Enhancing Students' Conceptual Understanding with Engineered Course Material Delivery

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Abstract

This paper describes applying a new brain-based instructional approach called "Tailored Instructions and Engineered Delivery using Protocols" (TIED UP) in an engineering classroom. Brain-based strategies leverage our knowledge about the functioning of the human brain to deliver the course information effectively. Although brain-based methods have been tested extensively in K-12 education, their application in STEM higher education has been scarce. This study demonstrates its effectiveness in teaching complicated engineering concepts such as mechanism synthesis and stress analysis. TIED UP adopts the brain-based instructional methodology to create a set of easy-to-follow protocols that any STEM instructor can adopt. The results show a significant improvement in the students' conceptual understanding compared to a control condition. The method may benefit the long-term retention of information learned in the class.

Introduction

Understanding engineering concepts can be arduous, which may create a heavy cognitive load on students. Often, instructors of engineering courses find it challenging to keep an engaging environment for the students in their classroom. A significant amount of literature suggests that students' academic outcomes are strongly correlated with their classroom engagement (Astin, 1984; Berger & Milem, 1999; Carini, Kuh, & Klein, 2006; Ewell, 1988). However, keeping the students engaged in a classroom is a complicated issue. There are several factors, as identified by the literature, that influence a student's engagement in the classroom. Examples include perceived ability (Mac Iver, Stipek, & Daniels, 1991), attributions (Weiner, 1982), learning strategies (Pintrich & De Groot, 1990), self-efficacy (Schunk, 1990), goal orientation (Ammes & Ammes, 1984; Nicholls, 1984) and motivation (Corno & Rohrkemper, 1985; Deci & Ryan, 1985). According to the recent results published by the National Survey for Student Engagement (NSEE), there are four performance indicators for student engagement: academic challenge, learning with peers, experiences with faculty, and campus environment ("Engagement Indicators & High-Impact Practices," 2016; Kuh, 2001). There are several ongoing efforts to improve engagement in engineering classrooms (Gallini & Moely, 2003; Hmelo-Silver, 2004; Koretsky et al., 2015; Mott & Peuker, 2015; Sandholtz, 1997; Smith, Sheppard, Johnson, & Johnson, 2005; Zhao & Kuh, 2004). In this paper, the authors explain a blended model of instruction they developed. This model leverages brain-based learning principles and tackles several issues, such as the lack of preparation for learning new concepts in the classroom, students' inability to relate the concepts to realistic situations, and the blind dependency on formulae with limited understanding of the underlying concepts. Based on the authors' classroom experiences, these appear to be the challenges that eventually lead to a students' lack of engagement in the classroom. In this paper, the authors describe the blended model and the results from its implementation at a large school on the West Coast.

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Background

Traditional Model of Classroom Learning

The traditional learning model is limited to supporting specific approaches, such as lecture-based instruction, rote memorization, etc. (Education, 2004). It mainly relies on didactic lectures. It offers several demonstrated advantages, such as students' direct exposure to the course materials and the instructor's confidence about the required concepts' coverage (Council, 2000; Schwartz & Bransford, 1998). However, in this method, the concepts, processes, and principles are abstract, and students often have difficulty visualizing the process. There is usually a lack of connection between the concepts and the related realistic examples (Anderson, 1982). Eventually, they may lose interest and confidence, significantly impacting their grades and subject knowledge. Even though grades do not define the subject knowledge, our exam-oriented education model counts them as crucial components. Often, traditional learning does not emphasize the deeper levels of learning a concept for a lifetime memory.

Learner-centered Instruction

According to the National Research Council's report (Council, 2000) on how students learn, there are three fundamental principles of learning: (1) instruction should build on students' pre-conceptions, (2) it should develop in-depth foundational conceptual knowledge, and organize this knowledge in a useful format and (3) students should develop a metacognitive understanding and monitor their progress. These principles propose four classroom environments: learner-centered, knowledge-centered, assessment-centered, and community-centered. While each approach has advantages and disadvantages, the pedagogy proposed here focuses more on the learner. In a learner-centered approach, the focus is on what the student knows, and the instruction aims to build on their existing knowledge.

One of the learner-centered approaches relevant to the pedagogy proposed here is the "backward design" approach. According to Wiggins and McTighe, (Wiggins & McTighe, 2005), backward design is an approach where a teacher starts the instruction with the end goal in mind and modifies the curriculum according to the needs evidenced by the performance measures. This approach prompts questions with the course's end goal in mind and encourages teachers to frame their instruction around those questions (Graff, 2011). This approach's effectiveness has been proven in several controlled studies (Burgess, 2012; Graff, 2011; Radinsky, Hospelhorn, Melendez, Riel, & Washington, 2014). The TIED UP approach uses a similar process for developing the course materials.

Brain-based Instruction & Learning

Brain-based instruction relies on documented evidence of the process of knowledge acquisition in our brains and strives to deliver new course concepts in an easy-to-input format to students (Akyurek & Afacan, 2013; Bonnema, 2009; Kosar, 2018). According to literature, the new knowledge acquired by the human brain is stored in our long-term memory as inter-connected nodes of information. This is the primary reason why when someone is reminded of a concept, they can also remember the associated concepts. Putting the spotlight on process-oriented learning, it focuses on creating experiences that cater to the inner workings of the student's brain, resulting in better learning experiences and better retention of information (E. Jensen, 1995). In this method, complex concepts in the course are broken down into relatively simple, unchallenging content, and the focus in the classroom shifts from rote memorization to meaningful learning (Jack, 2010; Mollenauer, 1978) and interaction (Nisha, 2010) while also incorporating constructivist models (Carl, 2002; Gülpinar, 2005). While all instructional techniques are brain-based, the above-mentioned focuses on creating an optimum way to channel information to the student's long-term memory (Caine, Caine, McClintic, & Klimek, 2005; Sousa, 2001, 2016). Since concepts are stored in the form of inter-connected nodes, the information is also taught in the same way so that they can be easily stored in the student's long-term memory.

The brain-based learning method relies on how information is stored, organized, and retrieved from the human brain (Gülpinar, 2005). Based on the neuroscience theories, previous research has developed several brain-based learning models – these include the "Brain/Mind Learning" (Caine & Caine, 1995), the "4MAT system" (McCarthy, White, & McNamara, 1987), and the "Brain Concept of Learning" (Hart, 1978). All these models focus on easing the storage and retrieval of new information in the human brain. An example of their practical use is the "Brain/Mind Natural Learning Principles" (NLP) depicted by Caine and Caine (Muhammet Ozden, 2008).

Research has also concluded that the brain is a "use it or lose it" organ. With active usage, neural circuits grow and re-wire (White, 2014) while the information is stored and retained. Learning is also made exciting, and information retrieval is made more accessible when a framework of concepts is provided instead of delivering stand-alone ideas. In short, brain-based learning puts forward some basic principles, such as practicing real-life experiences in the learning environment, establishing effective communication with learners, and guiding learners through their learning processes. The term "effective communication" refers to two-way communication where the instructor delivers concepts through prepared materials and then seeks frequent feedback on the students' materials. Then, the instructor adjusts the future materials according to the input.

While instructional practices based on brain-based learning principles are scarce in engineering, several researchers have explored their benefits in K-12 education (e.g., Beamon Crawford, 2007; Lombardi, 2008; McNamee, 2011; Saleh, 2012; Simpson, 2012; Sprenger, 2013). A meta-analysis of 31 empirical studies on brain-based learning shows that this technique can lead to better academic achievements than traditional instructional approaches (Gozuyesil & Dikici, 2014). Several papers from various parts of the world report controlled studies supporting this argument (e.g., Agin, 2001; Ali, Ghazi, Shahzad, & Khan, 2010; Duman, 2010; Griffee, 2007).

Dimensions of an Effective Learning Environment

In higher education instruction, multiple pedagogies exist, and all of these targets creating a better learning environment in the classroom. Each technique possesses its advantages and disadvantages. According to the literature, a blended model of instruction is better in real-life practice compared to following one specific technique. Borrowing the definition set forth by Verkroost et al. (Verkroost, Meijerink, Lintsen, & Veen, 2008), a blended model of instruction is a mix of various instructional techniques, both with and without the use of the technology. A blended model class borrows dimensions from multiple pedagogies to maximize the learning benefits for the students. According to Troha(Troha, 2002), there are four dimensions for a blended model class: (1) structured/unstructured, (2) individual/group, (3) face-to-face/distance, and (4) teacher/student-directed. The right combination of these dimensions is necessary to create an effective learning environment (Verkroost et al., 2008). The TIED UP approach is envisioned as a blended model that borrows elements from several proven techniques, including brain-based instruction, flipped model, problem-based learning, and peer learning.

Tailored Instructions and Engineered Delivery Using Protocols (TIED UP)

"Tailored Instructions and Engineered Delivery Using Protocols" (TIED UP) is a media-rich blended model developed for delivering engineering concepts. Leveraging the Brain/Mind Natural Learning Principles and prior research on brain-based instruction (Caine & Caine, 1995; Eric Jensen, 2008; Weiss, 2000), the TIED UP model outlines a set of nine protocols that STEM instructors can follow while delivering course concepts. A complete list of TIED UP protocols is available in Table 1. The use of these protocols in delivering engineering concepts is explained with examples in this paper's later sections. Developed at Tuskegee University, this model is reported to improve student grades and engagement in the classroom (Solomon et al., 2020). A detailed account of these protocols' development is available elsewhere (Solomon et al., 2017).

The TIED-UP approach consists of interconnected concepts and sub-concepts consisting of pre-requisite skills and new information, making it easy for students to have a meaningful understanding of the subject. The information is provided through classroom lectures, active learning techniques, real-time examples, animated videos, computational tools, etc.

According to relative teaching practice, visual and illustrated coursework could stimulate students' senses and virtually strengthen their ability to accept information. Visual information, including pictures, diagrams, charts, plots, and experimental demonstrations paired with the verbal technique of having a voice-over, provides a pathway for digesting the data and information and retaining it for a substantial amount of time (Goldberg, 2001).

The mode of delivering information through video was chosen because it can be integrated into traditional course delivery. It can serve as a keystone for blending theoretical and practical knowledge (Bryck & 2012). It can be a handy educational tool and may serve as a productive part of the learning experience.

Prior studies have shown that the TIED UP framework's implementation has been effective at Tuskegee University in improving student grades in a mechanical engineering course (Solomon et al., 2017, 2020). In this paper, the authors investigate this framework's scalability at another institution and its potential to improve students' conceptual understanding in an upper-division engineering course.

In terms of the blended-instruction model (Verkroost et al., 2008), TIED UP is a structured approach that uses an equal mix of individual and group work. Even for the homework problems, the students are encouraged to work in groups and learn from peers. The method also uses face-to-face and distance instruction equally. While the pace of the course is mainly teacher-directed, the materials used are primarily student-directed. The students are encouraged to share their thoughts on the course materials; if they cannot understand some of them, alternate content delivery techniques are sought.

	TIED UP Protocol
P1	Connect to old/prior information
P2	Create neural connections
P3	Incorporate an active learning component
P4	Facilitate the repeated use of neurons
P5	Include an emotional component
P6	Use the Zone of Proximal Development (ZPD)
P7	Create patterns of meaning
P8	Provide an element of choice
P9	Create a cognitive map

Table 1. The protocols followed in the TIED UP instruction

Research Question

Does the TIED-UP approach help students understand new concepts better than a traditional lecture format?

Method

In this study, the TIED UP methodology has been adapted for teaching a mechanical design course at San Jose State University, a large public university on the West Coast. The TIED UP approach has two components: the 'tailored instruction' and the 'engineering delivery.' The tailored instruction follows a step-by-step methodology for delivering the content. The course syllabus was disintegrated into a format in which concepts were presented as a matrix of interconnected ideas, creating an easy information flow. The 'engineering delivery' set forward an ideal method to deliver the undergraduate level course's engineering concepts.

Participants & the Mechanical Engineering Design Course

Junior-level mechanical engineering students attending the mechanical engineering design (MED) course at (name removed) University participated in this study. The MED course covered both mechanism design and machine design components. The study was conducted across two consecutive semesters and was taught by the same instructor. The "Lecture-based Instruction" (LI) data were collected during Spring 2017 (N = 37), and the "TIED-UP-based Instruction" (TI) data were collected in Fall 2017 (N= 26). Two female students each attended the course during the data collection semesters. Due to its unique location, the student population at (name removed) University has been diverse. Approximately 40% of the class is Hispanic, while another 40% hail from Asian countries. Before the students enrolled in MED, they were expected to have mastered the concepts of statics, dynamics, and strength of materials. Besides, they were expected to know complex, vector, and matrix algebra. The class met two times a week for a class period of 1 hour 40 minutes long each. Apart from the lectures, the course also consisted of a simple project where the students could apply the concepts they learned in the classes.

Data Collection Procedure

During the LI semester, the MED course was taught traditionally – using a combination of lectures, in-class problem solving, a semester-long project, and summative assessment using midterm and final exams. The students were asked to volunteer for the research study and received an extra credit equivalent to one homework assignment for their participation. If they agreed to participate, their data were used in the analysis. Two out of 39 students did not agree to participate; hence, their data were not used for the study. The data were primarily collected from a pre-requisite quiz and the regular exams in the course. The exams were re-graded at a concept level for this study (these grades were not used for their letter grade calculation).

During the TI semester, the course material was delivered using short, scripted, and animated concept videos, follow-up in-class discussion of the videos' contents, active learning techniques, and formative assessment techniques. The data collection was performed using the same techniques as followed in the LI semester. Identical exams and homework were used in both semesters for comparison. After the exams' grading, they were not returned to the students to reuse the same questions in the following semesters.

Course Material Preparation for the TIED-UP Classroom

The MED course was divided into two separate modules for developing TIED UP materials: mechanism design and machine design. For each of these modules, the following steps are followed to create the concept delivery materials.

Step 1: The first step involved breaking down the concepts and identifying relevant sub-concepts through an interconnected model. This step broke down the course concepts into smaller chunks that could be handled independently in a concept video of 6 minutes or less in length. Prior research showed that any more prolonged duration of the videos would result in a loss of interest from the student's perspective (MD, 2004).

Step 2: The nine TIED UP protocols were applied to each concept identified in the previous step. Additional research was also performed to ensure that the information necessary to satisfy the protocol was available. For example, the first TIED-UP protocol is to "connect to old information." Elaborative encoding of new information happens in one's memory when they relate it to the old data already stored in the memory (as in protocol 2 – establish neural connections). Research shows that this elaborative encoding greatly enhances the long-term retention of a concept (Daniel Schacter, 2011). If the new concept to be delivered is "von Mises stress," the students are expected to know about the pre-requisite concepts of stress, principal stress, and the combination of stresses. This step ensured that the concept video for delivering the "von Mises stress" idea included an introductory discus-

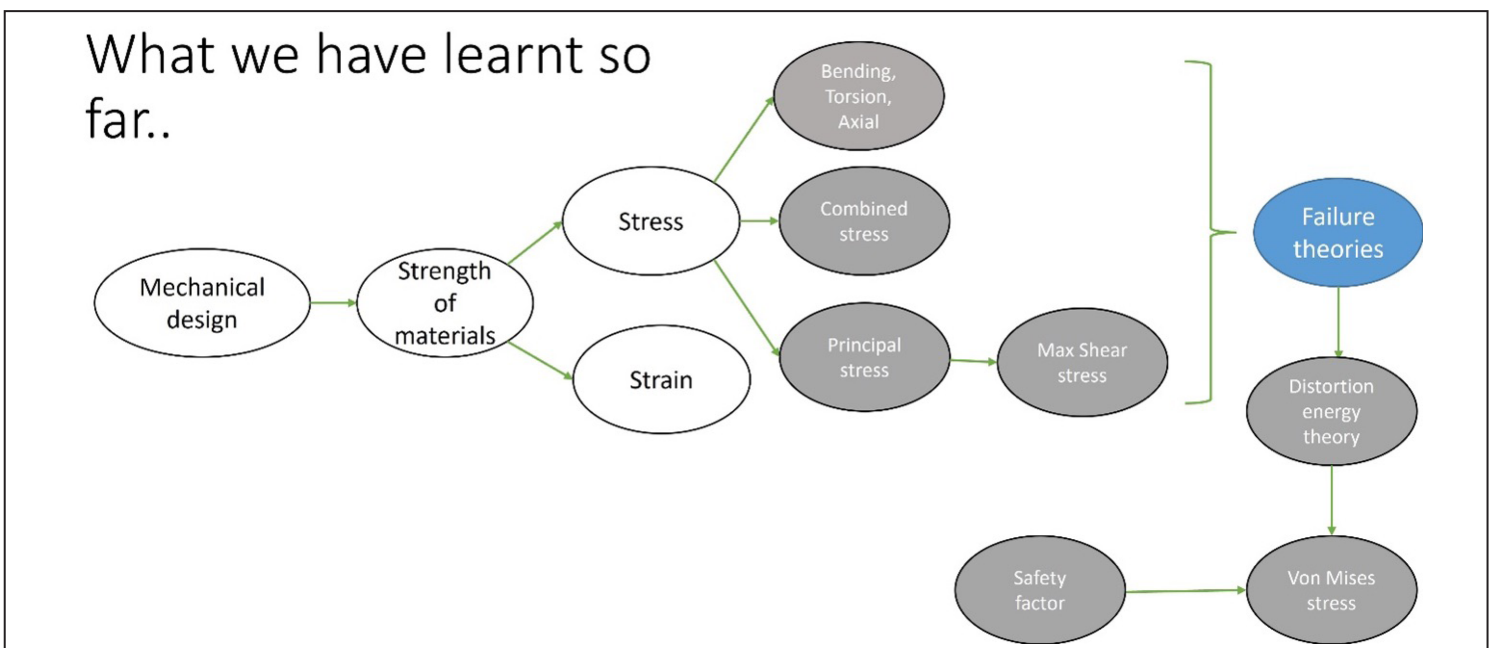

Fig. 1. The cognitive map is shown at the end of the class about "von Mises stress."

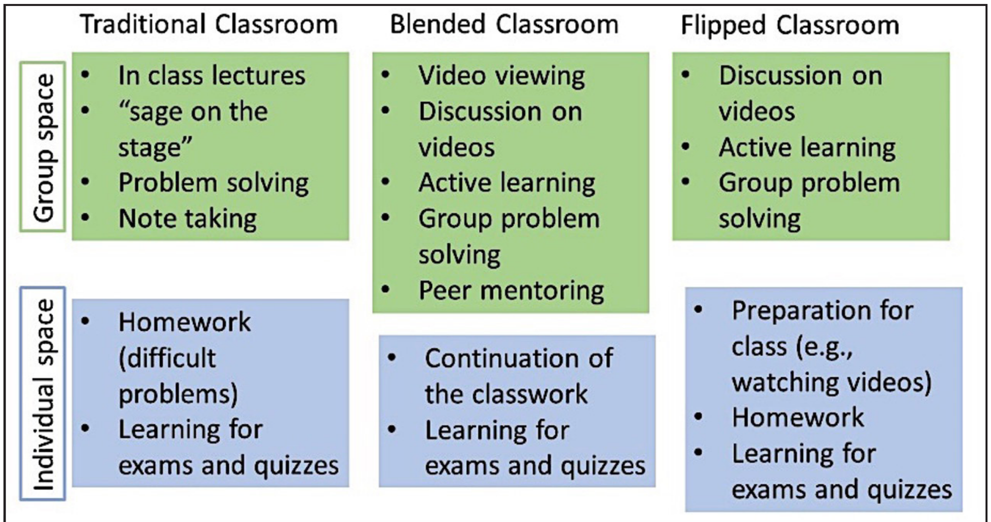

Figure 2. Comparison of a blended model TIED UP classroom with the traditional and flipped versions

sion about these prerequisites before introducing the new concept. Further, any new concept introduced in a class was also connected to the concepts the students learned in the previous classes of the same course.

Another protocol applied to the same concept was the "repeated use of neurons" (protocol 4). To satisfy this protocol, the same concept needed to be explained in different ways to make multiple rounds of review of the same concept possible. To achieve this, research was conducted to identify how this concept was taught at other universities. This was achieved using various textbooks, open-source course materials (available through multiple resources such as YouTube, MIT's Open Courseware, etc.), and discussions with the faculty teaching similar courses. Various ways to explain the same concept were identified, including these in the script. Simultaneously, it was ensured that no extra unnecessary information was given to the students to avoid confusion and cognitive overload.

Protocol 9 (create a cognitive map) was applied to all the concepts for this study. The value of cognitive mapping has been proved in prior empirical studies (e.g., Lindstrøm & Sharma, 2009). In an ideal scenario, the students are expected to meta-cognitively develop their cognitive map of the concepts they understand. However, due to the course's packed schedule, the instructor presented the cognitive map to date at the end of the discussion on each concept. These cognitive maps were also included in the concept videos. An example cognitive map for the concept of "von Mises stress" is shown in Fig. 1. This map shows what information the students already know and how the new concept builds on this previous information.

Protocols 5 (include an emotional component) and 7 (create patterns of meaning) were two other commonly used protocols. These were achieved by identifying practical examples related to the concept being taught. Most of the problems solved as a part of this course included realistic examples that the students were familiar with. For example, one of the exercises that students completed as a part of their in-class exercises was the basic design of a windshield wiper for their car. These exercises and examples targeted connecting the information they learned in the classroom with their day-to-day experiences.

The TIED UP model recognizes that students learn at different paces, and their learning styles also differ. Protocol 8, "provide an element of choice," addresses this issue. In a regular TIED UP class, most information is presented in an elementary form; however, additional representations of the same information are also given to those who want to learn more details about the concept. E.g., in the topic of "design of threaded fasteners," all the students were expected to master the basic concept of selection of fasteners. However, additional information sources were provided for students interested in specialized applications of this topic, such as higher temperatures and extreme pressures.

Out of the nine protocols, protocol 6, "use the zone of proximal development" (ZPD) (Clarà, 2017; Hamilton, Harding, Berque, & Reed, 2010), was not employed in this study. In this protocol, students solve their problems in a shared collaborative virtual workspace where the instructors can provide live feedback on their work. This study did not implement this protocol due to the unavailability of the required hardware.

On each concept, all the protocols except protocol six were applied. For some concepts, specific protocols were adequate to deliver the idea compared to a few others, e.g., on the topic of "von Mises stresses," the students were expected to connect to the pre-requisite concepts of stresses and transformation of stresses. Hence, "connect to old information" and "establish neural connections" were appropriate for teaching this topic. An active learning element where the students used a two-dimensional magnetic stress element was also developed. This activity allowed for the "repeated use of neurons" along with the discussion in the class and a peer discussion session. The exercise also helped establish a meaningful pattern of connections between what they learned in the previous lesson (about stress transformation) and the new concept. However, it was challenging to bring an emotional component to this concept as von Mises stress was not something a student could experience in everyday life. The students were directed to a tensor explanation of the stress concept to provide them with an element of choice. The class ended with a cognitive map, as shown in Fig 1. Thus, protocols 1, 2, 3, 4, 7, 8, and 9 were used for this concept while 6 and 7 were not. Each concept's delivery was carefully analyzed as in this example; as many protocols as possible were used for each. On average, at least four protocols (out of 9) were used to deliver each concept in the course. The specific protocols to deliver a concept were selected entirely based on the instructor's experience.

Step 3: For each concept, a script for the concept video was prepared so that the vocabulary was understandable to all the students, irrespective of their backgrounds. The script was designed to highlight critical information in the video. Highlighting essential information helped direct learner attention, targeting particular video elements for processing in the working memory. This could reduce the students' load by directing them to vital information which they could retain in their minds for a substantial amount of time. Visuals were created that go hand-in-hand with the script. This was called "visual imagery encoding," which involved storing new information by converting it into mental pictures (Daniel Schacter, 2011). In addition to the script, animations, and other demonstration videos were made at this stage.

Step 4: The next step was the creation of short concept videos. Camtasia® was used to record the videos. The course instructor narrated the videos as we believed that students connected more to the instructor they saw and listened to, and a change in the video's voice would distract them. The videos contained certain activities where they needed to pause and complete the activities before going to the next topic. Further, experimental demonstrations from outside sources were also linked to these videos. The videos were captioned in English to accommodate any student who needed them.

Step 5: The final step in the course material preparation process identified each class's proper active learning strategies. Throughout the TIED UP semester, four active learning tools were employed: group problem-solving, problem-based learning of individual concepts, student debate, and muddy points. Besides, several hands-on activities were introduced at appropriate times.

The Typical TIED-Classroom

Logistically, a typical TIED UP classroom resembles a flipped-model classroom. However, students are expected to prepare with the assigned materials in a flipped classroom and watch any concept videos before attending the class. In a TIED-UP classroom, the videos are shown at the beginning of the class and discussed extensively before moving on to the active learning exercises. During the showing, the videos are paused at critical locations and discussed. Two-way communication is facilitated where the instructor asks starter questions, and the students are encouraged to discuss as groups and report back to the instructor. Hence, we consider this as a "blended model classroom." The videos' primary purpose is to keep the information organized and deliver it to the students in a predetermined order to ease their learning process. Besides, the videos are always available to the students. In a follow-up survey, many students commented that these were helpful for their exam preparations, and they could understand the materials at their own pace. *Fig. 2* compares the blended model with the traditional and flipped model classes.

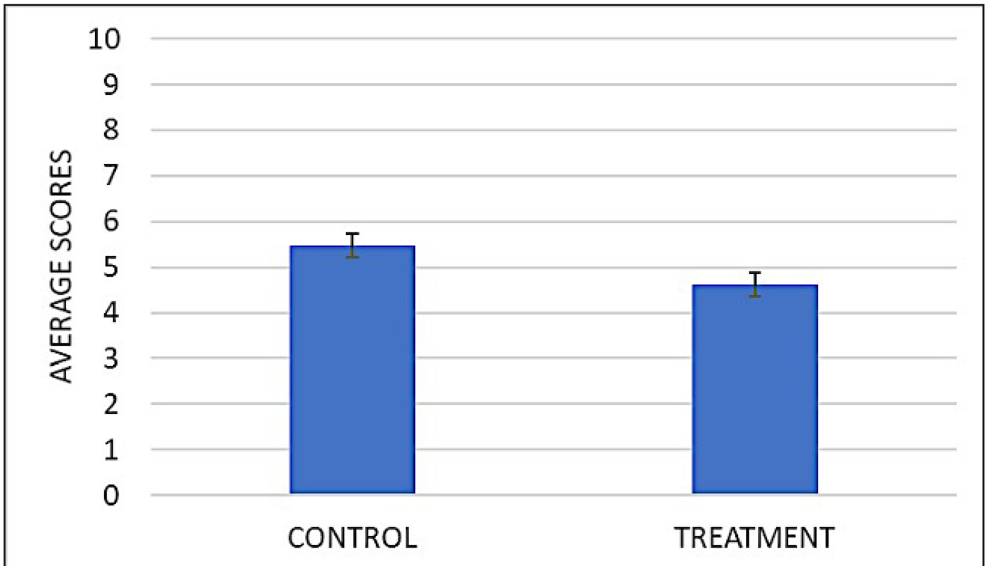

Fig. 3. Comparison of pre-requisite test data for the control and TIED-UP semesters. The error bars show (±) 1 SE.

Results

Pre-requisite data

A pre-requisite quiz was conducted on the first day of instruction for both LI and TI semesters. This quiz aimed to ensure that LI and TI did not significantly diverge in their pre-course knowledge. A set of 10 questions was given to both semesters. These were elementary conceptual questions taken from statics, dynamics, the strength of materials, and algebra. Averages of 5.14 and 4.60 were recorded for LI and TI, respectively (Fig. 3). The t-test value was 0.146 ($p > 0.05$), which showed no dissimilarity between the two groups.

The average scores for both semesters were unsatisfactory, possibly due to forgetting/lacking understanding of the pre-requisite concepts. This also paves the path for the TIED UP approach and conveys that the repeated retrieval of pre-requisite concepts is required to understand new concepts, failing which would make it difficult for them to grasp and understand the subject, which in turn may lead to student disengagement in the coursework.

Comparison between LI and TI Data

A statistical comparison is conducted across the two semesters to investigate if the TIED UP method improves understanding of the MED course concepts that are otherwise difficult for the students to understand. The analysis was performed by breaking down the midterm and final questions into a concept level and grading the problems for students' understanding of the concepts. Four topics were chosen from the mechanism design module and two from the machine design module. Almost all the topics had identical exam questions for both semesters, except for the numerical values.

1. To analyze the data, each question in consideration was broken down to a sub-question level such that the sub-question belonged to one of the following five categories:
2. A sub-question that tests a new concept that requires the knowledge of one or more pre-requisite concept(s) from a previous course
3. A sub-question that tests a new concept that requires the knowledge of one or more pre-requisite concept(s) from the same course
4. A sub-question where, in addition to the concept, the student needs a reasonable skill in elementary mathematics (e.g., algebra, trigonometry)
5. A sub-question where, in addition to the concept, the student needs a reasonable skill in advanced mathematics (e.g., calculus, differential equations)
6. A sub-question where the students should apply their theoretical knowledge in a practical scenario

To demonstrate this division of each question into sub-questions, consider the problem shown in Fig. 4. This question was taken from one of the midterm exams for the MED course. As the question describes, the students are expected to perform an analytical synthesis to derive a mechanism that satisfies all the constraints. This is a problem with multiple solutions, and the students must make educated assumptions to solve the problem. For grading purposes, the problem can be divided into the following sub-questions:

- Visualization of dyads for creating vector loops (category 2)
- Formation of vector loops and the vector loop equations (category 3)
- Generation of algebraic equations from the vector loop equations (categories 2 and 3)

The figures below show the two snapshots of a rotation to linear motion conversion mechanism. In this mechanism, the locus of the point P from position P1 to P2 is of interest. As a designer, your task is to analytically synthesize the mechanism required to achieve this movement. The lengths of all the links are unknown. The position vectors of P_1 and P_2 are known; hence $\mathbf{P_2P_1}$ is a known vector in this scenario.

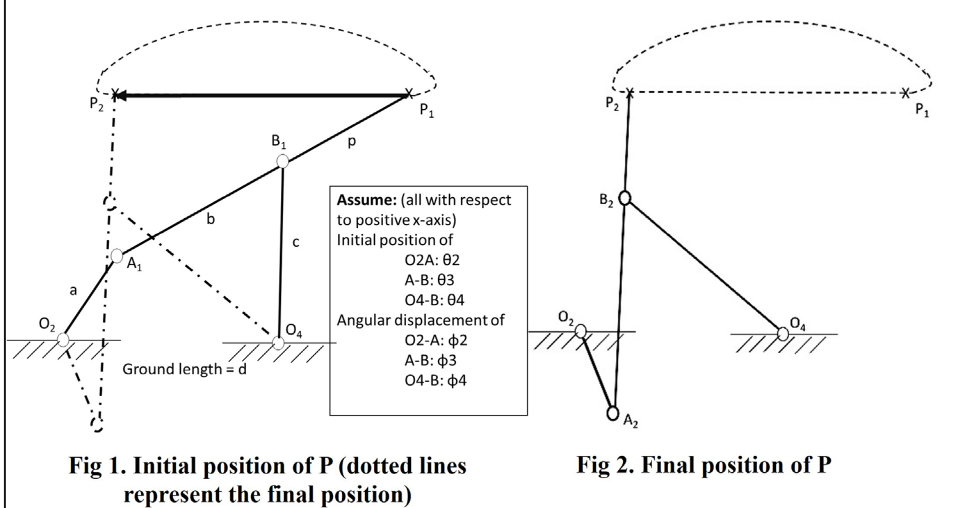

Fig 1. Initial position of P (dotted lines represent the final position)

Fig 2. Final position of P

Fig. 4. A sample question on analytical synthesis that was provided to the MED course students

Grade	Explanation
5	Displays an excellent understanding of the new concept(s) and the connected pre-requisite(s)
4	The understanding of the new concept(s) has errors but correctly connects the problem to the required pre-requisite(s)
3	Displays the knowledge of the pre-requisite concept(s) but fails to apply those correctly to the new concept(s)
2	Displays very limited knowledge of the pre-requisite(s), and that leads to error(s) in the new concept's application
1	Attempts the question but displays no knowledge of the pre-requisite(s) or the new concepts
0	No attempt to solve the question

Table 2. Grade distribution for sub-question categories 1-4

Grade	Explanation
5	Identified the required concepts, made necessary connections, and solved the question
4	Identified the required concepts, made necessary connections but made errors in solving the question
3	Identified the required concept, but the connections made were not satisfactory
2	Identified the required concept but failed to establish any connection between the concept and the question
1	Could not identify any concept associated with the question
0	No attempt to solve the question

Table 3. Grade distribution for sub-question category 5

- Simultaneous solution of a set of algebraic equations with proper assumptions (category 4)

Sub-questions in categories 1-4 were analyzed using the grading rubric shown in Table 2. These rubrics were developed through several iterations of TIED UP implementation at participating institutions (Solomon et al., 2017). The student's submission for each sub-question is carefully analyzed, and a score is given based on the rubric. The overall score for the question is calculated as the sum of the scores for these sub-questions. This sum is then normalized to match the overall score of the problem specified in the exam. E.g., in Fig. 5, if the exam sets a total score of 15 and the sum of the sub-question scores for a student adds up to 16 out of 20, then the student is awarded a score of (16*15)/20 = 12.

Sub-questions in category 5 differed from those in categories 1-4. While the latter provided information on the student's ability to identify and apply the connections between various course concepts, the former showed how well the student could use the new concept in a realistic situation. Another grading rubric was developed to grade the sub-questions in this category, as shown in Table 3. A similar approach was used to compute the overall grade for each question.

Fig. 5 compares the two semesters on the mechanism design module's sub-concepts. It can be observed that in some concepts, the students in TI showed improved understanding over LI, while in other concepts, the TI group demonstrated the same level of performance as LI. The p-values shown in the figure are from a two-tailed t-test that assumed unequal variance for the data. As indicated by the figure, out of the 15 concepts tested by the exams for this module, TI students showed statistically significant improvement in understanding five concepts. Based on the instructor's previous semesters' experience, these five represent some of the most challenging concepts in the mechanism design module. Students have struggled to understand those in the past. The data from the machine design module also showed a very similar trend.

To visualize the effect of TIED UP on student grade distribution, the percentage of students scoring each grade in the exams is compared. Fig. 6 shows the results of this comparison. It can be observed that around 66% of the TI group students scored a B or better on the exams. At the same time, only 22% of the LI students scored a B or better. It can be argued that more students are expected to achieve better exam grades with the TIED UP pedagogy.

Discussion

Overall, the results show promising trends. Evidence indicates that the TIED UP approach helped the treatment group grasp some of the complex concepts. The groups started at comparable pre-requisite knowledge levels, as shown by the average score in their pre-requisite quiz. While the pre-requisite quiz was primarily generated to establish a baseline for comparing the two groups, the results show an alarming trend. It shows that most of the students attend a higher-level class with partial knowledge of the pre-requisite concepts. This also matches the results reported by Solomon et al. (2020) in another educational setting.

A prior study on TIED UP has shown that this approach effectively improves the course grades of the participating students (Solomon et al., 2020). Students showed increased enthusiasm and engagement in the classroom. Course grades often do not accurately describe the student's understanding of the concepts and ability to apply the concepts to a problem. This research aims to address this issue. Hence, critical concepts from the MED course

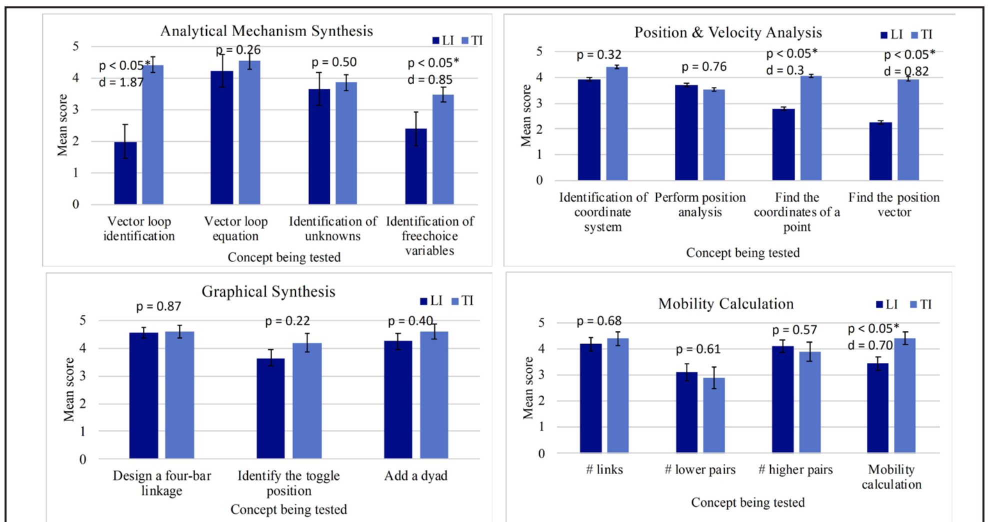

Fig. 5. Comparison between the two experimental groups on understanding the concepts in the mechanism design module. * represents statistically significant comparisons. All the error bars shown repre sent (±) 1 SE. For statistically significant comparison, Cohen's d is also shown for effect size

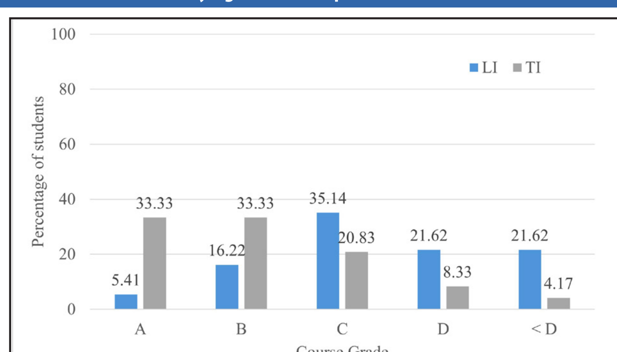

Fig. 6. Grade distribution across the two semesters being compared

have been identified and tested in the course exams. The TIED-UP approach is beneficial for concepts that students struggled with in the previous semesters. These results are consistent with those from a prior study that showed a significantly better conceptual understanding of Physics concepts in brain-based instruction (Saleh, 2012). Students demonstrated the same or better proficiency in the course concepts compared to the LI group.

One of the most significant advantages of the TIED UP approach, as reported by the students in the post-class general surveys, is that the materials convey the concepts in multiple ways. This helps the students grasp the concepts one way or the other. Hence, understanding the course concepts is at the same level as LI or better in TI. However, the efficacy of the TIED UP materials varies across different concepts. This may be due to the variation in the course materials used for conveying these concepts. In addition, the realistic examples presented as a part of the materials also enable students to see the relevance of concepts to practical engineering applications. The fundamental principles of learning suggest that learning is more robust when students can see the relevance of the learned material to their personal goals. Since this is one of the first implementations of the TIED UP method, further improvements are expected in future iterations.

While the premise of this testing is a mechanical engineering course, the pedagogy proposed here can be applied to any engineering discipline. This blended model borrows elements from various pedagogies, such as flipped classroom, problem-based instruction, peer learning, and group problem-solving, that are proven in engineering courses. Brain-based instruction principles are applied as a guiding tool for course material preparation. Hence, this pedagogy is expected to produce similar results in other engineering courses.

Conclusions

Overall, it can be concluded that the TIED UP approach has been very effective in teaching the MED course. The protocols were developed based on the brain-based learning literature and apply to any STEM discipline. The TIED UP approach can be useful, especially in engineering majors, where the concept delivery in the advanced-level courses largely depends on the previous classes' pre-requisite concepts. In most engineering courses, instructors can only afford to spend a little time revising these pre-requisite concepts. Typically, they assume the students are well prepared with the pre-requisite concepts, which is sometimes incorrect. Integrating such concepts into concept videos may allow the students to remind themselves about those and create meaningful connections between them and the new concepts in the course. The active learning tools integrated into the TIED UP model also reinforce the latest concepts in their memory. Overall, the TIED UP approach helps the long-term retention of information learned in the classroom. Future work in this project will investigate the retention of the concepts for longer terms.

This paper evaluates the TIED UP pedagogy only across one undergraduate-level course at a large public university. The results regarding its efficacy cannot be generalized to other classes, disciplines, and schools. Further studies are required to make this type of generalization possible. The videos generated in this approach explain the course concepts organized according to the protocols and provide multiple explanations for the same concept. However, according to existing research on the role of multimedia in education, a more effective approach is to address students' misconceptions (Muller, 2008). This aspect has not been explored in the current study. The two approaches will be compared in future research.

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