Modern approaches to lectures in STEM education — a review

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Abstract

Teaching methods in higher education for Science, Technology, Engineering and Mathematics (STEM) subjects is under constant development and improvement. The large classroom sizes and the often fact based content led teachers historically to remain with traditional teaching. However, modern forms of teaching in a lecture setting were developed in the last decades. In this report we we conduct an in-depth literature based review to 1) summarize the current situation in the classroom for STEM teaching and 2) explore different modern methods for improved teaching. We give examples of two often used methods, flipped classroom and peer instruction.

1 Introduction

The traditional form of holding a lecture is based on the information transfer model. Knowledge is transferred directly from the teacher who speaks and explains to the student who listens and may takes notes [Eisenberg et al., 2013]. Therefore, the student is in a passive role where she is supposed to concentrate and follow the teachers narration. In higher education of Science, Technology, Engineering, and Mathematics (STEM) subjects especially in the undergraduation level with large course sizes, this is often considered as the dominant form of teaching.

However, this teaching philosophy entails crucial limitations. Middendorf and Kalish [1996] note that the average attention span of students is in the range of 15-20 minutes. Confronting students with 60 minutes of lecture where they only have to listen does therefore not enable learning. The authors also highlight that the information transfer model is outdated and does not follow the latest research on human learning. Traditional lectures encourages memorization over understanding of concepts [Mazur, 2009] and therefore promotes surface learning instead of a deep learning approach [Beattie IV et al., 1997, Elmgren and Henriksson, 2018]. However, new information needs to be connected to existing knowledge which requires an active participation of students.

Hence, in the late 1970s the information transfer model was replaced with the emerging information scientific form of cognitive constructivism which highlights that knowledge has to be actively constructed in the mind of the student [Talja et al., 2005]. The idea of active student participation culminated in the new paradigm of active learning. According to Bonwell and Eison [1991], active learning can "be defined as anything that involves students in doing things and thinking about the things they are doing."

In this report, we conduct a systematic literature review to identify the currently applied forms of lectures in STEM education, what modern forms of lectures entail and how we can implement them effectively. Our goal is to give an overview of modern forms of STEM lecturing with concrete examples for STEM teachers to use.

2 Current status of lectures

A long list of studies have been conducted so far with the aim of analysing the current methods used in STEM higher education by teachers. The studies either rely on surveys and therefore a form of self-evaluation or on methods such as the Classroom Observation Protocol for Undergraduate STEM (COPUS) [Smith et al., 2013]. Using COPUS an observer can categorize every 2 minute interval into predefined student or teacher behaviors.

Among the survey based studies, there is a consensus that most teachers are aware of different active learning methods but only about half the teachers make use of them. Henderson and Dancy [2009] observe this statistic for research-based instructional strategies in introductory quantitative physics courses. Similarly, Borrego et al. [2010] surveyed engineering department chairs about seven engineering education innovations and observed almost identical results. For geoscience courses Macdonald et al. [2005] notes that lecturing (i.e. mostly the teacher presents or talks and the students listen) is the dominant form but most teachers additionally make use of interactive methods.

From the observation protocol based studies it becomes clear that frontal lecturing of the teacher is still widely used but practices vary to more interactive lectures [Lund et al., 2015, Smith et al., 2014, Stains et al., 2018]. There is no clear divide between both extremes of only lecturing or only interactive sessions but a variety of practices in between. While Stains et al. [2018] observes that this is independent of course level, Lund et al. [2015] notes that students in the first years of their study receive more interactive sessions. The studies agree that, the observations are independent of STEM discipline, but larger class size and fixed seating arrangement (versus flexible seating) correlated higher with more lecturing.

3 Forms of modern STEM lecturing

Already with the seven principles for good practice in undergraduate education developed by Chickering and Gamson [1987], which are general for all study directions, it was stated that it is helpful for learning to 1) establish contact between teachers and students, 2) develop cooperation among the students and importantly 3) encourage active learning. Sorcinelli [1991] supports these statements. The seminal meta-study by Freeman et al. [2014] gives evidence that including active learning elements in STEM education improves the performance of students. It was measurable that under active learning students performance increased by 0.47 standard deviations whereas students under traditional lecturing were 1.5 times more likely to fail the course. It was shown that active learning elements even decrease the achievement gap between over and underrepresented student groups [Haak et al., 2011, Theobald et al., 2020]. These findings has the consequence that STEM courses should re-consider their design and shift towards an interactive classroom with active learning elements. The results beg the questions what active learning is in detail, what activities can be used, how the activities can be implemented and how a course has to be changed to make room for these activities?

Active learning puts the student in the center and focuses less on the teacher [Catalano and Catalano, 1999]. It improves students interest and motivation for learning [Armbruster et al., 2009, Prince, 2004]. Almost any activity that involves the student actively with the course material could be considered active learning [Felder and Brent, 2009]. Depending on the course design, teachers may aim to either just re-gain students attention by small breaks from listening or re-design to a complete interactive course. However, Middendorf and Kalish [1996] notes that for example telling jokes to re-gain attention is not a suitable approach. While you may re-gain the attention of students, it does not enhance their learning. Active learning elements, need the students to interact with the course material actively. Barnes [1989] defined necessary principles for activities such as purposive, reflective, critical or complex to be crucial for active learning and Iverson [2016] studied the factors that support active learning practices in STEM undergraduate education.

There exist long lists of possible activities in the literature which can be utilized by teachers. It ranges from simple student generated questions, e.g. for an exam or a hypothetical press conference, to problem solving sessions or generating ideas in brainstorming sessions [Middendorf and Kalish, 1996]. As teacher you can also be more creative with activities such as debates, role playing, case studies or small group work [Bonwell and Eison, 1991, Brame, 2016, Meyers and Jones, 1993]. Even classroom assessment activities, such as problem recognition tasks where students are asked to classify a problem into a list of problem types, can be considered [Angelo and Cross, 2012]. This has the added benefit of feedback for the teacher about the student level of understanding.

However, many activities are more suited for small classes with possible flexible seating arrangement and less for STEM education with large class sizes. For example a role play about thermodynamic principles in a class of 150 students may not be the right choice. Group work with brainstorming sessions or discussions are often considered outside of the class room as extra work and not within the lecture itself.

Two activities that we will focus on in more detail in the next section are *flipped classroom* [Bishop and Verleger, 2013, Lage et al., 2000] and *peer-instructions* as Mazur [1997] named it.

- The idea of the flipped classroom is that students should not be confronted with new material for the first time in class. Therefore, for example video lectures are watched or reading is done individually before class. Time is freed up for practical hands-on work during the classroom session [Talbert, 2017]. The individually learnt concepts are applied and practiced in class where the lecturer take the role of a facilitator. This format enhances higher-order learning and collaborative work between students [Fung, 2020, Van Vliet et al., 2015]. Especially with the introduction of free online courses[1], the idea of the flipped classroom boosted. Abeysekera and Dawson [2015] identify that videos for self-learning should be limited to 7 ± 2 minutes from a cognitive load perspective [Clark et al., 2011].

- Peer instructions are one of the most used active learning formats with the use of technology [Felder and Brent, 2016]. One form of using this technique

[1]See for example MIT OpenCourseWare `ocw.mit.edu`, the Khan Academy `khanacademy.org`, coursera `coursera.org`, udacity `udacity.com`, edX `edx.org`, STEM Learning `stem.org.uk`, and many more.

is the following [Mazur, 2009]. The teacher poses a question which addresses a particular interesting or difficult topic or concept. Then the students think about the answer individually which they can submit through so called clickers[2]. The teacher obtains statistics and can decide to let the students discuss their answers in groups for a few minutes. After this group discussion, they can submit the answers again. The right answer and possible mistakes can then be discussed in class. See Mazur [1999] for a practical guide.

Other active learning methods specifically designed or analysed for teaching in STEM subjects are for example the Process-Oriented Guided Inquiry Learning (POGIL)[3] initially applied in chemistry classes [Moog and Spencer, 2008b]. It is a group-based and self-managed activity under supervision by a facilitator. The method focuses on the development of process skills [Moog and Spencer, 2008a]. Henderson and Dancy [2009] introduced 24 Research-Based Instructional Strategies for an introductory quantitative physics course. Borrego et al. [2010] concentrated on engineering department to present and analyse 7 active teaching innovations.

Including active learning parts in the classroom will inevitably reduce the time for pure lecturing. Therefore teachers ask themselves how to cover the complete syllabus [Felder and Brent, 2009]. First, in a typical lecture only a few minutes will be lost to the newly introduced active learning parts. Second, it can make sense to move some lengthy explanation or derivations to lecture notes and give students small quizzes around them to do at home.

4 Examples

In this section we will focus on two active learning activities which were included in STEM courses with their respective effect.

Example 1: Flipped classroom The flipped classroom principles [Bishop and Verleger, 2013] can be applied to almost any courses as shown by the MEF University, Istanbul which switched all courses to a flipped classroom after opening in 2014 [Şahin et al., 2016]. The method is suited for STEM education when applied correctly [Talley and Scherer, 2013]. The introduction of this method usually requires a re-design of the course. Lectures must be recorded in suitably long videos for self-study. The classroom time has to be changed to practical exercises guided by the lecturer. The type of practical exercise may vary from problem solving to case studies or laboratories depending on the courses.

While initially the concept of a flipped classroom is often seen as critical by the students [McLaughlin et al., 2013], studies show that student prefer this type of learning over traditional lectures [Fung, 2020, Ramírez et al., 2014]. One reason is that students are able to re-watch the lectures [Mok, 2014]. Jensen et al. [2015] identified that the improved student performance is due to the active learning elements rather than the order of learning (i.e. low-level learning before the class with video lectures and high-level learning in practical class sessions).

Example 2: Peer instructions Peer instructions [Mazur, 1997] can be used in almost any course but are specifically useful for STEM courses. It is for example

[2] Nowadays online tools such as `mentimeter.com` can be utilized.

[3] See also `pogil.org`.

widely adapted for physics courses nowadays [Felder and Brent, 2016]. The activity can be integrated around any concept that is newly introduced or problem that is difficult to solve or may require to think out of the box. It is crucial that the question is not too simple, which will be quickly dismissed by the students as a waste of time. Keeping the attention high in a typical lecture of 60 minutes may require 2-3 of these mental breaks. Each will take a couple of minutes. Therefore, it should be easy to compensate for this time by removing some lengthy explanations to the students reading.

Studies have shown that peer instructions with clicker questions are already widely adopted in STEM education [Stains et al., 2018]. Classes which use the technique have a statistically significant higher performance [Fagen et al., 2002]. Specifically Crouch and Mazur [2001] find that students improved in conceptual reasoning and quantitative problem solving. Enhanced understanding arises during the peer instruction group discussion even if no student in the group had the right answer initially [Smith et al., 2009]. Especially students with less background knowledge benefit from this technique which reduces the performance gap in disadvantages student groups [Lasry et al., 2008]. Similarly, the method can reduce the gender performance gap [Lorenzo et al., 2006].

5 Discussion and conclusion

The results from literature showed that a student-centered approach to lecturing yields better performance of the students compared with the traditional teacher-focused approach of lecturing. Including active elements or switching to a completely interactive course can be achieved in many different forms. We listed multiple approaches and methods to include in or replace a traditional lecture with. As the MEF University, Istanbul shows, a flipped classroom can be used in any field of studies. But teacher do not have to default to a flipped classroom but can be creative in her choice of method. The creativity is almost endless for this course development.

Modern forms of lecturing in STEM education is however probably best seen in light of its limitations. The initial resistance of students against active learning concepts is described by Owens et al. [2020] as originated by the increased effort by the students rather than active learning itself. This is an area that could be overcome with more active learning courses being taught. Cooper et al. [2018], England et al. [2017] discovered that active learning can increase the anxiety of students in STEM courses. The results depend heavily on the choice of method and how it was implemented by the teacher. The literature review by Shekhar et al. [2020] cite reasons such as lack of guidance, lack of time or increased workload for negative student response to courses with active learning. Changing a course to an active learning based one introduces a list of barrier for teachers as already identified by Bonwell and Eison [1991]. Most prominent is the lack of time, lack of incentive and the worries about covering the whole syllabus. Similarly, Shadle et al. [2017] list 18 categories of barrier but also 15 drivers for change.

It becomes evident from studies in STEM higher education that teachers have to include active learning elements in their courses. However, we have to be careful in the choice of active learning method and how to exactly implement it in order to reduce reluctance and anxiety from students. Therefore, it is important to study the particularities of the specific field and the student group in detail before changing the course for the worse.

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