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A proposed methodology and reflection for the use of concept maps in fundamental fluid dynamics education

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ABSTRACT

CONTEXT

Engineering degrees usually begin by teaching fundamental mathematical principles. After a year of this, academics expect engineering students to make a substantial conceptual leap from “what math is” to “how to use math in engineering”. Subjects which rely the most on first principles, such as fluid mechanics or dynamics, can be particularly challenging for students and educators. In Fluid Mechanics 1 (AMME2261) at the University of Sydney, a set of differential equations, known as the Navier-Stokes (N-S) Equations are introduced early in Year 2. Despite a large number of worked examples completed on this topic every year, it is clear that many students still find it very challenging to accurately apply the N-S equations to practical scenarios.

PURPOSE OR GOAL

Previous years’ results (final exam and an online quiz in week 10) have demonstrated variable student understanding of the N-S equations. We hypothesize that students will obtain a deeper understanding of this topic if a more visual approach is introduced in the teaching methodology. Our goal is to introduce students to the use of visual concept mapping for solving N-S equation problems.

APPROACH

An instructor created concept map for the N-S equations was introduced in Week 7. Students were subsequently encouraged to create their own concept maps for the same topic or earlier topics. Results from Quiz 3 and a specific final exam question are statistically analysed and compared to previous years. We reflect on the approach taken this year based on grade trends and general comments made by students and suggest methods to refine the approach for future offerings.

OUTCOMES

Grade trends suggest a statistically significant higher performance on the quiz and exam for 2022 compared to previous years. Upon reflection of the implementation this year and student engagement in the class, it is likely that the instructor generated concept map was found useful, however students did not engage with creating their own maps.

CONCLUSIONS & RECOMMENDATIONS

Concept mapping shows promise however it needs to be adopted early in the semester and embedded as part of formative assessment in order to better scaffold its integration into a unit of study. Nevertheless, early evidence suggests that it is at the very least, a useful way of presenting complex material and a useful way for students to consolidate knowledge.

KEYWORDS

Concept Maps, Fluid Mechanics

Introduction

Many engineering degrees begin by teaching fundamental mathematical principles. First year units of study tend to be a mix of calculus and linear algebra and are supplemented by other subjects focusing on introducing students to the professional aspects of the discipline. Parallel streams of learning can occur in this situation where students are taught math in isolation from other units of study which focus on introducing students to “what engineering is”. As these students are only starting university, they can find it difficult to easily link the two bodies of knowledge.

As students progress into the 2nd year of a mechanical engineering degree they are exposed to highly mathematical subjects including fluid mechanics, dynamics, and solid mechanics. At this point in time, students need to apply mathematical principles towards more practical engineering problems. Understandably, students find this challenging, and this is reflected through non-negligible failure rates in the very analytical 2nd year classes. Subjects which rely heavily on first principles, such as fluid mechanics, can be particularly challenging, both from the lens of a student and an educator.

In Fluid Mechanics 1 (AMME2261) at the University of Sydney, the Navier-Stokes (N-S) Equations are introduced. These are a complex set of partial differential equations, which are however at the core of a foundational understanding of fluid flow. Despite a large number of worked examples completed to demonstrate the practical use of these equations, it is clear that many students find it challenging to make the leap from viewing them as just some complicated looking partial differential equations, to viewing them as a useful engineering tool.

We contend that it is necessary to revisit the method by which these equations (and other equations of similar complexity) are presented to the students and to offer alternative methods for the students to learn how to apply them. Our goal this semester was to introduce students to the use of visual concept mapping for solving N-S equation problems. This approach is supported by prior evidence that demonstrates the ability of visual mapping to help students organise complex theories into simpler interconnected nodes (Pankratius, 1990).

Concept Map Literature Review

Concept maps are used to “graphically represent ideas” and the ways they relate to each other (Novak and Canas, 2008). They can be simple, with a central theme and some related topics. A concept map allows students to create their own meaning of the learning content and demonstrate their understanding of the connections between ideas. This can be particularly useful when students are presented with novel topics in Higher Education.

When students create their own meaning of learning material, connecting it to what they already know, a constructivist learning label can be applied to the process (Pankratius, 1990). The connection between ideas is what makes it active learning (Freeman et al., 2014).

In the concept or mind mapping process, students actively construct their knowledge visually, drawing lines between various concepts and linking them, showing the students’ understanding of the connection between the ideas or concepts. A study by Besterfield-Sacre et al (2004) found that information gained through rote-learning is lost within 6-8 weeks, however using concept maps reinforces learning. Students are then more likely to retain the knowledge about their particular area of study by creating their own “graphically organized” thoughts, theories, and concepts (Pankratius, 1990).

A meta-analysis of publications that have examined concept maps concludes that concept mapping activities are more effective than simply reading/attending lectures due to enhanced engagement. The study also found mapping to be slightly more effective than other constructive activities such as summaries or outlines (Nesbit and Adesope, 2006).

Concept maps can vary in complexity: a study by Turns et al (2000) notes increasingly sophisticated use of concept maps when it was introduced in the 1st week of class and again in the 9th week to monitor the effectiveness of the instruction. The study noted that students initially failed to use cross-links and discipline specific terms in their concept maps, however in Week 9, students were demonstrating a higher-level understanding of concept maps, using cross-links and more mature terminology (Turns et al., 2000).

Ellis et al (2004) based their use of concept maps on “rather than being a tool for teaching, concept maps are tools that students use to support their learning”. The study uses two maps developed for Continuum Mechanics I, a second-year engineering course at Smith College in the U.S to “communicate ideas, help students see the relationship among concepts, solve problems and support project work”.

Concept maps can be used in an active or passive way. An experiment by Mendez and Lofton (2020) trialled both approaches at two different institutions across two semesters. Firstly, in the passive approach, an instructor-created concept map was shown to the students regularly throughout the semester, with new material added as required. In the second institution the following semester, an active approach was adopted and students were encouraged to design their own concept maps, and were permitted to use them during assessments. The study found no significant differences in course performance when results were analysed, however concept maps were found to be a “useful tool for connecting and organising course topics for both students and instructors”. The meta-analysis conducted by Nesbit and Adescope (2003) discussed above, concluded that both instructor-created concept maps and student constructed maps were very useful.

Related to the advantages of instructor created concept maps is that it is well understood that visualisation of complex equations can significantly enhance the comprehension of advanced mathematical content (Guttierez and Boero, 2006). Encouraging students to visualize complex equations, through the use of concept maps, may therefore result in students being more comfortable with handling complex equations. Standard texts in fluid mechanics (e.g. Mitchell (2020)), are now coming with increasingly interactive material, however complicated equations have to be presented in their full form with “traditional” worked examples. Naturally, many educators would then opt to present the information to the students in a similar way in a tutorial or lecture theatre, however we explore an alternative way.

This paper will present the methodology we followed this semester for implementing a concept mapping approach into a foundational Fluid Mechanics unit - Fluid Mechanics 1 (AMME2261). The paper will draw on assessment results from the most recent semester and examine grade trends across 5 years of running the unit of study, whilst also reflecting on the level of student engagement at different points in the semester.

Methodology

The aim this semester was to introduce the use of concept mapping to only one part of the unit of study (fundamental fluid dynamics) as a trial. The class this year was approximately 140 students, mostly undergraduate Mechanical Engineering students, but also some undergraduate Aeronautical Engineering students. The fundamental fluid dynamics component of the unit of study takes places from Weeks 5-7. Prior to this part of the unit, students have already been exposed to the use of calculus in fluid mechanics through the completion of fluid statics and the computation of force distributions on submerged inclined and curved surfaces. This pre-existing basic understanding of the subject matter was in fact the reason for choosing the next topic in the unit to implement the concept map. Furthermore, as stated earlier in the paper, this is one of the key parts of the unit of study that has historically led to the lowest quiz average.

Concept Map Implementation

In this study we aimed to introduce concept maps as a tool for solving a worked example, rather than only as a general method to visualise how different parts of a subject or unit of study come together. An instructor-created concept map was presented to the students to consolidate knowledge related to the N-S equations, and we encouraged students to create their own concept maps for other parts of the unit. The instructor-created concept map itself was comprised of a visual sequence of inter-connected steps (“nodes”) for approaching an N-S problem. Each “node” in the concept map represents different assumptions, situations, or concepts which were learnt in previous weeks.

Solving an N-S problem always involves starting from a complex set of partial differential equations (the N-S equations) and then making certain assumptions to remove terms from the equations hence simplifying them considerably. This initial step of choosing which terms to remove, is the one that is particularly challenging for students, as it involves relating an assumption about the physical world, to a mathematical representation. The instructor created concept map is shown in Fig. 1 with further details on the implementation throughout the semester listed below:

The implementation plan for trialling the concept mapping this semester was as follows:

1. Present the N-S equation concept map (instructor-created, see Fig. 1) in Week 7 as a revision tool and as a tool to consolidate fluid dynamics knowledge learnt up until that point
2. Invite students to use the concept map as a revision tool but also use it as a benchmark to produce their own concept maps for other parts of the unit
3. Assess the results of Quiz 3 (Week 10) which examines fluid dynamics and compare to previous years
4. Assess the results of the N-S equation question on the final exam and compare to previous years
5. Reflect on student engagement and on how to better embed visual concept mapping for Semester 1 of 2023

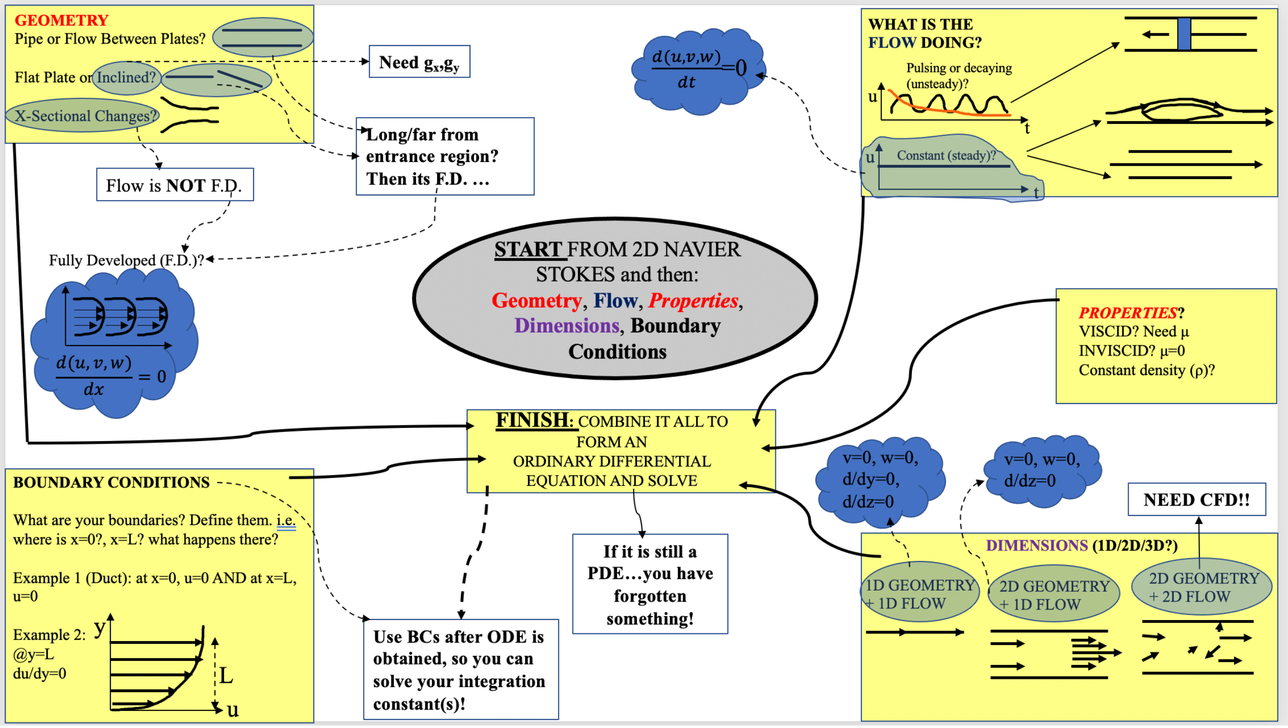

Fig 1: Instructor created concept map for simplifying the Navier-Stokes Equations towards an analytical solution

If the student follows the concept map correctly then a final simplified form of the N-S equations will result which can then be easily solved analytically using basic calculus. The final result would be an algebraic expression describing for instance how velocity in a particular type of flow varies with distance (e.g. how does the velocity change between two walls of a duct or how does the velocity change as a flow moves away from a flat surface?). This process of cancellation of the terms and subsequent implementation of calculus has always been a part of the unit that has been very challenging for students to grasp, and can also be challenging to teach, particularly for newer tutoring staff, as it is not always immediately obvious which terms should be removed for which scenarios.

It should be noted that in previous semesters, instead of a visual map, multiple worked examples would be done using the N-S equations with an instructor generated list provided during a revision lecture. This approach is still the main method of teaching this part of the unit in the tutorials, however the concept-mapping has now been adopted within lectorial sessions which run every week. Retaining both methods of teaching the N-S equations, i.e. worked examples in tutorials & concept mapping in lectorials is essential, given that it is widely understood that students learn in different ways (Felder, 2002). It should also be noted that the lectorials are a supplement to online lectures which are now fully recorded as mini videos on a tablet, where further worked examples are also presented.

Concept Map Details

The instructor-created concept map presented to the students shown in Fig. 1 was created in Microsoft Power Point. Material related to fluid dynamics covered in Weeks 5, 6, and 7 as it relates to the N-S equations is embedded within the map. The map is presented as a very process-driven sequence, with yellow squares forming the key 6 steps to approach a problem - i.e. students must consider 1) geometry, 2) what the flow is “doing”, 3) fluid properties, 4) dimensionality, 5) boundary conditions, and then finally 6) combine assumptions. Other arrows and smaller “cloud bubbles” and white boxes point to reminders or specific assumptions that are embedded within each of the main 6 steps. It should be noted that this map, when presented, was presented as an animated slide show and so segments of the concept map appeared one step at a time-rather than as a single image as it appears finally in Fig. 1. The sequence of showing particular steps in the map, was then utilised to solve a particular worked example during the lectorial class in Week 7.

In the worked example, students were asked to develop an algebraic expression describing a steady inviscid flow between two points (1D flow) in a converging pipe flow (not fully developed) using the concept map. For this particular example, use of the map of Fig. 1 correctly, would mean following the 6 steps clockwise from top left to bottom right to bottom left as follows: $d(u,v,w)/dx \neq 0$, $d(u,v,w)/dt=0$, $\mu=0$, and finally that $v=w=d/dy()=d/dz()=0$. Simplifying the 2D N-S equations based on those assumptions will result in the Euler equation, which if solved correctly, will lead to the Bernoulli equation. The concept map of Fig. 1 was also used to go through the Quiz 3 solution after the quiz was completed (to demonstrate its use again on a different problem). Following presentation of this concept map, students were invited to create their own for other parts of the unit as a revision tool for later parts of the unit. A student-created concept map is likely to yield very different benefits given it is a far more active form of learning compared to the instructor version (Mendez and Lofton (2020)).

Statistical Analysis

Quiz 3 this year was run similarly to previous years, with a long answer question which as with all previous years, assessed use of the N-S equations in fluid dynamics. The average grades for the quiz were calculated and was compared to previous years. A single-tailed t-test was performed in Microsoft Excel to test the hypothesis that the 2022 grades would be higher than previous years based on a $p<0.05$. Prior to a t-test, an f-test was performed to check for unequal variances. Grades from 2018 onwards were used, enabling comparison between 5 cohorts. A similar analysis was also performed on the N-S exam question from the 2020 exam onwards. Only 2020 onwards is used for this purpose as that is when the exam became open book and fully online.

Results

Grade trends for Quiz 3 from 2018-2022 are shown in Table 1 and final exam raw marks for the N-S equation question are shown in Table 2. Note that Quiz 3 and the final exam are the more challenging assessments in the unit of study. Averages for the quizzes and final exam are always lower than the overall grade average for the unit of study (the latter of which also accounts for tutorial and lectorial assignments and lab reports). The overall unit average mark is typically 65% +/- 5% depending on the year. Note, that marks are not fitted to a distribution as we follow standards based assessment and therefore the median score can vary from year to year, as can the failure rates and grade distributions.

Observations from quiz

The format of this quiz has been identical for the last 5 years and consists of four short answer and/or multiple choice questions and one extension answer question. Students are given 45 minutes to complete the quiz. All of the questions on Quiz 3 examine some aspect of fluid dynamics however mostly covering differential conservation of mass and/or momentum. The long answer question has been a N-S problem since 2018. The questions for the quiz are different every year though the steps to solve the extension answer question are largely similar.

As discussed earlier, students are shown an instructor-created concept map in Week 7, and are then invited to use it as part of revision for their quiz and final exam. However, it is not mandated that they use this concept map to solve any question on the quiz.

Table 1 shows the results for Quiz 3 over multiple years. Quizzes that were most similar to 2022 were those from 2018 and 2020 as the extension answer question examined variations of a similar type of problem (that of a viscid shear flow). In this problem students must start from the N-S equations, make an appropriate series of assumptions and then cancel terms from the N-S equations based on the assumptions they make. Subsequent to that, what they need to do depends on what the question is asking, however it generally involves some calculus, boundary conditions and then perhaps a plot of some form.

Correctly following the concept map of Fig. 1 would lead a student to the correct form of the N-S equations quickly, and then with very basic calculus, the final answer. For the Quiz 3 extension answer question, 2.5 out of 3 marks are allocated for the correct concept and method, only 0.5 marks are allocated to obtaining the correct final answer.

Analysis of the quiz results demonstrates that the average grade for 2022 is higher compared to all previous years. The grades for 2022 are higher by a statistically significant amount ($p<0.05$) when compared to all years where data is available, except for 2018. The percentage of grades above a distinction level are also highest for 2022, though it is noted that the level is very similar to 2018, where no concept map was presented.

Observations from final exam

Table 2 shows the raw mark trends from the N-S question on the final exam. The results show a statistically significant increase ($p<0.05$) in grades from 2020 to 2021, from 2021 to 2022 and from 2020 to 2022. Likewise, the percentage of Distinctions (a grade greater than 75%) also increases from one year to the next. From 2020 to 2021, the average grade increased by 30% and from 2021 to 2022 it increased by a further 45%.

There could be an alteration to the marking process of the final exams or a change in the general difficulty of the questions. The increase in grades that already occurred from 2020 to 2021 makes it difficult to draw definite conclusions however the data clearly suggests that an even more significant increase in grades occurred since last year.

Discussion

Quiz and Exam

With respect to the quiz grades from Table 1, the lack of statistical significance between 2018 and 2022 may be due to a broad variety of factors which cannot be known for certain however one noteworthy point is the design of the question itself. For both problems in 2018 and in 2022, a sketch was provided for the students, as opposed to the one in 2021, being only a word-based question. It is therefore plausible that it is not only the introduction of a visual map for the N-S equations that helped the students, but also simply that the problem was easier to approach. In contrast, for the final exam questions, no sketch was provided on any of the years and the questions were very open ended (this was purposeful given the online nature of the exam). Given the exam is a summative assessment, it is possible that more students made use of the instructor-created concept map as part of their overall revision, however one must also bear in mind that unlike in previous years where physical exams papers did not leave the examination hall, from 2020 onwards, exams conducted online allowed for easy access and hence online past papers used as a source of practice problems.

Whilst this is not necessarily an issue, the confounding factors do make it more challenging to isolate the influence of the new teaching methodology. Nevertheless, there is substantial evidence from both the quiz and the final exam, that students generally performed better on the N-S equation problem this year.

Reflection on concept map implementation

In Week 7, after presenting the instructor-created concept map, students were invited to create their own for a different part of the unit. This was done in Week 7 and time was also set aside in the revision lectorials (Weeks 12/13) for students to create concept maps, however most of them did not engage with this process in any of those weeks. The possible positive effect of the concept map on the results of Quiz 3 is therefore very likely only attributed to the instructor-created map.

A very small selection of students (5) submitted their own concept maps, which while on examination by the unit coordinator showed potential to be useful, engaging with the students during the lectorials suggested that most were unsure of where to start in terms of actually creating a map. In contrast, during presentation of the instructor-created concept map in Week 7, students were engaged with the presentation. The presentation of that map was the first time that all of the fluid dynamics material was consolidated in one place, and it was made clear to the students that this map could be used to solve any N-S problem for Fluid Mechanics 1. There is therefore an intrinsic motivation for students to engage with the presentation of the map as they know that it will be useful for future assessments. This does not suggest that students would only engage with the concept map if they know it is assessed, however the role of assessment in shaping student learning is understood (Gibbs, 1999).

Year	**Average raw mark +/- 1σ**	**p-value (t-test pairing with 2022)**	**N-S Sub-Topic Assessed**	**Important Notes**	**% Di+**
2018	2.94+/-1.29	0.08	Viscid Shear Flow	Sketch Provided-not open ended	30%
2019	2.64+/-1.29	**0.0005**	Inviscid Flow		24%
2020	2.89+/-1.14	**0.03**	Viscid Shear Flow	No Sketch Provided	20%
2021	2.74+/-1.08	**0.002**	Inviscid Flow		20%
2022	3.12+/-1.24	N/A	Viscid Shear Flow	Sketch Provided	33%

Table 1: Grade trends for Fluid Dynamics Quiz where σ is the standard deviation and Di is a distinction (75%+) grade.

Year	**Average raw mark +/- 1σ**	**p-value**	**N-S Sub-Topic Assessed**	**Important Notes**	**% Di+**
2020	29 +/- 23	**0.0003** (paired with 2021) **p<1e-5** (paired with 2022)	Flow over surface	No Sketch Provided	3%
2021	38 +/- 24	**p<1e-5** (paired with 2022)	Flow over surface	No Sketch Provided	11%
2022	55 +/- 30	N/A	Flow through confined geometry	No Sketch Provided	33%

Table 2: Grade trends for N-S final exam question where σ is the standard deviation and Di is a distinction (75%+) grade.

Reflection on student engagement

There is substantial evidence that suggests that it is essential that engineering students engage with hands-on active learning (Felder 2002, Steele 2015, Nair et al 2009), and the introduction of concept maps has that potential even in theoretical units of study like fluid mechanics. In the initial trial of the visual concept map this year, as the focus was an instructor generated concept map, the potential hands-on benefits of introducing this visual form of learning were not realised. Introduction of formative assessment (with a pass/fail grade for engagement only) during the lectorials, where students are supervised to create visual maps for different parts of the unit would have been a better approach, and this will be considered for next year.

What will also likely be important is to provide more general resources to students to support their efforts to create a useful concept map for themselves. Whilst there was an observed lack of engagement from the students in creating their own concept maps, this could be due to confusion around the starting point, given that it is not an obvious listed chronological sequence of events. Scaffolding the process from earlier weeks is therefore essential such that feedback can be embedded into the process. From the lens of an educator who is also a subject matter expert, an instructor-created map will largely draw on substantially amassed prior experience that would dictate expert-level decision-making and enriched awareness to ‘exceptions to the rule’, however this cannot be expected of novice learners who are just starting to learn the material. Construction of a good concept map fundamentally relies on working within a knowledge domain that the learner is familiar with (Novak and Canas, 2008) and it also relies on the formulation of a *“focus question”* (Novak and Canas, 2008). An approach of embedded teacher-student feedback loops between student attempts, sequenced by appropriately timed expert modelling of decision-making commentary, could be adopted in future offerings of the unit of study.

Limitations of implementation

Despite the potential usefulness of an instructor-created map for students, there was no real formal process that the instructor followed to create the map this semester, it was largely driven by experience and intuition. In addition to following principles already mentioned in the introduction (i.e. Novak and Canas, 2008) future development of related teaching material can also draw on principles such as those by Mayer (Mayer, 2005) related to the development of multimedia material presentation and content organisation to consider learner cognitive load. Upon examination of these principles post-semester, it is evident that they can be used a) to optimise instructor-created maps but also b) as guides for student-created maps. Since practical hands-on, student-created concept mapping formative learning activities will generally encourage peer-to-peer learning as well as better collaborative skills development (Rosca, 2005), this will also help the students become better teachers to their peers, further creating engaging learning environments. There is scope for future studies also to examine the impact of appropriate educational technologies that support concept map creation on student learning.

Conclusions

Introduction of concept maps into teaching a foundational engineering unit of study has shown significant potential, at least with respect to the use of instructor-created maps. These maps encourage students to visualize complex problems and encourage an approach which breaks down a problem into smaller nodes. Grade trends analysed from the last five years suggest an improvement in the student’s ability to solve Navier-Stokes equations compared to previous years which is promising. However, further research and formal surveying is required to fully understand the underlying drivers, as it currently remains unclear how much of the improvement is due solely to the introduction of the concept map this year, or due to the continual improvement of the unit of study through student or peer feedback, or for other unknown reasons. Despite the potential advantages shown, introduction of a concept mapping approach early in the semester through a scaffolded process, is likely necessary in order to encourage more meaningful and wider adoption by students to further reap benefits of this approach for a challenging topic area.

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