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# Peer instruction can be as effective as lecture-based instruction in Biomedical Engineering

**Dr. Eileen Haase PhD, The Johns Hopkins University**
**Dr. Harry R Goldberg, The Johns Hopkins University**

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## Abstract

Peer instruction has been identified as an effective teaching method yet it is often used for supplementary instruction rather than as a core technique. This study provides quantitative evidence that peer teaching can effectively substitute for faculty-led instruction under certain conditions. One of the authors of this report received a Fulbright Scholar Award to train fifty biomedical engineering students in Biochemistry at Mbarara University of Science and Technology (MUST) in Uganda. At the start of this faculty member's time in Uganda, it became obvious that the instructor/student language barrier was too great to rely on lecture-based instruction, even though the official language of Uganda is English. Consequentially, the faculty member primed student learning through the use of short presentations and then enabled the students in the classroom to advance the knowledge base of their colleagues. The results indicated that the Ugandan students started at a significantly lower level of understanding compared to students at a university in the United States as measured through "individual readiness assessment tests" (Uganda: 43$\pm$9% vs US: 69$\pm$11%). However, the Ugandan students did just as well as the US students after working together on a "group readiness assessment test" (Uganda: 92$\pm$5% vs US: 93$\pm$4%).

During each class, students had multiple opportunities to work together in teams. These activities included group assessments, problem-solving, and short presentations on applications of course material, in addition to homework assignments. Both groups of students, Ugandan and US, had similar scores on the first exam, although there was a significant difference in the second exam (Uganda: 78$\pm$13; 73$\pm$11 vs US: 75$\pm$11; 80$\pm$14). The results of this study demonstrate that overall knowledge is not diminished when peer instruction is the primary form of learning.


## Introduction

The authors, along with many other engineering educators, have been strong proponents of active learning. Active, collaborative, cooperative, and problem-based learning have been demonstrated repeatedly to be more effective than lecture alone [2]. Students are 1.5 times less likely to fail in courses that use active learning [3]. When one of the authors was granted a Fulbright Scholar Award to teach a biochemistry course in Uganda, the plan was to reproduce teaching methods used in the United States such as clicker questions, think-pair-share, and team activities which would be easy for the students to adopt [4]. However, within the first five minutes of class in Uganda, it was evident that there was a significant language barrier. While the official language of Uganda is English, and all of the university courses are taught in English, it was not the native language of any of the students. There are over forty official languages in Uganda [5]. Some students never had a class taught in English until after they arrived at the university. Not only did the Ugandan students have difficulties understanding the faculty, the

faculty member was unable to understand the students. Through necessity, peer-instruction was implemented starting the first day of class.

Peer-instruction is a proven teaching method in STEM education [6] [7] and is used in the US version of this course taught at Johns Hopkins University (JHU). The primary teaching method used throughout East Africa, including Uganda, is the traditional faculty-presented lecture [8]. In this format of instruction, student comprehension of the content is tested through two three hour exams, a midterm and final. Students work individually throughout the semester and there is minimal learning from peers. Due to the language barrier, the faculty utilized peer-instruction as the primary teaching method, much more so than in the US version of the course. Class time was focused on practicing core concepts. By implementing "learner-centered teaching" which incorporates, "active, cooperative/team-based, inquiry-based, project-based, and problem-based learning", the MUST students not only learned the course content, but enjoyed the process [9].

## Methods

*Opening Day*

Students were randomly assigned to teams of four students prior to the start of the course; the same teams were maintained throughout the semester, although they had permission to request a change. Within five minutes of the very first class, the teams were given a hypothetical situation and a problem to solve. The hypothetical situation was that an unknown molecule was infecting students on campus with a deadly disease (which turned out to be eerily predictive of the COVID-19 pandemic). Teams brainstormed methods to solve one of the following:

(1) Diagnose/identify the mysterious disease,
(2) Keep the disease from spreading
(3) Treat or manage the disease.

Students had ten minutes to work on a solution, and each team had sixty to ninety seconds to share their ideas with the rest of the class. The goal of this thirty minute exercise, which took place before any lecture began, was for the students to engage in team-based activities from the very first minute of the course. The faculty also wanted students to think about the role of biochemistry in solving health care problems and provide motivation for the course topics. Though learning through team-based activities and solving open-ended problems was completely new to the Ugandan students, they readily embraced the concept. The JHU course also began with this same exercise.

*Class Format*

The MUST students (n=51) met once a week on Thursdays for a three hour lecture (3 credit course). The JHU students (n=137) met three times a week (MWF) for fifty minute lectures, and had another fifty minute section with a teaching assistant to review homework problems and review sample exam questions (4 credit course). It was expected at the start of the semester that the MUST students would complete 75% of the material taught to the JHU students due to the

difference in total class meeting times. Through many years of teaching the content, it was determined that there was no appreciable difference in the difficulty of the topics.

*Team Based Learning*

Both classes took weekly Team Based Learning (TBL) quizzes, seven of which were identical for the MUST and JHU students (the authors received IRB approval for this study). Team based learning is a proven method of peer instruction. [9][10]. The first half hour of each three-hour class was spent on a TBL quiz based on the homework and in-class exercises from the previous week. Each quiz contained ten multiple-choice questions: first given as an individual readiness assessment test (iRAT), and then as a group readiness assessment test for the team (gRAT). A sample ten-question TBL is included as Appendix 1. During the gRAT, the team used a scratch-off card to determine the correct answer and in this way, students received immediate feedback on their answers. This resulted in a greater understanding of the correct solution to each question [11]. Every member of the team was expected to share their opinion before scratching off the answer. TBLs are noisy debates with proven results. Not only do students demonstrate increased comprehension with TBL, but also better long-term retention of the material [12].

*Course Assessments*

The MUST students had two exams, a midterm and a cumulative final, each three hours in length. The JHU students had three exams, two in-class fifty minute exams and a three hour non-cumulative final. The MUST midterm and final exam questions were not identical to the JHU exams, due to differences in the number of topics covered (due to course length), timing within the semester, and length. However, many of the questions were identical and the exams were very similar in difficulty based on Bloom's Taxonomy.

The weekly homework assignments could be worked on in teams and were graded for completion. The purpose of each homework assignment was to reinforce the course material without pressure. The homework included multiple choice, problems, short answers, and open-ended questions designed to prepare students for the weekly quizzes and exams. There were three team projects: a two-minute elevator pitch for a favorite enzyme, a tutorial on a nucleic acid technology (such as PCR, CRISPR, etc.), and a funding pitch for an African health care issue (AIDS, Ebola, cholera, malaria, etc.). The three hour weekly class session was used to review the previous week's material, introduce new concepts, allow students time to work through problems alone and with each other, and explore applications of the topics.

The Ugandan educational system required that the final exam for the course was worth 60% of the course grade. The high-stakes final exam in the MUST Biochemistry course motivated the faculty to focus on key principles using proven learner-centered teaching methods during class. It was vital that students thoroughly understood all of the core concepts and receive feedback multiple times throughout the semester to ensure that they would be successful on their final exam. For this class, the remaining 40% of the course assessment was divided between the midterm (20%), team based learning quizzes (15%), and team projects/homework (5%) (see Table 1).

| Table 1 – Grading for Biochemistry in Uganda | |
|---|---|
| **Assessment** | **Percentage** |
| Homework (including team projects) | 5% |
| Team Based Learning Quizzes | 15% |
| Midterm Exam | 20% |
| Final Exam | 60% |

The MUST Biochemistry course covered the topics listed in Table 2. These topics were also covered during the first 75% of the JHU course. Additional topics in the JHU course included cell signaling, the cell cycle, and cancer.

| Table 2 –Ugandan Biochemistry Course Topics |
|---|
| Binding and Thermodynamics |
| Carbohydrate, Fat, and Nucleic Acid Structure and Function |
| Protein Structure and Function (hemoglobin) |
| Enzymes (reaction rates, competitive and non-competitive inhibitors, Michaelis-Menten, allosteric interactions) |
| Genetic Expression and Nucleic Acid Technology |
| Protein Processing and Secretion |
| Metabolic Systems (glycolysis, TCA cycle, oxidative phosphorylation) |
| Nernst Potential and Membrane Potential |

*Classroom Experience: Three Stages*

Modern instructional techniques actively involve students in classroom activities, but they are often secondary to the faculty's role. This technique had been the basis of the JHU course, in which faculty lectures interspersed clicker questions, think-pair-share, and team problems. The faculty introduced topics, discussed applications, and worked through examples for approximately 60% of each class, with 40% devoted to active learning. As described in Figure 1, the techniques used at MUST inverted this process - here students were central to the delivery of content. Faculty "lectures" consisted of a few five minute sessions, just a handful slides emphasizing one key point through figures and text, before encouraging students to work through a problem. During class, one team after another came to the board to present their solutions to their peers and answer questions about the topic. If necessary, the faculty would clarify the answer in writing on the board. Due to the language barrier, when the faculty talked it did not help students understand the material. The Ugandan students learned the material by working through problems together, talking to each other, and asking each other questions.

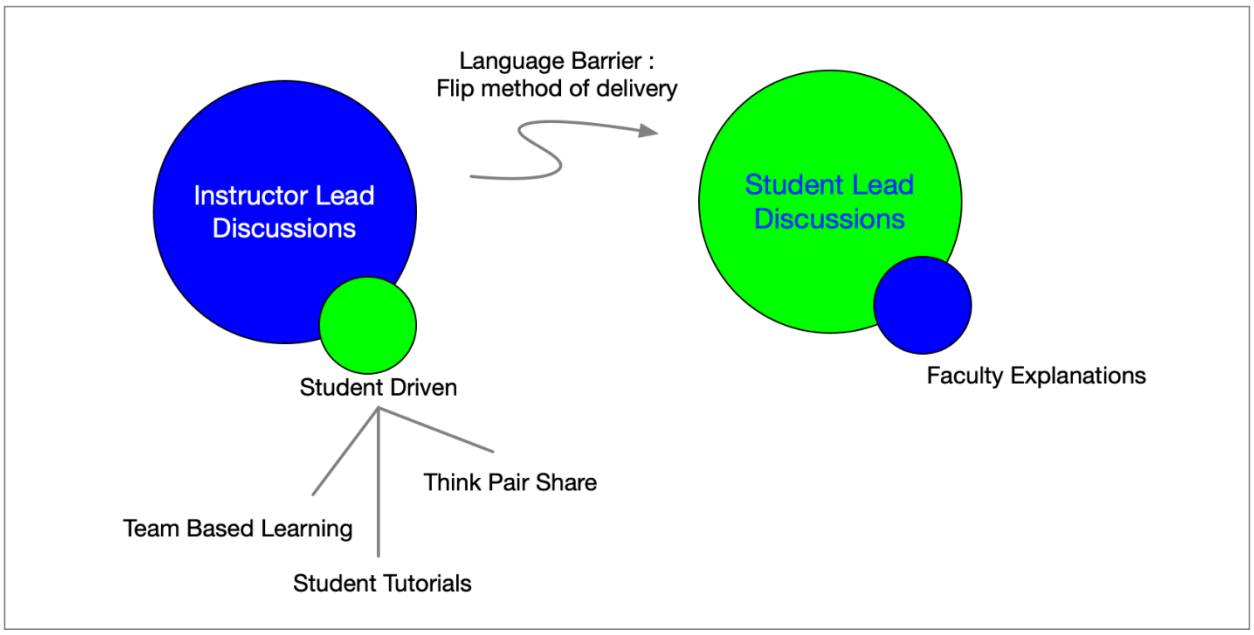



Figure 1: The figure on the left represents typical instructor-led learning (blue) supplemented with learner-centered (green) activities such as team based learning, think-pair-share, and reviewing tutorials. Due to the language barrier, knowledge transfer used in this study (right) placed students as the primary providers of content. This represents an inversion of traditional methods of instruction.

After the initial opening day exercise, the flow of information during the classroom experience followed the description in Figure 2. The rounded rectangles contain the explanation for each step. There were three stages to the classroom experience:

- Step 1: Review and warm up (team based learning, “TBL”)
- Step 2: Delivery of new content by students with faculty guidance
- Step 3: Providing students with the resources they need to prepare for the next lesson

The team based learning in Step 1 ensured that each student was prepared to build on the previous week’s content. The new content delivered during Step 2 was reinforced through multiple in-class exercises and proven peer-instruction methods such as “think-pair-share” cooperative/team-based problems, and inquiry-based projects [9]. The faculty member was responsible for defining the course content, implementing multiple modes of learning, and creating frequent assessments. In Step 3, students prepared for the next class by reviewing the previous week’s homework solutions, reading class notes and slides, following links to videos and tutorials available freely, and working through new homework problems.

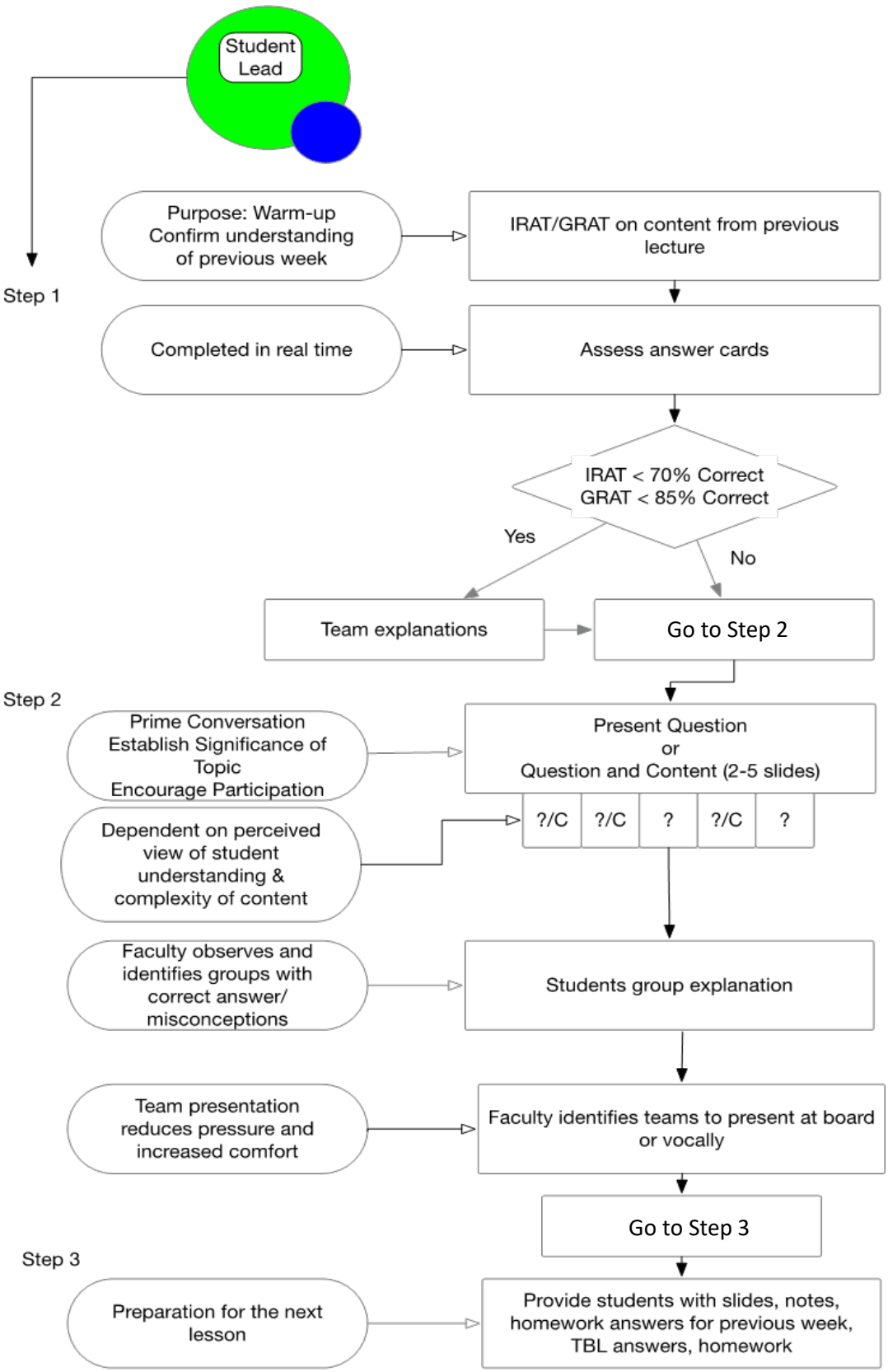



Figure 2: The flow of content through the classroom experience

*Ugandan Educational System*

The cost of education is a major issue in Uganda. The vast majority of people in Uganda live as subsistence farmers and less than 5% of the population graduates from high school [13]. None of the students had purchased the recommended textbook, which cost over $100, well over an average month's wages in Uganda. There were a few students (~15%) with laptops, and about half had smartphones. Many students had phones that could not access the internet and contacted faculty through WhatsApp™ or text message rather than with email. All course materials were emailed (slides, course notes, homework problems, answers to previous homework problems, answers to previous team based learning quizzes, and links to relevant sites) after each three-hour Thursday class. The students were given thumb drives and could use the computers at school to view and download all of the course material as part of Step 3. The faculty took great care to ensure that the homework, class material, and exam questions were well aligned.

## Results: Quantitative

*Team Based Learning: Results for iRATs and gRATs*

Over the course of the semester, both the JHU (n=137) and MUST (n=51) students took seven identical TBL quizzes. The iRAT and gRAT were each worth 50 points and contributed equally to the student's grade. Our statistical analysis used a two-tailed paired t-test to compare iRAT and gRAT scores for individual students averaged over the seven quizzes. Both groups of students demonstrated a significant improvement between the iRAT and the gRAT ($p<0.001$). We used unpaired t-tests to compare the MUST and the JHU students. The MUST students had significantly lower iRAT scores than the JHU students ($21.4\pm4.5$ vs $34.6\pm5.6$, $p<0.0001$). The MUST students improved significantly more on average, $24.7\pm4.5$ points on their gRAT, whereas the JHU students gained half as many points, $12.0\pm5.3$ points ($p<0.0001$). Because the MUST students had such a large increase between the iRAT and the gRAT, the gRAT scores for the MUST students were not significantly different than for the JHU students ($46.1\pm2.7$ vs $46.6\pm1.9$, $p>0.05$). The results are summarized in Figure 3.

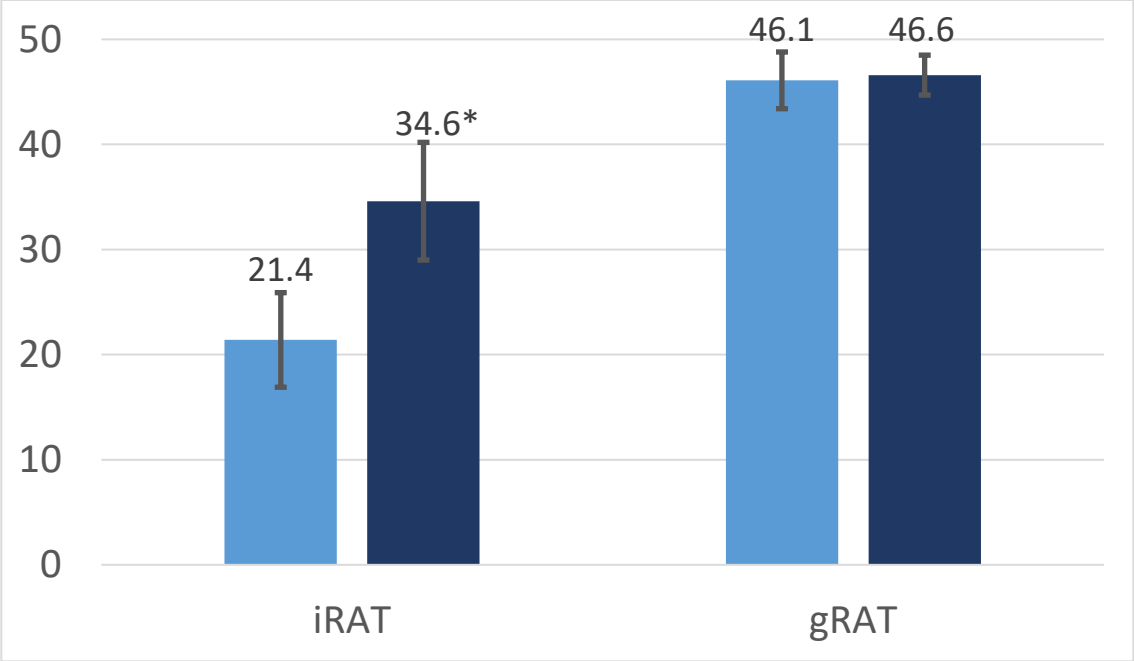



Figure 3: Team Based Learning Results: On a 50 point test, the Ugandan (MUST) students (light blue) started at a significantly lower level of understanding compared to JHU students (dark blue*) as measured through "individual readiness assessment tests" (iRAT) (MUST: 21.4±4.5 vs JHU: 34.6±5.6, unpaired t-tests, $p<0.0001$). There was no significant difference in the "group readiness assessment" (gRAT) scores (46.1+2.7 vs 46.6+1.9, unpaired t-tests, $p>0.05$). Both the MUST students (n=51) and the JHU students (n=137) had a significant increase in test scores between the iRAT and gRAT for the seven matched quizzes (paired t-tests, $p<0.001$). Values graphed are the means ± standard deviations (n=7 quizzes).

*Exams: Similarities and Differences*

Although both classes had exams on the same material, they were administered at different times during the semester and were of unequal test time. Consequently, the exams were not identical although they used many of the same questions. For the first exam, there was no significant difference in score (MUST: 78.0±13.3 vs JHU: 75.2±10.7, $p>0.05$, unpaired t-tests). For the second exam, there was a small but significant difference in the test scores (MUST 72.8 ±11.5 vs JHU: 79.9±14.2, $p<0.05$, unpaired t-tests). The Ugandan students were taking 27 credits, nine three-credit classes. The lower scores for the MUST students on the second exam could be due to the fact that the Ugandan students had nine three-hour cumulative final exams over a two week period, and the biochemistry exam was the very last exam. For the JHU students, the second exam was a one hour in-class non-cumulative exam. There was no significant difference on the averages of the two similar exams ($p>0.05$). The results are summarized in Figure 4.

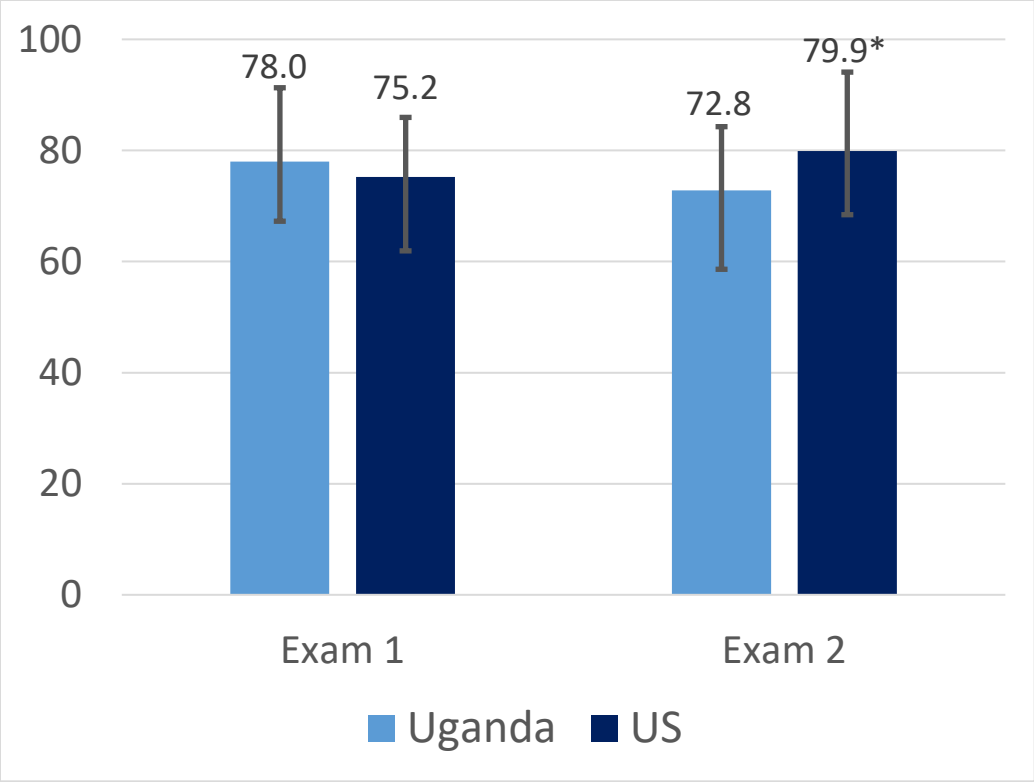



Figure 4: Exam results - comparison of two similar exams for Uganda (MUST) (n=51) vs US (JHU) (n=137) students. There was no significance difference in the scores for Exam 1 (Uganda: 78.0±13.3 vs US: 75.2±10.7, $p>0.05$, unpaired t-tests). There was a small but significant difference in the scores for Exam 2* (Uganda: 72.8 ±11.5 vs US: 79.9±14.2, $p<0.05$, unpaired t-tests). Exam 2 was the final exam for the Ugandan students, but the second of three exams for the US students. Values graphed are exam mean score ± standard deviations.

**Results: Qualitative**

*Student Support for Team Based Learning*

Data from the end-of-semester anonymous survey indicated that the TBLs were a popular change for the MUST students with 95% agreeing both the iRAT and gRAT were important. Just over half (54%) of the JHU students agreed, with a large number (43%) desiring only the gRATs. The vast majority (96%) of MUST students wanted TBL to be used in other courses, compared to 75% of the JHU students. Survey data for both the Ugandan (MUST) and US (JHU) students are listed in Table 3.

| Table 3 – Student Support For Team Based Learning | | |
|---|---|---|
| We had weekly team based learning (TBL), which used two quizzes; an iRAT (individual readiness assessment test) and gRAT (group). Please select the answer below which best describes your experience with TBL. | | |
| | **Uganda** | **US** |
| Studying for the iRAT made me keep up with the material, and participation in the gRAT further strengthened my understanding. You should continue to have both iRATs and gRATS | 95% | 54% |
| I would prefer to have only the gRATs | 5% | 43% |
| I would prefer to have only the iRATs | 0% | 1% |
| I did not find TBL helpful | 0% | 3% |

*Ugandan Student Support for all active learning methods*

The survey data indicated that 97% of students felt that they were provided the prompt and fair feedback on assessments (quizzes, homework, and exams) which was critical for their success in the course. It was important that the course was taught at the "right level and built on knowledge from previous courses" and 96% of students agreed with this statement. Most of the "teaching" during class time was from one student to another, and not directly from the faculty. But the faculty set the content, pace, in-class activities, and assessments. The MUST students were in their first year of study, and this course, "Biochemistry", was their first class within the biomedical engineering department. One of the goals of the course was to excite the students about their future careers in biomedical engineering. All of the students agreed (100%) that the course topics were "interesting with relevant examples" and 98% felt that "biochemistry is an important course in BME and provides essential knowledge and skills". A summary of the results from the end-of-semester survey is provided in Figure 5.

The enthusiasm of the Uganda students for active learning was not surprising. Previous studies have indicated that active learning is not only more effective, but also more fun [9]. From the first day of class, the focus was on engaging students to be responsible for their own learning. Most students (95%) felt that doing the research for the class presentations was a significant learning experience and that the BME department should continue using them. The students also believed (85%) that listening to their peers' presentations was valuable, but the return on their investment of time was not as great as it was when completing their own projects. Almost 90% of the students felt that the course met the posted learning objectives. All of the students (100%) believed that "the supplementary materials (lecture slides, notes, links to websites, papers) helped me to understand the course material", and 99% of the students felt that "Homework assignments helped me to better understand the lecture topics and adequately prepared me for the quizzes and exams".

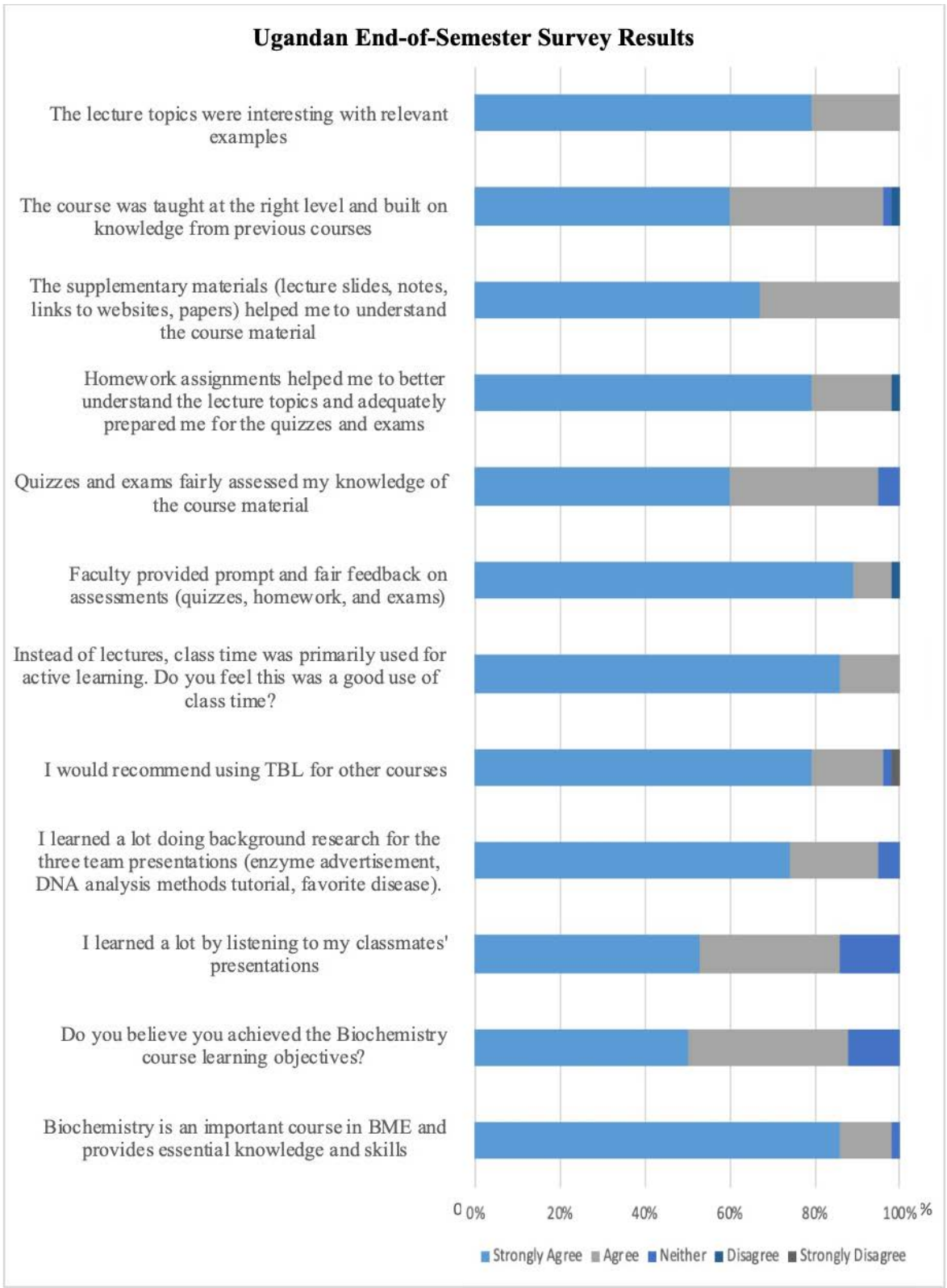



Figure 5: Uganda End-of-semester anonymous survey results (n=42).

A selection of the end-of-semester anonymous survey comments are listed in Table 4.

| **Table 4- Ugandan student comments from an anonymous end-of-semester survey** |
|---|
| *it was so wonderful…due to full participation of we students especially in iRATS, gRATS, presentations and discussions, we were able to understand most of the content.* |
| *It has taught me how to do work in my group* |
| *Assignments, presentations, quizzes, tests should also be introduced to other course units* |
| *BME as a course requires alot..... If all lecturers would use this approach.... We would not only pass highly... But also get motivated to read and understand.... And apply whatever we are reading.... Learning was so fun with you* |
| *Our problem in Africa is that the teaching mainly focuses on cramwork and not clear understanding coupled with applications. However, your mode of instruction raised my spirits and can't help yearning for more* |
| *I've loved the method of prompting students to understand as opposed to cramming which is a MOST USED in our institution.* |
| *Through the many weekly quizzes, I have been able to understand my weaknesses and do better. Quizzes are a really good teaching practice.* |
| *The continuous weekly assessment was a great way to help us understand all the topics.* |
| *Your lectures and quizzes were of great help. Thank you and please keep it up with the quizzes* |
| *When I started my second semester of my first year I was mostly worried of Biochemistry. I am happy to say that right now I see it as the simplest of all my course units, not because of its contents but because you broke it down in the simplest way for us to understand. The regular quizzes helped us to and can ably say thank you very much. I never thought I could hear you properly because of your accent and speed but you tried to slow down your explanations for us to understand. Thanks to u you and we hope even after this semester you can always come around.* |
| *She provided all necessary reading materials, for which I credit her above average. However it was hard hearing her accent during the first lectures.* |
| *I happen to be among the students that never offered chemistry nor biology at my A-level. Truth be told, l most times hate those classes, but something about the instructor made me fall in love with the course, no wonder , I think it is the only course that has registered 100% attendance every week in-week out apart from a few occasions .I mean, the passion she has for what she does speaks for itself, wooo, she is the last person I wanna let down, hoping for the best* |

**Discussion**

The MUST students did not do as well as the JHU students on the iRATs. This could be due to a number of reasons; the lack of practice with timed quizzes, difficulty in taking a timed quiz in English, and/or the differences in background knowledge from high school. The weekly quizzes forced students to prepare on their own (iRAT), but also gave them a chance to teach and learn from their classmates (gRAT). The MUST students embraced active learning and quickly understood how effective these evidence-based teaching methods were in helping them learn. In fact, they requested that other engineering faculty incorporate frequent assessments and active learning into their courses (see Figure 4). Since the author had no prior experience with the Ugandan education system, the frequent assessments also gave the author the feedback needed to teach the course at the correct level.

Ugandan students have a very formal relationship with faculty, and are often concerned about asking questions. Peer instruction bypasses this reticence by encouraging students to work together to understand key concepts at a higher level, resulting in a much deeper comprehension of content [6]. Another benefit of peer instruction is to reduce the knowledge gap between the learner and student-instructor, while maintaining faculty oversight [1]. By the end of the semester, the MUST students felt confident about the course material and prepared for the high-stakes final exam (60% of their total grade).

**Limitations**

One of the limitations of this study was the lack of follow-up testing to evaluate long-term retention. Previous results from the JHU students indicated that material taught using TBL was better retained than material that did not employ TBL [12].

There was also a difference in the time spent each week with an instructor for the Ugandan and JHU cohorts. MUST students had class once per week for three hours, for three semester credits. JHU students met four times per week and received four semester credits. The Ugandan course only covered 75% of the material taught in the equivalent JHU course but the exam questions covered the same material with equal rigor.

Few Ugandans (4%) had a significant background in biology (an upper level high school biology course). Consequently the material was completely new for almost all of the students in the class. This made it difficult for students to seek information from classmates or to answer their peers' questions initially, potentially resulting in lower iRAT scores. Around 78% of the US students had Advanced Placement Biology in high school and consequently had higher iRAT scores.

**Conclusion**

There is no question that the scarcity of quality healthcare is one of the biggest challenges in sub-Saharan Africa today. This is due not only to a lack of resources, but also inadequate education and training. The Ugandan students demonstrated significant improvements in knowledge through peer-instruction, team-based learning, and group projects. While active learning in Africa is unusual, it has previously been successful in sub-Saharan Africa biomedical engineering [14] and biology [15]. These students, the future educators of Africa, embraced active learning and will hopefully incorporate these evidence-based teaching methods into their own courses one day. Their enthusiasm for peer instruction helped the entire class achieve quiz and test results that would have been impossible due to the language barrier. Peer-instruction has been promoted for decades as a proven evidence-based teaching method. In this study, we have provided evidence that peer-instruction should have a more central role in education.

## Appendix 1: Sample Team Based Learning Quiz

1. Which of the following statements about Kd is **NOT** true?

a) A small value of Kd indicates high affinity, resulting in the ligand molecule binding more tightly to receptor
b) A small Kd indicates that the reaction will take place faster than with a high value of Kd
c) A small Kd has most molecules bound as [RL]
d) A small Kd indicates more ionic, Van derWaals, hydrogen and hydrophobic interactions
e) A small Kd indicates that the molecules are held together with weak bonds

2. You disrupt all hydrogen bonds in a protein. What level of structure will be preserved?

a) primary structure
b) secondary structure
c) tertiary structure
d) individual amino acids
e) individual atoms

3. Recall: $pH = pKa + log\frac{base}{acid}$ Explain the significance of the pK value in relation to the pH.

a) If pK > pH the species will be primarily acid
b) If pK > pH, the species will be primarily base
c) If pK=pH, half of the species is dissociated
d) Both b and c are true
e) Both a and c are true

4. If the equilibrium constant for the reaction A $\rightarrow$ B is 0.5 and the initial concentration of A is 25 mM and of B is 12.5 mM, then the reaction:

a) will proceed in the direction it is written, producing a net increase in the concentration of B.
b) will produce energy, which can be used to drive ATP synthesis.
c) is at equilibrium.
d) will proceed in the reverse direction, producing a net increase in the concentration of A.
e) will reach equilibrium when [A]=0.5[B]

5. A reaction with a positive $\Delta G$ value can be made energetically favorable by increasing the:

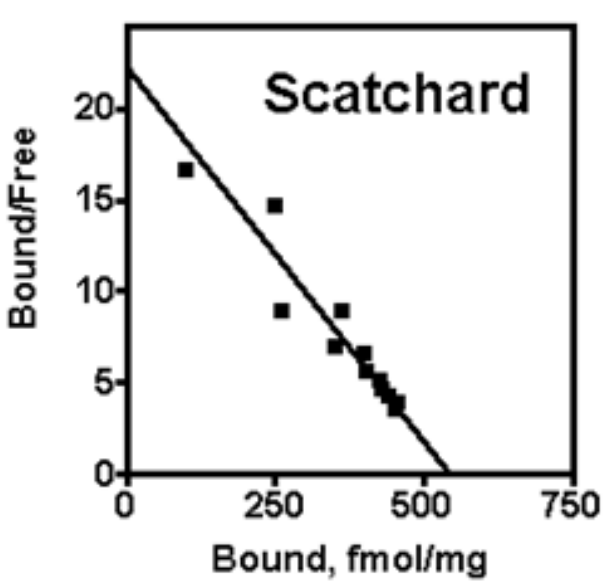
a) $\Delta G^{\circ\prime}$
b) starting concentration of products
c) adding an enzyme
d) starting concentration of reactants
e) the first two answers are correct.

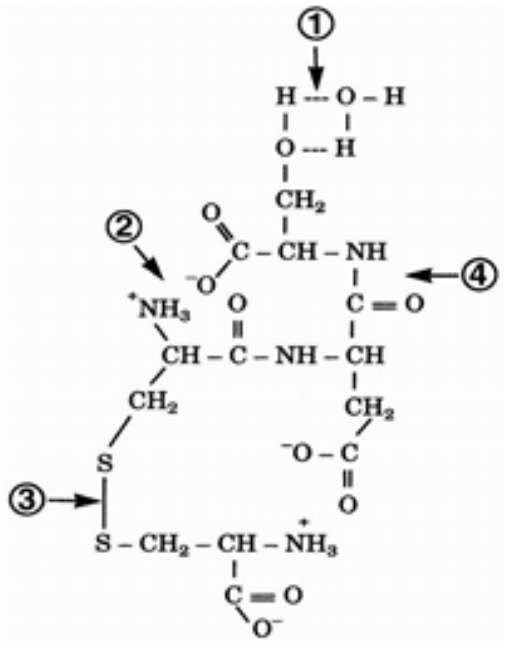
6. You have a mutant polymerase that is a more stable at high temperatures but less stable at lower temperatures. This suggests that _____ are dominant in maintaining its functional folded structure.

(a) Hydrophobic interactions
(b) Ionic bonds
(c) Hydrogen bond
(d) Disulfide bond
(e) Van der Waals interactions

7. Estimate the value of Kd from the Scatchard graph on the **left below** for the binding of a ligand to a receptor:

a) -10 b) 550 c) 25 d) 250 e) 750




8. In the figure on the **right above**, four bonds are indicated by numbers. Match the bonds with their correct description below.

a) (1) Electrostatic interaction; (2) hydrogen bond; (3) disulfide bond; (4) peptide bond
b) (1) Hydrogen bond; (2) peptide bond; (3) disulfide bond; (4) electrostatic interaction
c) (1) Hydrogen bond; (2) disulfide bond; (3) electrostatic interaction; (4) peptide bond
d) (1) Hydrogen bond; (2) electrostatic interaction; (3) disulfide bond; (4) peptide bond
e) (1) Hydrogen bond; (2) electrostatic interaction; (3) peptide bond; (4) disulfide bond

9. Any reaction A ⇔ B is at equilibrium when

a) $\Delta G^\circ = 0$
b) $\Delta G = 0$
c) [A] = [B]
d) $\Delta G = \Delta G^\circ$
e) both forward and backward rates reach zero

10. Imagine starting conditions in which the reaction X → Y is unfavorable, yet the cell needs to produce more Y. How can this be accomplished?

I. Add an enzyme to increase the speed of the reaction
II. Couple the reaction to a favorable reaction whose negative $\Delta G$ has a value larger than the positive $\Delta G$ of the X → Y reaction
III. Export Y from the cell or compartment where the X → Y reaction occurs.

a) I, II, and III b) 1 and II c) I and III d) II and III e) II

**ANSWERS: b, a, e, c, d, a, c, d, b, d**

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