The effectiveness of brief, spaced practice on student difficulties with basic and essential engineering skills

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***Abstract*—Through extensive testing and interviews of sophomore, junior, and senior engineering students in a Materials Science Engineering course at The Ohio State University, we found that these students struggle with many skills necessary for their coursework. Often these "essential skills" were prerequisite to the course and little to no instruction time was spent on them. Online training was developed to attempt to improve these skills. Students participated in the training several times over the term, with each assignment taking 10-20 minutes and consisting of 10 questions. Students were allowed unlimited attempts on each assignment and were required to achieve mastery (80% or better) for full credit. Training covered a wide range of topics: interpreting log plots and log scales, using metric prefixes for various conversions, estimating typical values of common material properties, employing dimensional analysis, and operating equations when given variables in mixed units. Unlike the success achieved by the log plots training, most of the topics saw little and insufficient improvement as a result of training, despite the basic nature of the skills. Future improvements to the training will focus on determining which factors will help to convince students of the importance of mastering these prerequisite skills.**

Keywords—engineering, computer training, online homework, mastery learning, student understanding, essential skills

I. INTRODUCTION AND THEORETICAL BACKGROUND

Many engineering students at The Ohio State University are required to take an introductory course in Materials Science Engineering. Students are expected to leave the course with mastery of certain categories of knowledge which are utilized frequently during coursework, some of which are considered prerequisite to the course. An example of this knowledge is the ability to read and interpret log plots, training on which has been successful across multiple terms [1]. Through interviews with instructors and exploratory pilot testing, we found that students have significant difficulties with a number of other basic skills essential to a functional understanding of materials science engineering and engineering in general.

The "essential skills" studied here consist both of prerequisite skills to the course—e.g., metric prefixes and conversions, dimensional analysis, and operating equations when given variables with mixed units—as well as skills the instructor expects to impart to the students—e.g., order of magnitude estimates and patterns of common material properties.

One critical aspect of the essential skills is that they are necessary for solving the types of problems posed in exams—even the simpler ones. Therefore, it is expected that students are near 100% accuracy with these skills. Even if students are 80% accurate with these essential skills, this lack of mastery is a critical bottleneck for successful performance. Here we demonstrate that a worrisome 20-50% of students performed poorly in many of these categories. Despite this, instructional time was typically not dedicated to the prerequisite skills. In this study, we developed a series of computer-based training tasks, assigned as homework, to attempt to address these issues. The training employs the method of mastery learning, in which time on task is allowed to vary to allow each student to obtain a required level of mastery.

The two most influential versions of mastery learning are Bloom's Learning For Mastery [2] and Keller's Personalized System of Instruction [3]. Though these strategies vary in many ways, Block and Burns describe their similarities in [4]: (1) they prespecify a set of course objectives that students will be expected to master at some high level, (2) they break the course into a number of smaller learning units so as to teach only a few of the course's objectives at one time, (3) they teach each unit for mastery--all students are first exposed to a unit's material in a standard fashion; then they are tested for their mastery of the unit's objectives, and those whose test performance is below mastery are provided with additional instruction, (4) they evaluate each student's mastery over the course as a whole, on the basis of what the student has and has not achieved rather than on how well he has achieved relative to his classmates.

In a meta-analysis of courses utilizing mastery criterion for learning, Kulik showed in [5] that mastery learning is effective in improving student performance on exams at all levels of learning. This improvement is greater for students with weaker content knowledge, making mastery learning a useful remediation tool.

Another successful, and more recent, approach to learning is to use computer training as part of coursework. This has been successful in many forms: Multimedia learning modules

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viewed before lecture improved performance on immediate and delayed post-tests when compared to reading static text and figures alone [6]; deficiencies in math are largely remediated by the adaptive ALEKS tutor program [7]; and integration of physics simulations, such as circuit building, into lab have been successful in improving content knowledge as well as proficiency at actual lab tasks [8]; to name a few.

The prerequisite nature of many of the knowledge gaps we observed in Materials Science Engineering students suggests that computer-based training graded for mastery may be able to provide successful remediation of these difficulties.

This paper aims to investigate and describe student difficulties with engineering essential skills. A more complete understanding of the knowledge state of the current student population is invaluable to future steps in correcting these difficulties. Also presented are the results of mastery-based training, which can be used as a model or starting place for future corrective measures.

II. Methods

Exploratory data taken during Autumn quarter 2011 showed poor performance at the essential skills described in this paper. During Autumn semester 2012, computer-based training was given to N = 271 students in an introductory Materials Science Engineering course at The Ohio State University. Most of the students in this class are sophomore and junior engineering majors. For 6 weeks during the term, beginning in week 6, students completed the "Essential Skills Quizzes", each worth approximately the same amount of credit as one homework assignment. There were 6 quizzes, each remaining open to the students for one week. Students all followed the same training pattern; they were allowed unlimited attempts on each quiz and were required to achieve mastery--80% or better--to obtain full credit. Content in the six Essential Skills Quizzes was divided approximately evenly between interpreting log scales and the "essential skills" mentioned above. Time spent on each week's quiz varied due to the mastery grading criterion, but averaged around 15 minutes per quiz. The "essential skills" comprised the entirety of Essential Skills Quizzes 2 and 4, and half of Essential Skills Quiz 6. The remainder of the six Essential Skills Quizzes covered log scales; these results are not considered here.

In addition to the Essential Skills Quizzes, students were again awarded approximately one homework's worth of points to attend a "FLEX homework" session, where the students completed the essential skills assessment, which took about 30 minutes; cumulative time spent during the term on essential skills training and assessment averaged around 70 minutes per student. In order to better assess the impact of both the essential skills quizzes and instruction, the population was randomly split into two conditions: 127 pre-Essential Skills Quiz (week 4) participants and 144 post-Essential Skills Quiz (week 13) participants. Twenty students per condition were selected for interview data; these students were video recorded while taking the essential skills assessment and were asked to think out loud and respond to prompts from the proctor. An overview of the experimental design can be seen in Fig. 1.

Condition	Week 4	Weeks 6-12	Week 13
Pretest	**FLEX Homework** Essential Skills Assessment (≈30 minutes)	**Computer Training** Essential Skills Quizzes (≈40 minutes total)	None
Posttest	None	**Computer Training** Essential Skills Quizzes (≈40 minutes total)	**FLEX Homework** Essential Skills Assessment (≈30 minutes)

Fig. 1. Experimental conditions used in this study. Students in both conditions took the same assessment but at different times; all students completed the Essential Skills Quizzes concurrently.

Training with the Essential Skills Quizzes was administered on Carmen, a course management website used by The Ohio State University and developed by Desire2Learn. Each quiz draws randomly from a categorized question bank, so that the content each student sees is the same for a given quiz, but the specific questions may not be. This also means that consecutive attempts at a single quiz by a single student will not yield the same 10 questions, but rather a new set of 10 on the same topics. This pseudo-randomization was included to attempt to reduce the number of students simply copying down solutions from earlier attempts or from other students.

Training was consistent with the four common traits of mastery learning described by Block as follows: (1) the "essential skills" to be learned and their importance to the students were specified to the students prior to training, (2) he topics covered by the Essential Skills Quizzes were divided into 6 separate quizzes, with one quiz given per week, (3) each Essential Skills Quizzes was mastery graded and all students were given quizzes over the same content. Upon completing an attempt, Carmen provided the correct answers to all questions on the quiz, allowing the students the opportunity to learn from their errors, (4) As the entire course was not taught in mastery learning style--just the Essential Skills Quizzes--student mastery over the course as a whole could not be evaluated. However, students were awarded more points for mastering more of the quizzes. In this sense, students were rewarded by their mastery alone, not by the time it took to achieve.

Thus, the computer-based Essential Skills Quizzes fit within the standard framework of mastery learning, as described above.

III. Results

All comparisons were between-student. Correctness between pretest and posttest was compared using a Chi-squared test and numerical values were compared using appropriate t tests. Effect sizes are reported using Cohen's d such that a positive d means improvement, not merely an increase in proportion. Results are presented by category:

A. Metric Conversions

Engineering students are expected to be proficient in converting between metric units (micrograms to kilograms, centimeters to nanometers, megapascals to gigapascals, etc.). Pretest students averaged only 74.8% correct on simple metric conversion problems--surprisingly far from ceiling, given the simplicity of the skill and its constant use in the engineering

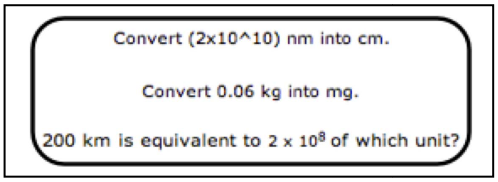

Fig. 2. Metric conversion training questions came in three types: scientific notation questions (top); decimal form questions (middle); and "find the unit" questions (bottom), which were given with multiple choice options.

courses the student had already taken. Training on metric conversions comprised 6 of the 10 questions in Essential Skills Quiz #2 plus 2 of the 10 questions in Essential Skills Quiz #6, and involved three problem types (Fig. 2).

Despite the fact that students had to achieve mastery during the Essential Skills Quizzes, we found that training on metric conversions resulted in no significant change in student performance. One of the three metric conversion questions on the essential skills assessment asked students to make a volumetric conversion from cubic centimeters to cubic meters. There was no significant difference in scores from pretest (73%) to posttest (71%). The most common error was to treat the problem as a length conversion (centimeters to meters), ignoring the volumetric nature of the problem (Fig. 3). It should be noted, however, that volumetric problems were not included in the training, thus students failed to utilize any skills they may have acquired from this quiz.

The remaining two metric conversion questions involved only linear conversions and gave conflicting results. One question asked students to convert from micrograms to megagrams, working in scientific notation; this question significantly improved from 62% to 74% ($\chi^2(1)$^2 = 4.053, p = 0.044, d = 0.25). The other question asked students to convert from kilometers to centimeters in decimal form; this question showed a marginal decrease from 89% to 82% ($\chi^2(1)$^2 = 2.652, p = 0.103, d = -0.20).

Overall, student performance on metric conversions yielded rather limited and inconsistent results. Given the importance and relative simplicity of the task, student performance is unacceptable low. On average, students scored just 74.8% correct on the three metric conversion questions before training and 75.5% after (t = 0.193, p = 0.847).

B. Dimensional Analysis

Students in engineering are expected to understand units, meaning they need to be able to analyze the dimensional relationships between variables in an equation with minimal

Response	Pretest	Posttest
Correct	73.2%	70.8%
Treat as length conversion	11.8%	15.3%

Fig 3. Common answer patterns on an example metric conversion problem. Students were asked to convert from cubic meters to cubic centimeters. The most common error was to treat the problem as a length conversion, as though converting from meters to centimeters. Neither of these changes were statistically significant.

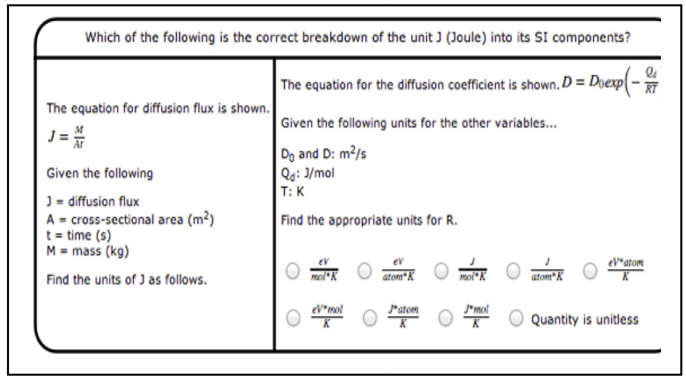

Fig 4. Dimensional analysis training questions came in three categories: unit breakdown questions (top); find the missing unit questions (left), where students were given an equation and units for all but one of the variables, then asked to solve for the units of the remaining variable; and specialized find the missing unit questions (right) dealing with the difference between the gas constant, R, and the Boltzmann constant, k. Each category consisted of both multiple choice questions and directed fill-in-the-blank questions where the student indicated the powers of respective units. An example of multiple choice responses is shown (right).

effort. For example, students should be able to determine the units of a given quantity in an equation based on the other variables involved (e.g., Fig. 4). Students would also be expected to know whether to use the gas constant or the Boltzmann constant—identical constants in different units—depending on the units of the other variables. Training on dimensional analysis involved three problem types and consisted of 7 of the 10 questions in Essential Skills Quiz #4, plus 3 of the 10 questions in Essential Skills Quiz #6.

In contrast to other essential skills categories, training on dimensional analysis resulted in significant gains in student performance for the category as a whole, improving average scores on the dimensional analysis portion of the assessment from 43% to 57% (t = 3.922, p = 0.0001, d = 0.48); it is worth noting that this is still far from ceiling, despite a relatively large effect size. Significant gains were also seen on many individual questions. One item on the assessment gave the students the equation for the theoretical density of a crystalline metallic solid as well as appropriate units for all but one of the variables. The students were then tasked with finding the units for the remaining variable. Significant improvement was shown after training (χ^2 (1)^2 = 6.781, p = 0.009, d = 0.32), with correctness increasing from 71% to 84%.

Another similar question involved determining the units of a variable in the exponent of the equation for the equilibrium number of vacancies in a material. Through interviews, it became apparent that some students were merely balancing the sides of the equation, ignorant to the fact that the exponent itself must be unitless. Part of the way through the pretest, this question was updated to the form shown in Fig. 5. This updated question showed significant improvement in terms of correctness ($\chi^2(1)$ = 7.500, p = 0.006, d = 0.49) from 33% to 56%, while the most common error--the belief that more information was needed to answer the question--decreased significantly ($\chi^2(1)$^2 = 4.545, p = 0.033, d = 0.38) from 42% to 25%. Most students claiming to need more information indicated that the rest of the equation was required.

A certain quantity changes in proportion to $e^{\frac{Q_V}{RT}}$, where
Q_V = energy required for vacancy (eV/mol)
T = temperature (K)

Find the appropriate units for the gas constant R.
If you cannot determine this without more information, what more information is required?

Response	Pretest	Posttest	
Correct	32.6%	56.4%	*
Need more info	41.9%	25.0%	*
Inverse Error	4.7%	7.1%	

Fig. 5. An example dimensional analysis question from the essential skills assessment and patterns of right and wrong answers. Asterisks indicate statistical significance at the p < 0.05 level. Student committing an inverse error submitted an answer that was the reciprocal of the correct answer.

Interestingly, students who believed that the problem could be solved with the given information showed an improvement in correctness from 56% to 72%, though this result fell just outside the range of significance ($\chi^2(1)$^2 = 3.670, $p = 0.055$, $d = 0.43$). The lack of statistical significance--despite a respectable effect size--is likely due to small pretest sample sizes, a deficiency owed to the change in pretest versions of the problem and the larger proportion of students believing more information was needed in the pretest condition.

C. Mixed Unit Equations

Engineers in the field use equations to calculate values from measurements, and the instruments providing these measurements don't always do so in consistent units. As such, it is essential that engineering students be able to operate equations--to find the value of the dependent variable--when presented with independent variables in mixed units.

The equation for the diffusion flux is shown.

$J = \frac{M}{At}$, where

A = cross-sectional area
M = mass (or number of atoms)
t = elapsed time.

Given M = 1.0 mols of a gas passing through an area of 1 cm^2 over a time of 40 ms, what is the diffusion flux in atoms/(m^2s)?

Response	Pretest	Posttest	
Correct	39.7%	46.2%	
Wrong Units	15.1%	6.3%	*
Forgot only mole to atoms conversion	10.3%	11.9%	
Off only by some power of 10	23.0%	20.3%	
Forgot mole to atoms AND off by some power of 10	19.0%	13.3%	

Fig 6. An example of a mixed unit equation train question is shown. All questions in this category had the same form, but many dealt with different equations.

The equation for the theoretical density of a crystalline metallic solid is $\rho = \frac{n A}{V_C N_A}$, where

n = number of atoms associated with each unit cell
A = atomic weight
V_C = the volume of the unit cell
N_A = Avogadro's number

Given n = 4 atoms/unit cell of aluminum (A = 27 g/mol) with V_C = 4.42*10^-23 cm^3/unit cell, find the theoretical density in kg/m^3

Fig. 7. An example mixed unit equations question from the assessment and patters of right and wrong answers. Asterisks indicate statistical significance at p< 0.05 level.

As a part of training, students were presented with an equation as well as values for the independent variables involved, which were purposefully given in mixed units (Fig. 6). Students were then asked to calculate the dependent variable in specified "target units." Training on mixed unit equation consisted of 3 of 10 questions in Essential Skills Quiz 4. Training was somewhat successful in improving average assessment scores on mixed unit equation questions from 36% to 48% ($t = 2.765$, p= 0.006, d=0.34), leaving posttest scores still below 50%.

While overall scores in the mixed unit equations category showed significant improvement in student performance, two of the three individual questions in the essential skills assessment failed to do so. Scores on the diffusion flux question, increased from 40% to 46%, but this improvement was not statistically significant ($\chi^2(1)$^2 = 1.144, $p = 0.285$, $d = 0.13$). The question statement and common errors--explicitly converting to incorrect target units, forgetting the mole to atoms conversion, and erring exactly by some power of 10--are shown in Fig. 7. For this item, the only error significantly affected by training was students giving an answer in different target units than specified in the problem statement.

A similar question involving a conversion from psi to gigapascals using Hooke's law also showed no significant change in student performance ($\chi^2(1)$^2 = 2.279, $p = 0.131$, $d = 0.18$) from pre (35%) to post (44%).

The simplest question provided students with a force in newtons and an area in square millimeters, then asked for a force in kilopascals; this was the only mixed unit equation question to show significant improvement ($\chi^2(1)$^2 = 8.992, $p = 0.003$, $d = 0.37$), with correctness increasing from 35% to 53%. It is worth emphasis that this was the simplest of the three questions of this type presented in the essential skills assessment, and 47% of students are still submitting incorrect answers after training.

D. Typical Values of Material Properties

Engineers are expected to know approximate values for various material properties and other physical constants. For example, an engineer should know that melting points and Young's moduli are usually higher for metals than polymers. They should also be able to provide a rough value for a specific material that is within a reasonable range. Training on typical values contained two problem types (Fig. 8) and consisted of 4 of the 10 questions in Essential Skills Quiz #2.

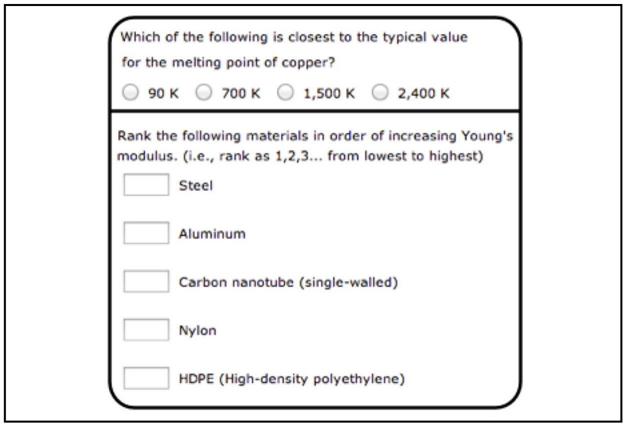

Fig 8. Typical values training questions had two categories: multiple choice (top); and ranking questions (bottom), which contained 2-5 materials to be appropriately ranked by some material property.

Training on estimates of typical values of material properties produced a range of results from significant gains to marginal losses. Cumulative student performance on questions in this category showed a nonsignificant change (t = 1.461, p = 0.145, d = 0.18) from pre (35%) to post (40%).

A series of three questions asked students to estimate the Young's modulus of three materials: copper, aluminum, and high-density polyethylene (HDPE). Since student responses to these questions spanned such a broad range, we analyze the results a number of ways. One metric was to use an "acceptable range" for the numerical answers, which was set by a course instructor (see Fig. 9). By this metric, student responses to the question on copper showed significant improvement (χ^2(1)^2 = 5.377, p = 0.020, d = 0.30), with the percentage of students in the acceptable range increasing from 34% to 49%. Student estimates of the Young's modulus of aluminum showed no significant improvement (χ^2(1)^2 = 0.805, p = 0.370, d = 0.11) from pre (40%) to post (45%). HDPE started and remained at 25% within the acceptable range, showing no change at all. Note that none of the posttest values are higher than 50%, despite the fact that training contained problems dealing with Young's modulus.

A second metric was to determine whether student responses were in any of four increasingly large "ballparks": within 20% of the correct answer, within 2x the correct answer, within 5x the correct answer, and within 10x the correct answer. This metric revealed a slightly more detailed picture which can be seen Fig. 10. While student performance on the copper question showed some improvement across the board, most of this came from significant increases in the larger ranges--students in the "within 10x" range increased from 48% to 75% (χ^2(1)^2 = 18.531, p < 0.0001, d = 0.57). Conversely, students in the "within 20%" range did not significantly change (χ^2(1)^2 = 1.988, p = 0.159, d = 0.18) from pre (9%) to post (15%). Student responses for aluminum displayed strange behavior; students in the "within 10x" range significantly increased (χ^2(1)^2 = 10.349, p = 0.001, d = 0.41) from 55% to 74%, while those in the "within 20%" range actually saw a significant decrease (χ^2(1)^2 = 5.395, p = 0.020, d = -0.30) from 21% to 10%. In essence, student responses settled into something resembling orbit around the correct answer. This approach yielded no significant change in student responses for the question about HDPE for all ranges.

Material	Actual Value	Accepted Range
Copper	117 GPa	50 - 300 GPa
Aluminum	69 GPa	25 - 200 GPa
HDPE	800 MPa	500 MPa - 10 GPa

Fig 9. "Acceptable ranges" for the Young's modulus of materials used on the essential skills assessment, specified by the instructor.

The final metric attempts to focus more on the relative values of student responses, rather than the magnitude of the value itself. Through discussions with the course instructor, it was expected of the students that they at least give higher Young's modulus values for the metals than for the polymer. Students giving a higher value for HDPE than for aluminum decreased significantly (χ^2(1)^2 = 9.280, p = 0.002, d = 0.40) from 55% to 36%; students giving a higher value for HDPE than for copper decreased significantly (χ^2(1)^2 = 6.250, p = 0.012, d = 0.32) from 59% to 43%. The percentage of students incorrectly giving a higher Young's modulus for HDPE than for both aluminum and copper fell significantly (χ^2(1)^2 =4.314, p = 0.038, d = 0.27) as well, from 49% to 36%. These values can be seen in Fig. 11. Despite statistical significance, it is again worth noting that posttest students still make at least one of these errors about 40% of the time.

Students were also asked to rate their confidence in their answers. Student confidence increased significantly for copper (t = 2.477, p = 0.014, d = 0.43) and HDPE (t = 2.410, p = 0.017, d = 0.43), but decreased non-significantly for aluminum (t = -1.159, p = 0.248, d = -0.20). Neither pretest nor posttest confidence rankings exceeded 2.2 out of 5 for any of

Material & Range	Pretest	Posttest	
Copper (within 20%)	8.9%	14.8%	
Copper (within 2x)	27.7%	39.3%	
Copper (within 5x)	40.2%	68.1%	*
Copper (within 10x)	48.2%	74.8%	*
Aluminum (within 20%)	20.7%	10.2%	*
Aluminum (within 2x)	33.6%	31.4%	
Aluminum (within 5x)	43.1%	59.9%	*
Aluminum (within 10x)	55.2%	74.5%	*
HDPE (within 20%)	1.8%	0.7%	
HDPE (within 2x)	6.2%	5.9%	
HDPE (within 5x)	15.9%	17.0%	
HDPE (within 10x)	28.3%	25.9%	

Fig 10. Classification of student estimates of the Young's modulus of copper, aluminum, and high-density polyethylene (HDPE) in relation to the actual value. Asterisks indicate significant change at the p < 0.05 level, though not all of these changes were improvements.

Error	Pretest	Posttest	
HDPE > Aluminum	55.4%	36.0%	*
HDPE > Copper	59.3%	43.4%	*
HDPE > Both	49.1%	36.0%	*

Fig 11. Relative value error frequencies for typical value problems asking student to estimate Young's modulus of aluminum, copper and HDPE. As these are errors, a decrease in percentage corresponds to increasing correctness.

the three materials involved, and changes in student confidence did not match student improvement in terms of correctness.

Finally, posttest students were asked to give approximate melting points for metals, polymers, and ceramics—this question was not included in the pretest. Student responses were judged based on the correct relative order of melting points; 71% of students ordered the melting points correctly. This leaves almost 30% of posttest students unable to correctly rank typical melting points of three distinct material classes.

E. Interview Data

Twenty students each from pretest posttest conditions were subjected to "think-aloud" interviews as they completed the FLEX assessment. The most striking feature of these interviews was that many students not only admitted that they lacked certain knowledge and skills, but seemed content with that fact. Some excerpts from interviews are shown below:

- "Usually I look [the metric prefixes/conversions] up."
- "[Metric prefixes are] readily available on the internet and textbook."
- When asked if they felt it was important to memorize: "I feel like there's always a table for it."
- Some students described their lack of memorization of these topics as a conscious choice: "I've always been able to look them up. So, as of now, I haven't *decided* to memorize them." (Emphasis is author's)

The prevailing view for certain knowledge components seems to be something along the lines of "Why memorize it when I can always look it up?" Perhaps the whole experience is best described by one student in particular. When this student struggled on metric conversions, the proctor stated "I can answer any questions you have [about metric prefixes and conversions] once you're done." to which the student replied "Or I can just go on Wikipedia."

IV. Discussion

Computer-based, mastery-graded training on engineering "essential skills" has been effective for some knowledge, while failing to be effective other knowledge. 20-30% of students were unable to perform simple metric conversions, and neither instruction nor training was able to alter these numbers. Almost 30% of posttest students were unable to correctly rank the typical melting points of polymers, metals, and ceramics. More than 50% of students were unable to correctly operate

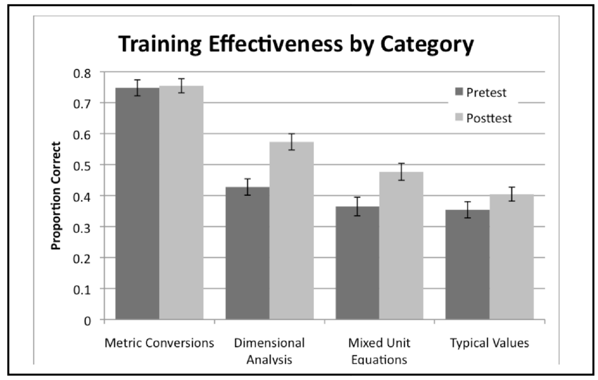

Fig 12. Training effectiveness as measured performance on the essential skills assessment, averaged by category. Only dimensional analysis and mixed unit equations showed statistically significant improvement at the $p<0.05$ level.

equations when given variables in mixed units; once again, instruction and training did little to alter these numbers. While some limited success was seen in student estimates of common material properties, 50% of posttest students were unable to estimate the Young's moduli of two metals within an instructor-specified acceptable range; a similar question involving a polymer saw 75% of students outside the acceptable range. Not only were the values incorrect, about 40% of students gave a higher Young's modulus for the polymer than for the metals.

An overview of student performance as a result of training in the four categories considered in this study can be seen in Fig. 12. Even where training was effective, as in dimensional analysis, posttest scores are still far from ceiling. The highest-performing question still saw 16% of posttest students unable to solve for the units of a given variable when given an equation and units for all other variables. As many as 25% of students leave the course not knowing that an exponential is unitless and, of the ones that do, still 25% cannot correctly solve for the units of the variable in question. Further more, 50% of student could not successfully convert a force in Newtons and an area in mm^2 to a stress in kilopascals.

Though training was more effective for some categories than for others, it was not as effective overall as necessary for such essential and fundamental skills, i.e. a posttest performance of greater than 90% correct. There are a number of possible explanations for these observations. These include:

- The training was too short (≈20 minutes for each topic).
- Posttest scores were already approaching ceiling (71% for the unit conversion).
- The students did not exert their full efforts in answering the post test questions.
- The students did not learn some of the categories because they believe that the knowledge and skills are not relevant to them.
- The students did not learn the some of the categories because they perceive the information as something not to be learned, but looked up online or in a text.

It is likely that some combination of these explanations are relevant, but as stated earlier, we have evidence from interviews that the last bullet is important for at least some of the topics. The interview data hint at an explanation for this lack of consistent success. “Or I can just go on Wikipedia.” Unlike training on log plots, the answers to which questions cannot be easily “googled,” many of the essential skills can be performed with the aide of computer tools and text references—unit conversions can be typed into the Google search bar, the metric prefixes are inside the front cover of the text, Wolfram Alpha will operate equations and perform conversions for you. Because these references are so readily available, many students do not see committing these essential skills to memory as a task worthy of their time. In the process of maximizing points earned per time spent, these tasks simply fall by the wayside. The relative success of dimensional analysis training is in line with this explanation; you can’t “google” dimensional analysis very easily, so knowledge in this category was better retained in training.

As far as students not exerting a full effort in the posttest, this is likely to play a factor, but from a number of years of experience with tests in this context, we have found that students *do* answer these questions with a reasonable amount of effort.

Note that one threat to the external validity of this study is that pre to post training gains on the test were in fact not due to the training but rather from the instruction in the course. That is, all effects reported here may be the result of a combination of training *and* course instruction, and it is not clear which (if not both) caused the gains. Therefore further research in this area would benefit from a more controlled design in order to isolate the effects of training and instruction. In any case, it is clear that, from an instructional point of view, significantly higher gains are desired.

V. Instructional Implications and Next Steps

The results of this study offer invaluable insights into the knowledge state of undergraduate engineering students. Instructors should be aware of these fundamental deficiencies in their classrooms and should take measures to ensure students are made aware of their shortcomings as well. Simple mastery-based training has been shown to be effective with some skills; future training can use this study as a starting point or a model upon which to build. At the very least, some form of intervention—instructional or otherwise—seems necessary to prevent allowing students with such critical deficiencies to slip through the academic cracks.

The continued poor performance of students suggests that it may be useful to focus on determining with factors might help convince them of the importance of mastering these essential skills, thus motivating the students to achieve mastery. In this study, the essential skills were somewhat separate from the activities of the lecture and recitations. One way to mitigate this effect is to increase the direct involvement of the instructors, helping to create a dialogue with students as to why mastery of these skills is important.

Another possible approach to further improving mastery and fluency is to progressively limit the time allowed for the Essential Skills Quizzes, particularly those containing knowledge that can easily be looked up online. This will help compel students to internalize and automate the essential skills and related knowledge.

Finally, this study suggests that instructors should consider two practical categories of essential skills and knowledge. The first is the category of skills and knowledge that lend themselves well to short, spaced training. The second category is comprised of simple knowledge or skills that one can quickly access via other resources such as the internet. This study suggests that the latter category seems to be resistant to brief training, as students often recognize easier methods for success in place of committing the skills to memory. In this second case, the relevant instructional goal would be to improve students’ mastery in efficiently accessing this information.

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