Enhancing Conceptual Understanding of Electricity and Magnetism: Experiences from an Indian University

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Abstract

Context

Students studying for disciplines such as Electrical and Electronics engineering need a good foundation in Electricity and Magnetism (EM). Therefore, it is imperative to know the prior knowledge of students in this topic to address misunderstandings and misconceptions.

Purpose or Goal

Our motivation is to help students to improve their learning in EM in the post-covid era. We want to introduce suitable pedagogy and learning technology that helps address conceptual misconceptions and engages students.

Methods

We administered the conceptual inventory (CI) known as Brief Electricity and Magnetism Assessment (BEMA) to students at an Indian university studying for a physics degree. Students took BEMA in the first week of the semester (pre-test) and once at the end of the semester (post-test). We introduced the world class Pearson products, viz, Mastering Physics (MP) and Learning Catalytics (LC) and undertook a survey on MP and LC to understand the students' perspective.

Outcomes

We found that the scores from BEMA went from 24 % (pre-test) to 39 % (post-test) which is statistically significant with a large effect size (0.99). The results from the MP and LC surveys are positive which indicate that these tools were well received by students.

Conclusion

There is an improvement in the conceptual understanding of EM. MP and LC are important factors in the student learning of the subject. Students indicate that they find MP and LC quite useful. Also, the E-learning fatigue needs to be addressed to help students improve further. We intend to introduce BEMA and other CIs to engineering students through our engineering faculty colleagues and use tools such as MP and LC to help students build a solid foundation in EM and physics in general.

Keywords— Concept Inventory; Conceptual Understanding; Learning Technology

I. INTRODUCTION

THE physics courses in an engineering curriculum directly impact core engineering subjects. A deep conceptual understanding of physics is essential to build a strong Engineering background. Typical physics courses included in an engineering curriculum include Mechanics, Thermodynamics and Electricity and Magnetism. A course on Electricity and Magnetism (EM) is usually introduced in the first-year engineering and physics degree programs as it forms a basis for science and technology. Usually, students study EM in the second semester as a calculus-based physics course after going through an introduction to classical mechanics and some courses in mathematics in the first semester.

Unlike mechanics where students are familiar to situations that they can relate to daily life such as moving objects and forces, EM is perceived to be abstract, difficult, and often confusing (Chabay & Sherwood, 2006). In EM, students are expected to grasp a level of abstraction in concepts such as field, potential and flux. These abstract concepts involve in-depth mathematical description requiring differential and integral calculus in ways that students may have not had an experience previously. As a student progresses to higher years, subsequent courses depend on the concepts learnt in EM. Therefore, it is important for students to understand the fundamental concepts in EM thoroughly. This is possible if we can supplement the traditional lectures with suitable educational technology to enhance the learning of EM as well as engage them in a meaningful way thereby improving the quality of education.

When students enter university after high school education, research has shown that they have misconceptions and misunderstandings in physics (Halloun & Hestenes, 1985; Trowbridge & McDermott, 1980; McDermott et al., 1987). This led to the development of concept inventories to test student understanding (Lindell et al., 2007). A Concept Inventory (CI) is a research-based assessment instrument that probes students' understanding of a particular concept or a set of concepts that can help measure the effectiveness of teaching approaches (Porter et al., 2014). Concept inventories are intended to assess understanding and they assess different things from conventional exams (Sands et al., 2018).

Typically concept inventories contain multiple-choice questions. These questions are a result of a systematic study of the misconceptions and misunderstandings in a subject. The incorrect choices in multiple choice items are called distractors, based on the common student misconceptions (Sadler et al., 2009). Concept inventories are tests usually taken twice within the instruction sequence and do not usually part of summative assessments. They fulfil several requirements for assessing learning gain. These requirements include Validation through research, Standardization by using the same test on different students in different institutions to allow for meaningful comparisons of different students' understanding of the concept in question and Longitudinal in the sense of the same test used at two different points in time to allow for a meaningful assessment of gain by the students (McGrath et al., 2015).

The Force Concept Inventory is one of the earliest CI to be developed in the topic of force and motion and has been administered to thousands of students over the years (Hestenes et al., 1992). Apart from physics, there are several concept inventories in different disciplines such as chemistry, engineering and biosciences that are administered in universities across the globe. Examples include the biology concept inventory (Garvin-Doxas et al., 2007), and the astronomy diagnostics test (Hufnagel, 2002). Currently, there are around 60 CIs in different topics in physics and astronomy for various introductory and upper-level topics in physics and astronomy.

For Electricity and Magnetism (EM), one of the most widely used CI is the Brief Electricity and Magnetism Assessment (BEMA) (Ding et al., 2006). Many studies have used BEMA and it has been found very useful to instructors to help them evaluate their pedagogy and curriculum and understand students' level of conceptual understanding of EM (Kohlmeyer et al. 2009; Pollock, 2009; Ding et al., 2006).

II. Motivation and AIM

We would like to know how we can help enhance the conceptual understanding of EM. In the post-covid era, we are not aware of many studies on conceptual understanding of EM. Therefore, we would like to know how students in the post-covid era fare in conceptual understanding of EM using BEMA. Studies has shown that research-based teaching methods, such as interactive engagement, lead to improvements in students' gains when compared to traditional lectures (Hake, 1998). Therefore, we have incorporated Mastering Physics and Learning Catalytics in our class that enhances and engages students in their learning of EM.

In this paper we aim is to answer the following:

1. What is the impact of introducing Mastering Physics and Learning Catalytics on the conceptual understanding in EM?
2. What are the students' perspectives of Mastering Physics and Learning Catalytics?

III. Methodology

In this study, we chose students in a physics degree program at an Indian university taught by one of us. There was only one class. The students mainly went through the online mode of learning during their final years of high school due to Covid pandemic. There were 29 students who joined in September 2022. In the first semester they studied courses such as Mechanics, Chemistry and Mathematics. They continued in the second semester face-to-face starting in January 2023 where they studied EM among other subjects. This 4-credit course on EM was taught 4 hours per week for a semester spanning around 16 weeks.

Students were introduced to the world class Pearson products, viz, Mastering Physics (MP) and Learning Catalytics (LC) when they came to campus in the first semester for their Mechanics course. These products came with the textbook "University Physics with Modern Physics" by Hugh D Young and Roger A Freedman, 15th edition. We used the same book for EM as well in the second semester. The university purchased student licenses.

Mastering Physics is an online homework, tutoring and assessment system that has been used worldwide for several years with much success. It was developed at Massachusetts Institute of Technology (Lee et al., 2008). It was conceived because it was not feasible for instructors to sit down with every student on an individual basis. The system offers students hints and/or answer-specific feedback to address their misconceptions. It helps students when they encounter learning obstacles and gives them the individual coaching, they need to overcome those obstacles. Diagnostics features in MP allows instructors to know the learning misconceptions and difficulties faced by students which need to be addressed during the face-to-face session. MP can be integrated into Learning Management Systems such as Blackboard, Canvas and Moodle. Also, MP has an Adaptive Follow-Up feature. Based on each student's performance, Adaptive Follow-Up assignments provide additional coaching and targeted practice as needed to help the

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students. MP contains the e-Textbook with video tutor solutions and demonstrations and offers several different question types such as ranking, drawing, and keying in equations. It also contains the widely used PhET simulations which aid immensely in the learning of Physics. The grade book in MP contains scores, time taken and difficulty level for the questions set in the assignments which can be used to track student progress. To get started with MP and LC, students were first given an orientation by Pearson which consisted of a detailed explanation of the products.

We set 8 assignments in MP for the semester. These assignments were on topics such as Static Electricity, Gauss's law, Circuits, Magnetism and Electromagnetism. Each assignment consisted of different question types such as multiple-choice questions, numerical questions and ranking based questions. These were selected by us based on the world-wide statistics provided by MP regarding the median time taken as well as the difficulty level of the questions as perceived by students from all over the world. Each assignment was assigned for 2-3 weeks to be completed outside class hours. The time spent on an assignment was around 1-2 hours. We allowed students to take up to 6 attempts per question with a 3 % penalty imposed for each attempt taken. This ensured that students were motivated to do the problems without worrying too much on the scores. We provided the opportunity for students to think about solving problems with interest and enthusiasm instead of just submitting the assignments only for getting good grades. The assignments constituted around 12 % of continual assessment component (the other components were mid-term exam, end semester exam and other continual assessments).

Learning Catalytics is an interactive classroom tool developed at Harvard and used in several disciplines all over the world. In this system, instructors can pose a variety of questions that help students recall ideas, apply concepts, and develop critical thinking skills. Students can submit their responses through their smartphones, tablets, or laptops. The real-time display of student responses allows instructors to immediately address any student misconceptions. Instructors can adjust their teaching approach as well as initiate peer-to-peer discussion, collaboration, and communication. There are 18 question types in LC such as composite sketch, hotspot, expression, and direction which allows the deployment of a wide range of questions to engage and motivate students. This has a direct impact on their learning. We deployed LC in the classroom especially as a revision before exams. This helped students refresh their concepts and they were excited to see features such as sketching answers for questions. The real time feedback gave the instructor an insight into the misconceptions which were addressed immediately.

Students went through BEMA during week 1 (pre-test) at the start of the semester (before MP and LC were deployed) and nearly at the end of the semester in week 15 (post-test). BEMA consists of 31 multiple choice questions to be taken in 45 min. The items in BEMA cover the core concepts of EM such as electrostatics, direct current circuits, magnetostatics, and Faraday's Law. We administered a survey on MP and LC to understand the students' perspectives and feedback.

IV. Findings

There is an improvement of 15 % in the average post-test BEMA (39 %) score of students when compared to the average pre-test BEMA score (24 %) and is statistically significant at 5 % level with an effect size of 0.99. We also found that 86 % of students improved their scores in the post-test. The results are shown in Table I and Table II.

TABLE I
STATISTICS OF BEMA ANALYSIS

Number of students	Average pre-test score (%)	Average post-test score (%)	SD (pre-test)	SD (post-test)
29	24	39	11	17

TABLE II
RESULTS OF BEMA SCORES

Number of students	p-value (at 5 % level)	Effect size	Normalized gain
29	3×10^{-6}	0.99	0.19

We also found the Normalized gain to be 0.19. Normalized gain is a quantitative way of understanding the effectiveness of a course in promoting conceptual understanding (Hake, 1998) and is given by $\langle g \rangle = (\langle Post \rangle - \langle Pre \rangle)/(100 - \langle Pre \rangle)$.

The students' survey consisted of questions consisting of 5-point Likert scale as well as open ended to understand their perspective on MP and LC. The Likert scale being such that a rating of 1 being Strongly disagree to 5 being Strongly agree.

The result of the survey is as follows:

TABLE III
RESULTS OF MP AND LC SURVEY

Question	Average score out of a max 5
The number of assignment questions in MP is appropriate.	3.67
The assignment questions in MP make me aware of how much I have learnt.	4.17
MP is user friendly.	3.33
MP is an effective tutoring system.	3.83
LC is easy to use.	3.73
LC is very engaging.	3.70
I would like MP and LC for other physics topics	3.63

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The following are a sample of the responses to the open-ended questions:

Can you elaborate on positive aspects of Mastering Physics and Learning Catalytics that helped you?

"Helped to understand concepts on a practical basis and not only theoretical. Was effective in fixing my mistakes if there were any, some problems were intuitive, whereas some needed some brain power. The steps and hints helped me to progress through questions."

"Mastering physics and Learning Catalytics help to understand the topics very well."

"It helps to properly assess myself and helps to realize and understand my weak topics."

"Mastering physics has many questions that makes you understand the concepts better."

"Helps to know how much I have learnt."

Can you suggest some improvements that can be done in Mastering Physics and Learning Catalytics?

"Upload videos related to certain the topic which should be short and easy to understand."

"It is a bit tricky to input answers in mobile."

"No improvements needed."

"Nothing in particular."

Any other comments/feedback on Mastering Physics and Learning Catalytics.

"Overall, it was a decent experience using Mastering Physics and Learning Catalytics. Just a few tweaks here and there would make the experience smoother and more fluid."

"Excellent material for learning."

"I loved it".

"It is really good."

V. DISCUSSION

We find that the increase in BEMA post-test score is statistically significant. The effect size is large, and this implies that the difference in the post and pre-test score is important. We think that the MP and LC have contributed in a positive way that is reflected in the improvement of the scores and the student survey. Research has shown that activities that promote Interactive Engagement contribute to concept building (Hake, 1998) compared to just traditional lectures. Content taught in the lectures in the classroom is supplemented and enhanced by MP and LC. During online learning, it is important to have activity-based pedagogy that can engage students in a meaningful way which can involve tools such as virtual labs and simulations (Nedungadi et al., 2015; Nedungadi et al., 2017; Nair et al., 2015; Achuthan & Murali, 2017; Raman et al., 2015; Chandrasekhar et al., 2020). Therefore, we think that the features in MP and LC help in addressing abstract topics such as fields by visualization, video lab demonstrations as well as giving detailed explanation to students which is useful in increasing the conceptual understanding of topics. We also realize that courses in semester one such as mechanics and some calculus-based math courses need to be mastered well. Since we introduced MP and LC in the first semester, students benefited from the experience in mechanics before they embarked on EM and could get used to MP and LC to take on new abstract ideas and concepts.

Our study also opens doors for more research in this topic. We observe that the normalized gain is only 0.19. Moreover, even though there is a 15 % increase in the post-test scores, in other related studies, in the pre-covid era, the improvements are much higher. For example, a 35 % increase in the post-test score is noticed by Pollock (Pollock, 2008) while a 20 % increase is reported by Eaton (Eaton et al. 2019). One reason for not achieving a higher score in the post-test may be due to E-learning fatigue. This E-learning fatigue happens when students feel a sense of overload due to constant use of technology, creating mental and physical dynamics that result in less efficient and uncomfortable learning (Reed, 2022). We know that students in our study spent a considerable amount of time learning online due to Covid 19 before they started university. Hence, E-learning fatigue may have set in for many students in exploring features in MP such as the Dynamic Study Modules (DSM). The DSM tool in MP consists of many conceptual questions in every topic that require respondents to think as well as indicate their confidence level before submitting their responses. We think that while the assignments were very helpful, spending time on other features in MP needs to be highlighted to students.

Based on the MP and LC survey (Table III), students' perspectives are quite positive. From the open-ended responses, students seem to benefit from the fact that MP and LC give feedback on how much they have learnt and where they lag. Such a system where students know their learning gaps is useful so that students can take timely appropriate actions. This will have a bearing on their subsequent learning as a stronger foundation in topics will pave way to a deeper learning of future topics and courses with confidence.

The data for instructors from MP and LC helps directly to address the learning of students on a personalized basis. MP gives a variety of statistics such as average assignment scores, time taken by students and difficulty level perceived by students (Figs. 1-3). Similarly, LC gives valuable feedback in real-time in the class where students misconception can be immediately addressed (Fig 4). Learning Analytics is an emerging area in education (Chan et al., 2017). We see immense potential to do Learning Analytics using MP and LC that can benefit students early in the semester. For example, if a student is taking too much time to do questions in a particular topic, instructor can discuss with the student (Fig 2). On the other hand, if a student takes a very short time to do a multiple-choice question and takes a lot of attempts, the student has not put the required effort and is trying his/her luck to obtain the right answer. Again, the instructor can intervene and help the student realize the importance of hard work and encourage the student to spend time thinking about physics problems.

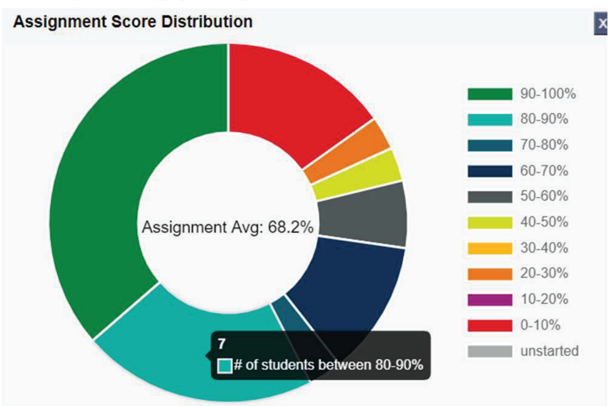

Fig 1. An example of an assignment score.

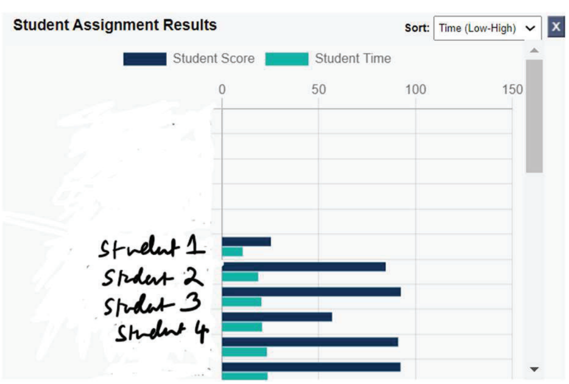

Fig 2. Student scores and time spent.

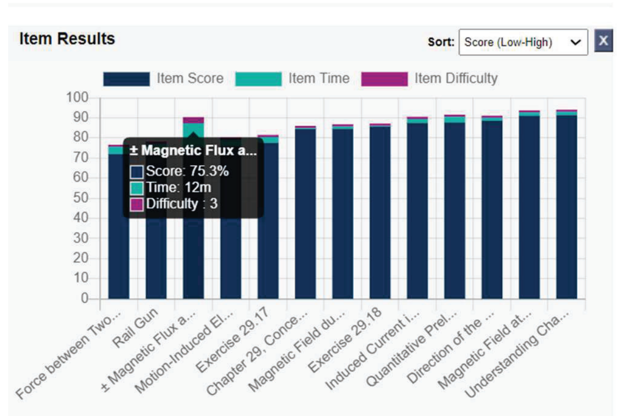

Fig 3. Item score, time and difficulty level perceived by students.

Fig 4. LC question and responses.

VI. CONCLUSION AND FUTURE WORK

We find that there is an increase in conceptual understanding of Electricity and Magnetism at an Indian University which we found through the concept inventory, BEMA. The post-test scores of students showed an average of 15% increase compared to pre-test scores that are statistically significant with a large effect size. We have used Mastering Physics and Learning Catalytics in our course which we think played an important role in improving the conceptual understanding of EM. We have also shared that the data from MP and LC can be used to do Learning Analytics to benefit students. The students were quite positive in their responses to MP and LC. They find MP and LC useful and engaging. They also find that it helps them to understand how much they have learnt. We also discussed the potential of MP and LC to give us meaningful data to perform Learning Analytics.

We think our study needs to be conducted with more students so that we can be sure of our conclusions. Hence, we are going to continue with MP and LC with the new cohorts of students. We recognize that students were diligent in submitting the assignments. However, we need to encourage students to utilize other tools in MP such as the Dynamics Study Module which can enhance their conceptual understanding. We hope to include these tools in our future curriculum formally so that students take these seriously and overcome E-learning fatigue. We hope to share our experience with the engineering faculty in our university on the concept inventories, MP and LC. This will help engineering students build a strong base in physics for a successful learning in their discipline. We would like to use Learning Analytics and conduct a more in-depth study to further improve the learning of physics and engineering. Another project is to continue our investigation by doing an in-depth item analysis in BEMA. We aim to conduct interviews with students and perform a qualitative study. We would extend our study to other topics such as mechanics and administer concept inventories such as Force Concept Inventory to understand the challenges faced by students in mechanics.

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