [1]

> The force vector **F** has a magnitude of 650 lb and acts through point **A** at a slope of 2 vertical to 5 horizontal. Determine the **x** and **y** components of **F**.

The problem statement immediately presents the student with a significant digit dilemma. Are there two or three significant digits in the given "650 lb"? Are the slope values exact or should the student use only one significant digit? The problem statement is not clear and requires the student to make an assumption or follow a course policy, which circumvents proper significant digit analysis.

During high school chemistry and physics courses, students are taught that "a significant digit, or 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." [1] Most freshman engineering courses also stress this fundamental definition as a specific topic during the first few lessons. But, what happens after the topic is covered? Most texts and many course exercises revert to problems inundated with zeros for ease of grading. In the typical engineering course, a blanket statement is used to address this problem. The policy is, "Unless stated otherwise, assume ALL "0"s in text problems are significant digits." [2] This statement is necessary since most texts contain this zero manifestation. The result is a system that fosters a lack of proper significant digit accountability in problem-solving.

It is the responsibility of instructors to ensure problem statements and diagrams are complete in terms of both units and significant digits. Unless zeros are inserted to teach or test significant digit analysis, each problem should have a defined set of parameters from which a significant digit analysis can be followed. For the above example, a more correct and realistic problem statement might be:

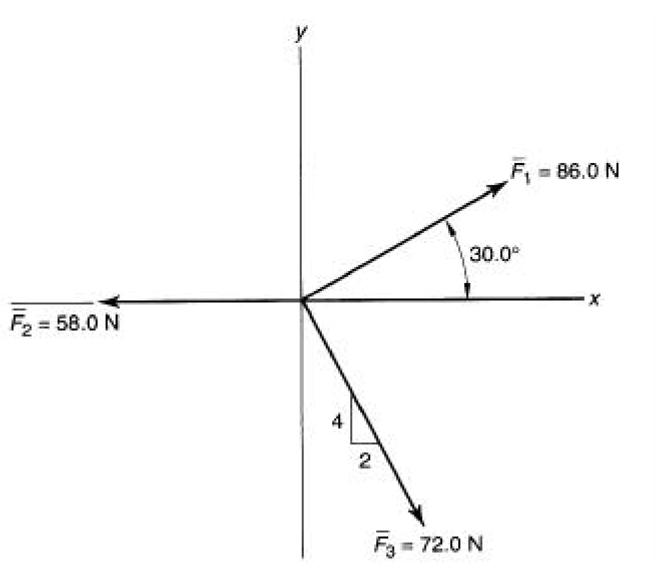
> The force vector **F** has a magnitude of 6.50 (10^2) lb and acts through point **A** at a slope of 2.01 vertical to 5.47 horizontal. Determine the **x** and **y** components of **F**.

This statement leaves no doubt in the student's mind as to the accuracy of measurements (real life measurement capability) and allows the student to follow proper engineering practice.

An incomplete problem statement also affects the third step of Eide's engineering problem-solving presentation, theory. The problem statement must communicate the accuracy and precision of given numbers in addition to units. This information is then used to drive unit conversion requirements and many mathematical relationships. For example, which gravitational value should be used to calculate the weight of an object placed on your desk with a mass provided in kilograms? - 9.8, 9.81, 9.807, or 9.80665 m/s^2? What if the temperature was being changed from degrees Celsius to Kelvin? Would it be correct to use 273, 273.2, or 273.15? The correct answer would be based upon the significant digits of the given information. A conversion value should never be allowed to affect the problem's solution. If the provided information is ill-defined, the student is forced to make assumptions if following correct engineering problem-solving procedures or, if not required to make an appropriate assumption, systematically taught that significant digits are not important, by default. Texts and course problems must either properly define values or deliberately not define values to ensure the basic skills of problem-solving become an integral part of every problem.

As mentioned above, student assumptions are required to correctly trace units and/or significant digits throughout a problem if the problem statement is not complete. The student may be required to make an assumption concerning zeros being significant digits or numbers being exact. Based upon these assumptions, a student's solution may vary from another's solution but still be correct. If a student does not make appropriate assumptions for incomplete problem statements and/or if an instructor or text does not provide a well defined problem statement or does not require appropriate student assumptions, poor problem solving skills are conveyed, accepted, and practiced by students.

The second greatest area of systematic oversight in texts and in teaching units and significant digits is in Eide's fifth step, solution steps. An example is the following problem from a college engineering textbook: [1]



Example problem Given the two-dimensional, concurrent, coplanar force system illustrated in Fig. , determine the resultant, $\bar{R}$, of this system.

Solution

1. It is convenient to make a table of each force and its components assuming conventional positive x and y directions.

Force	Magnitude	x-component (→)	y-component (↑)
$\bar{F}_1$	86.0	86.0 cos 30.0° = 74.48 N	86.0 sin 30.0° = 43.00 N
$\bar{F}_2$	58.0	58.0 cos 180° = −58.0 N	58.0 sin 180° = 0
$\bar{F}_3$	72.0	$72.0\left(\frac{2}{\sqrt{20}}\right) = 32.2$ N	$72.0\left(\frac{-4}{\sqrt{20}}\right) = -64.4$ N

You should verify the computation of each of the components, taking particular note of the signs.

2. Applying Eq.

$\rightarrow \Sigma F_x = R_x = 74.48 - 58.0 + 32.2 = 48.68$ N

$\uparrow \Sigma F_y = R_y = 43.00 - 64.4 = -21.4$ N

3. Applying Eq.

$|\bar{R}| = \sqrt{(48.68)^2 + (-21.4)^2}$

$= 53.2$ N

$\theta_R = \tan^{-1} \frac{-21.4}{48.68}$

$= -23.7°$

Alternatively, $\bar{R}$ can be expressed as

$\bar{R} = 48.68\hat{i} - 21.4\hat{j}$ N

The solution steps fail to display proper unit and significant digit tracing. In step one, the solution matrix displays numbers and operations needed to derive a number with units. This is mathematically impossible. The numbers must be associated with a unit to obtain a unit. Also, the four-significant-digit x and y components of force F_1 are obtained by multiplying two numbers, each with three significant digits. This is incorrect. Only a number with three significant digits may be derived. Similarly, based upon an implicit assumption concerning the slope of force F_3, its x and y components contain three significant digits versus one digit. In step two, three numbers without units are added together to obtain a number with units, which again displays an oversight in unit tracing. Also, number(s) with a precision in the tenths are added or subtracted to a number with a precision in the hundredths to obtain a number with a precision in the hundredths. This is incorrect. The sum can only have a precision in the tenths. Then in step three, numbers without units are again used to derive answers with units. How is a student supposed to feel about unit tracing and significant digit accountability if texts and daily problem-solving presentations do not follow proper procedures? The following is a possible correct format, which reflects proper unit and significant digit tracing.[3] (The original problem statement should be amended to stipulate that the slope of force F_3 is exact.)

Solution

1. It is convenient to make a table of each force and its components assuming conventional positive *x* and *y* directions.

Force	Magnitude	*x*-component (→)	*y*-component (↑)
$\bar{F}_1$	86.0 N	$86.0\text{ N}\cos 30.0^\circ = 74.5\text{ N}$	$86.0\text{ N}\sin 30.0^\circ = 43.0\text{ N}$
$\bar{F}_2$	58.0 N	$58.0\text{ N}\cos 180^\circ = -58.0\text{ N}$	$58.0\text{ N}\sin 180^\circ = 0.0\text{ N}$
$\bar{F}_3$	72.0 N	$72.0\text{ N}\left(\frac{2}{\sqrt{20}}\right) = 32.2\text{ N}$	$72.0\text{ N}\left(\frac{-4}{\sqrt{20}}\right) = -64.4\text{ N}$

You should verify the computation of each of the components, taking particular note of the signs.

2. Applying Eq.

$$\rightarrow \Sigma F_x = R_x = 74.5\text{ N} - 58.0\text{ N} + 32.2\text{ N} = 48.7\text{ N}$$

$$\uparrow \Sigma F_y = R_y = 43.0\text{ N} - 64.4\text{ N} = -21.4\text{ N}$$

3. Applying Eq.

$$|\bar{R}| = \sqrt{(48.7\text{ N})^2 + (-21.4\text{ N})^2} = 53.2\text{ N}$$

$$\theta_R = \tan^{-1}\frac{-21.4\text{ N}}{48.7\text{ N}} = -23.7^\circ$$

Alternatively, $\bar{R}$ can be expressed as

$$\bar{R} = 48.7\hat{i}\text{ N} - 21.4\hat{j}\text{ N}$$

Although the above example is from a text, the same problems occur in daily instruction. In an effort to solve problems, instructors become fixated on the solution approach and overlook the basics. Students are systematically taught that the solution is the only goal. Unit and significant digit accountability are perceived as topics that they should know but need not apply.

The need for attention to basics is very apparent in the last step of Eide's engineering problem-solving presentation method, identify results & verify accuracy. Look at the two solutions to the above sample problem. Both solution processes derived the magnitude and direction of the resultant vector R. Neither solution, however, presented the resultant vector in a final non-Cartesian format form, although the textbook did provide a diagram. Also when the solutions were provided in a Cartesian format, the initial example continues to display both unit and significant digit errors. The unit, N, is only attached to the second value, and 48.68 should be 48.7.

These oversights in texts and our daily practices do not foster good habits in students and reflect poorly upon instruction methods and textbooks. It is not good practice for instructors or students to pay lip service to unit tracing and significant digit accountability. To set policies such as:

> "Your final answer should be accurate to:
>
> 1. Three significant figures of the first non-zero number begin with 2-9.
> 2. Four significant figures of the first non-zero number begin with a one.
>
> Carry full intermediate results in calculator registers so as to avoid round-off errors in your final answer." [4]

does students and the engineering community a disservice.

Summary

The above oversights in unit and significant digit accountability are not due to faculty shortcomings in basic engineering principles and procedure knowledge. The oversight is a faculty time versus effort problem. Is the effort required to make textbooks and daily solutions correct in terms of units and significant digits worth the time? Is the effort placed on teaching and requiring students to always use units and account for significant units in deriving their solutions worth the time? Arguably, the answer to both questions is "Yes". The recent Mars Climate Orbiter is a prime example of failure to focus attention on the basics. A simple communication breakdown with respect to units resulted in the loss of a $125 million satellite.[5] If the engineering system of teaching emphasizes unit conversions and significant digit basics as an ingrained persistent procedure, similar losses might be avoided.

Teaching and textbooks must constantly reinforce the basics. The engineering community has given teachers the responsibility of ensuring that students know the basics. The community is dependent upon instructors to endow students with proper unit tracing and significant digit accountability skills along with a deep embodiment for attention to detail.

Recommendations

It is imperative that instructors emphasize the basics to include unit tracing and significant digit accountability throughout all texts and daily problem-solving solutions. A simple way to ensure significant digits are properly considered is to display all numbers in scientific notation. In this way, significant digit accountability is systematically enforced throughout the engineering problem-solving process. As for unit tracing, every solution process should always require value and unit combinations. Numbers should never stand alone unless they are constants. It is the unit that gives every number meaning.

It is the responsibility of each freshman engineering professor to set the stage for the smooth transition of each student into the engineering profession. As a result, professors need not only cover course technical material but also constantly reinforce the basics. As a result, all graded exercises should appropriate points for proper tracing and accountability of units and significant digits throughout a student's problem-solving presentation and not just for the answer.

It is further recommended that integration of and compliance with standard engineering practices in terms of unit tracing and significant digit accountability receive special attention as a part of ABET self-assessment.

Problem Answer: There are several possible solutions to the problem described in the Introduction, which are based upon assumptions made about the number of significant digits provided in the problem statement. The more common solutions are:

a. Assumed all given values are exact => 39 457.6 J
b. Assumed only that all zeros are significant digits => $3.9(10^4)$ J
c. Assumed nothing about given information => $4\ (10^4)$ J

Bibliography
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5. "Tiny, simple mistake led to loss of Orbiter", *The Roanoke Times*, October 1, 1999, p. A2.

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