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GIFTS: Assumptions, Approximations, and Dimensional Analyses, Oh My!

Dr. Charles E. Pierce, University of South Carolina

Dr. Pierce is the Director for Diversity and Inclusion and Associate Professor in the Department of Civil and Environmental Engineering at the University of South Carolina. He is also the ASEE Campus Representative.

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Engineering students often struggle to estimate reasonable solutions to open-ended problems. For many students, comprehensive instruction on estimation processes is lacking and there are limited opportunities to develop estimation skills. Making estimates is much different from closed-form solutions. Closed-ended problems require students to select appropriate equations, solve for unknown variables, and determine the correct answer. Solving open-ended problems, on the other hand, can push students to prioritize the identification of relevant variables rather than seek equations. In other words, students must ask themselves "what factors influence the solution?" The next steps are to make choices for the factors, often with limited information and knowledge, and create mathematical expressions that help them compute an answer. These are commonly referred to as *"back-of-the-envelope"* calculations. The choices made about what variables to consider and how to assign values to them have considerable impact on the solution.

In Introduction to Civil Engineering at the University of South Carolina, students practice estimation skills with Fermi questions, which can be likened to real engineering problems. First, students learn to make assumptions and approximations while understanding how to differentiate one from the other. An *assumption* is an estimate of the existence of a *fact*. An *approximation* is an estimate of the *value* of some quantity to a desired degree of accuracy. Assumptions are qualitative statements that often answer a "Yes" or "No" question. Numbers should not appear in an assumption, although there are some exceptions. For example, one might assume that an item is disposable, suggesting that it can be used a single time. Approximations, on the other hand, must contain values with appropriate units of measure. Values that simplify calculations without sacrificing accuracy should be prioritized; 100 pieces of an item is a much better approximation than 99 pieces. Making approximations reinforces the importance of being careful and intentional about units. Assumptions and approximations are often correlated, and our students are encouraged to establish and document those connections. Doing so deepens their understanding of the distinction between the two.

An estimated solution is then calculated by setting up and performing dimensional analyses with selected approximations. A *dimensional analysis* is a method to express *physical quantities* in terms of fundamental dimensions when there is not enough information to set up precise equations. A unit conversion represents the most common form of dimensional analysis. Deciding whether the calculation makes sense requires, among other things, knowledge of and comfort with the units associated with the answer. Repeated opportunities to perform dimensional analyses supports conceptual understanding of units that, in turn, can lead to enhanced quantitative reasoning skills.

Perhaps the most significant benefit of estimation is it emphasizes the process of solving a problem, rather than the answer. Our course leans on a famous quote from an esteemed structural engineer, Sir Ove Arup, in which he stated: *"Engineering problems are under-defined; there are many solutions, good, bad and indifferent. The art is to arrive at a good solution. This is a creative activity, involving imagination, intuition and deliberate choice."* Students collaborate during class in small teams of no more than five students to document their estimation processes that lead to good solutions. This approach has been effective, and it is recommended to use collaborative learning principles when incorporating estimation in a first-year course.