SHARE: Fermi problems to improve early-project teaming

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Motivation

Teaming in engineering design is widely studied, with several works detailing and evaluating its importance to professional development [1], [2], sense of belonging [3], and identity within engineering [4]. The ability to work in teams is highly sought after employers and highlighted as a key outcome in the ABET Criteria for Accrediting Engineering Programs [5]. This paper explores the use of Fermi problems as an intervention for low stakes, early-project teaming. Fermi problems exercise estimation and dimensional analysis skills, typically through unusual questions that require broad content knowledge. For example, one of the classical Fermi problems asks, "How many piano tuners are in Chicago?" Evaluation of these problems is typically with a logarithmic scale, in which respondents provide answers to the closest power of 10 (e.g. the generally accepted answer to the piano tuners question is 2, or 10^2 piano tuners). Fermi problems have been shown to be effective in teaching concepts such as mathematical modeling, decision making, and information literacy [6], [7]. This work brings the intervention to a biomedical engineering design course and employs it primarily for early-project teaming, as a potential replacement to more resource-heavy and time-consuming teaming exercises [8], [9].

Learning Objectives

The learning objectives of this intervention are as follows:

1. Apply content knowledge and dimensional analysis to make order-of-magnitude estimates
2. Develop and practice respectful team communication by soliciting ideas from all team members and debating conflicting viewpoints
3. Reflect on team dynamics and communication styles, focusing on applicability in a long-term engineering project

Implementation

This intervention was used in a biomedical engineering capstone design course immediately after teams and projects were assigned. This course is the first in a two-semester sequence, in which students work in teams on a year-long, industry-sponsored design project. All students in the course were fourth-year undergraduate students majoring in biomedical engineering. The course enrollment was 80 students, with teams ranging from 5 to 7 students (total of 13 teams). In this implementation, teams were given a total of 40 minutes to answer the following 6 Fermi problems (complete directions, as seen by students, and answers with rationale shown in Appendix Table 1):

1. How many piano tuners are in Chicago?
2. How many pennies need to be stacked to reach the height of the Empire State Building?
3. In days, how long would it take the average reader to read every Wikipedia page?
4. How many leaves are on an average, fully-grown oak tree?
5. How many donkeys would it take to pull a Boeing 747 at its maximum takeoff weight?
6. How many red blood cells would it take to cover the land area of Boulder County?

To incentivize participation and effort, the winning team was awarded treats from a local bakery. The assignment was graded by counting the cumulative number of orders of magnitude in error across all 6 questions; the resulting grade had no impact on students' final grades, including participation-based grades. The use of internet sources, including generative AI, was restricted to encourage creative thinking and increase the likelihood of disagreement between team members. Following the activity, students reflected on the following prompts in a team-wide discussion:

- How did your team manage communication in a large group? Did you appoint a moderator? Did someone naturally take the lead?
- How did you balance hearing everyone's ideas? Did you establish a turn-taking system? Or was there a more natural flow of conversation?
- Without naming names, did you notice that some members spoke more or less than others? In a project setting, how could that be managed to ensure equal participation?

Reflection and Situational Factors

In a class-wide discussion, students shared they found value in learning each other's communication styles and problem-solving strategies. Some students enjoyed the less serious nature of the questions, which may have led to more relaxed conversations and positive experiences. In critical responses, some students expressed a desire for the learning objectives to be made more clear at the start of the period. In contrast with prior comments, some students suggested that questions be more focused on biomedical engineering.

The following reflections combine the comments from the class-wide discussion with observations by the instructional team; no formal data collection method was used in this pilot implementation. Beneficial situational factors were: (1) teams had just been formed, so there was increased "start-of-the-project" energy, (2) there was a prize for the winning team, which encouraged friendly competition, and (3) many team members did not know each other well, thus increasing the benefit of early-stage teaming. Detrimental situational factors were: (1) the intervention occurred after an hour-long lecture, so some students were noticeably tired or unmotivated, (2) the time length of the activity was too long, exacerbating effects of the previous factor, and (3) the learning objectives were not made clear, so some students did not understand the pedagogical purpose of the activity. In future implementations of this intervention, it is suggested that:

- Learning objectives are made clear to the students, which may improve their metacognition during and after the activity. This will also address student concerns that the point of the activity is unclear.
- The time length is shortened to 30 minutes, and the questions are cut down to 4, instead of 6. This would mitigate the limitations associated with student attention and motivation.
- A greater number of biomedical engineering-related questions are used. This would create a better balance between retaining the less serious nature of the activity and having more topical questions for students in biomedical engineering. Two suggested questions with answers and rationale, are detailed in Appendix Table 2.

Future work will explore methods to quantify teaming benefits, as well as evaluate the implementation's effects on longitudinal team dynamics in conjunction with other teaming activities, such as peer evaluations [10], [11].

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Appendix

Appendix Table 1: Intervention directions and answers

<table>
<tr><td colspan="2">

Directions: Estimate the numerical answer to each of the following questions. You may use any technique or method you wish. Here are the rules:

- You must work together as a team on all questions. You cannot assign questions to individual team members and work quietly and separately. The point is to talk to each other!
- You may NOT use the internet in any way. You may NOT have phones or laptops out for any reason, including to use as a calculator (a calculator would not help you much anyways).
- Answers must be rounded to the closest power of 10. In other words, round your answer to 1, 10, 100, 1,000, 10,000, etc. Answers such as 500, 10,270, and 3 will not be "graded."
- You have 40 minutes to answer these questions.
- Accuracy will be graded by how many orders of magnitude you are off. For example, if the answer is 100 and your answer is 1,000, you are off by 1 order of magnitude.

</td></tr>
<tr><td>(1) How many piano tuners are in Chicago?</td><td>

Answer: 10^2 piano tuners

Rationale*: $3{,}000{,}000\ people\ X\ \frac{1\ piano}{20\ people}\ X\ \frac{0.5\frac{tunings}{year}}{1\ piano}\ X\ \frac{1\ piano\ tuner}{1{,}000\ tunings/year} = 75\ piano\ tuners\ (rounded\ to\ 10^2)$

</td></tr>
<tr><td>(2) How many pennies need to be stacked to reach the height of the Empire State Building?</td><td>

Answer: 10^5 pennies

Rationale: $381\ m\ X\ \frac{1{,}000\ mm}{1\ m}\ X\ \frac{1\ penny}{1.52\ mm} = 251{,}000\ pennies\ (rounded\ to\ 10^5)$

</td></tr>
<tr><td>(3) In days, how long would it take the average reader to read every Wikipedia page?</td><td>

Answer: 10^4 days (also accepted 10^5 due to logarithmic rounding)

Rationale: $7{,}000{,}000\ articles\ X\ \frac{1{,}800\ words}{1\ article}\ X\ \frac{1\ minute}{250\ words}\ X\ \frac{1\ day}{1440\ minutes} = 35{,}000\ days\ (rounded\ to\ 10^4)$

</td></tr>
<tr><td>(4) How many leaves are on an average, fully-grown oak tree?</td><td>

Answer: 10^5 leaves

Rationale: $600\ m^2\ crown\ area\ X\ \frac{4\ m^2\ leaf\ area}{1\ m^2\ crown\ area}\ X\ \frac{10{,}000\ cm^2}{1\ m^2}\ X\ \frac{1\ leaf}{100\ cm^2} = 240{,}000\ leaves\ (rounded\ to\ 10^5)$

</td></tr>
<tr><td>(5) How many donkeys would it take to pull a Boeing 747 at its maximum takeoff weight?</td><td>

Answer: 10^4 donkeys

Rationale: $830{,}000\ lbs\ X\ \frac{1\ donkey}{150\ lbs} = 5500\ donkeys\ (rounded\ to\ 10^4)$

</td></tr>
<tr><td>(6) How many red blood cells would it take to cover the land area of Boulder County?</td><td>

Answer: 10^{19} red blood cells

Rationale: $1{,}900\ km^2\ X\ \frac{10^{18}\mu m^2}{1\ km^2}\ X\ \frac{1\ red\ blood\ cell}{153\ \mu m^2} = 1.2\ X\ 10^{19}\ red\ blood\ cells\ (rounded\ to\ 10^{19})$

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</table>

**Note that provided rationale are approximate.*

Appendix Table 2: Suggested alternate questions

(1) In miles, how much suture is used in surgical procedures in the United States?	**Answer:** 10^4 miles **Rationale*:** $35{,}000{,}000\ surgical\ procedures\ X\ \frac{30\ inches\ of\ suture}{1\ procedure}\ X\ \frac{1\ mile}{63{,}360\ inches} = 17{,}000\ miles\ (rounded\ to\ 10^4)$
(2) How people in the world currently use a pacemaker?	**Answer:** 10^6 pacemakers **Rationale:** $8\ x\ 10^9\ people\ \ X\ \frac{1\ person\ with\ access\ to\ pacemaker}{10\ people}\ X\ \frac{1\ arrhythmia\ case}{40\ people}\ X\ \frac{1\ pacemaker}{10\ cases} = 2{,}000{,}000\ pacemakers\ (rounded\ to\ 10^6)$

**Note that provided rationale are approximate.*