UNIVERSITÉ DE SHERBROOKE

Faculté d'éducation

Les concepts seuils des trois cours de physique principaux du programme Sciences de la nature au CÉGEP

The Threshold Concepts in the Three Main Physics Courses of the CEGEP Science Program

par

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ABSTRACT

Threshold concepts (TC) play a crucial role in the learning sequence. They need special attention when revising the curriculum, a process currently underway with the current CEGEP Science Program revision in Quebec. The extensive literature on threshold concepts in Mechanics suggests a higher number of threshold concepts in the Mechanics course (NYA) than in other physics courses. This qualitative study analyzed the concepts present in the three physics courses of the current Science Program as well as those introduced in the new versions of the courses following the program revision. The objective was to identify the courses' threshold concepts and verify if Mechanics (NYA) has the largest number. To do so, the participants, physics teachers at an Anglophone college, engaged in a Delphi process. To be included in the list, a concept had to be considered transformative and have at least one other characteristic or known consequence usually associated with threshold concepts.

The results showed that while Mechanics (NYA) and Electricity & Magnetism (NYB) have more threshold concepts than Waves & Modern Physics (NYC), there is no significant difference in the number of threshold concepts between NYA and NYB. This result was unexpected as the abundance of potential threshold concepts in NYA discussed in the literature indicated that there would be more TC in that course than in the other two. Still, there was a correlation between the thresholds identified in this study and those previously discussed in the literature.

The difference in the total number of threshold concepts per course appears to be highly influenced by the grouping of the concepts. Thus, drawing a conclusion based on the total number of TC per course alone might not hold much value. However, as reported by the participants, the identification process is still worth undertaking. It can serve as the basis for discussions about the curriculum and reflection on teaching and learning the courses' concepts.

Keywords: CEGEP, Mechanics, Electricity & Magnetism, Waves & Modern Physics, physics, Science Program, program revision, physics education, physics education research, threshold concepts, misconceptions, student motivation, surface learning, Delphi process

RÉSUMÉ

Le cours de Mécanique passe pour être plus difficile que les autres cours de physique et bon nombre d'étudiants ne montrent pas d'amélioration considérable de leur compréhension conceptuelle après l'avoir suivi (Lasry et al., 2014). Il existe plusieurs explications : les différentes façons de résoudre les problèmes et les stratégies d'apprentissage entre novices et experts, la présence de conceptions alternatives, l'influence de la motivation et des attitudes, les interférences entre différents sujets et, plus récemment objet de discussions, la nature des concepts dans le cours. Les concepts seuils forment des obstacles potentiels, capables à nuire au processus d'apprentissage. Ils peuvent être intégratifs, problématiques, à sens-unique et transformer irréversiblement la pensée des étudiants (Meyer, 2010). L'utilisation continue de conceptions alternatives, l'incapacité à établir des liens entre les concepts, les difficultés dans l'apprentissage d'autres concepts (Carstensen & Bernhard, 2008), le recours à l'approche superficielle pour l'apprentissage et la résolution de problèmes (Flanagan et al., 2010), ainsi que le désengagement du processus d'apprentissage (Davies, 2006) sont les conséquences d'un manque de maîtrise des concepts seuils.

En raison de leur rôle central dans le processus d'apprentissage, les concepts seuils nécessitent une attention particulière durant la révision du curriculum, un processus actuellement en cours dans le réseau collégial du Québec pour le programme des Sciences de la nature. Même si, finalement, aucune modification n'est apportée à la séquence d'apprentissage, prêter attention aux concepts seuils peut aider les enseignants à mieux comprendre les difficultés des étudiants et à améliorer leur enseignement (Loertscher et al., 2014; Perkins, 2006; Timmermans & Meyer, 2019). Au minimum, le processus d'identification des concepts seuils peut servir de point de départ à des discussions sur la manière de dispenser les cours (Brown et al., 2021).

Cette étude qualitative a analysée les trois cours principaux du programme des Sciences de la nature : Mécanique (NYA), Électricité et magnétisme (NYB) et Ondes, physique moderne et enjeux environnementaux (NYC). Le but étant de répondre à deux questions de recherche: premièrement, « que sont les concepts seuils dans les cours en question? » et, deuxièmement, « le cours de mécanique (NYA) possède-t-il le nombre de concepts seuils le plus grande ? » Les participants, tous professeurs de physique d'un cégep anglophone, se sont engagés dans un processus Delphi afin de créer une liste de concepts seuils pour les trois cours du programme. Pour représenter un concept seuil, le critère utilisé devait être transformatif et présenter au moins une autre caractéristique ou une conséquence fréquemment attribuée aux concepts seuils.

Les résultats montrent que le cours Ondes et physique moderne (NYC) présente le nombre de concepts seuils le plus bas des trois. En revanche, aucune différence significative n'est à observer entre NYA et NYB, les deux cours au nombre de concepts seuils plus élevé. Ce résultat est surprenant, étant donné l'abondance de la littérature concernant les concepts seuils en mécanique et compte tenu des problèmes des étudiants dans ce cours. Une analyse plus profonde suggère que le nombre total de concepts seuils dépend de la manière dont ils sont regroupés. Par exemple, "les champs" peuvent être considéré comme un concept unique ou séparés en deux catégories : "les champs magnétiques" et "les champs électriques". Indépendamment de ce problème, les concepts identifiés dans cette étude et ceux discutés dans la littérature examinée

sont étroitement corrélés. Considérer uniquement le nombre total de concepts seuils n'a que peu de valeur – c'est le processus d'identification lui-même qui doit être entrepris pour servir de base aux discussions et réflexions concernant le curriculum, l'apprentissage et l'enseignement.

Il reste toujours la question de savoir ce qui rend le cours de mécanique plus difficile. Est-il possible que les étudiants soient mieux préparés à aborder les concepts seuils vers la fin du programme? La séquence fait-elle une différence? Ou bien, le premier semestre a-t-il simplement servi de filtre, décourageant ainsi ceux qui rencontrent des difficultés en mécanique à poursuivre le programme?

Une étude plus approfondie des concepts seuils dans le reste du programme est nécessaire afin de pouvoir évaluer les connexions entre les cours, l'influence de la séquence et le moment auquel les concepts seuils forment un obstacle insurmontable. Enfin, compte tenu des avantages du processus d'identification des concepts seuils, il serait bon de l'étendre à d'autres cégeps et autres programmes.

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LIST OF ABBREVIATIONS

CEGEP	Collège d’Enseignement Général Et Professionnel: A type of postsecondary school in Quebec.
FCI	Force Concept Inventory
HSG	75 credit bridge courses in Science offered at Vanier prior to 2012.
IE	Interactive Engagement
ITCK	Integrated Threshold Concept Knowledge
MI	Modelling Instruction
NYA	Code for the Mechanics course
NYAX	Modified two-semester NYA course offered at Vanier in 2012-2013
NYB	Code for the Electricity & Magnetism Course
NYC	Code for the Waves & Modern Physics Course
PER	Physics Education Research
TC	Threshold Concept
TI	Traditional Instruction
ZPD	Zone of Proximal Development

In honour and gratitude for Steve.

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INTRODUCTION

For decades, physics education research (PER) has been looking into two questions: Why do students struggle with Newtonian mechanics, and how can the teaching methods be improved to help them? To measure the conceptual understanding and evaluate the success of pedagogical interventions, a standardized test, the Force Concept Inventory (FCI), is often given to CEGEP and University Mechanics students at the beginning and the end of the semester (Hestenes et al., 1992; Hestenes & Halloun, 1995). The situation is concerning. According to the results of thousands of FCIs, the Mechanics courses at both CEGEPs and Universities do not significantly improve understanding for many students (Hake, 1998; Lasry et al., 2014; Magtibay & Caballes, 2019). The courses fail to help students achieve the considered mastery level (85% FCI score (Hestenes & Halloun, 1995)) of Newtonian mechanics. Students taught with modern teaching methods, such as interactive engagement (IE), have normalized gains (% post-course FCI - % pre-course FCI)/(100- % pre-course FCI) in FCI scores that are more than twice of those achieved with traditional instruction (TI), but most still fail to achieve the mastery level (Hake, 1998). A recent study at an Anglophone CEGEP on the use of modelling instruction (MI) reported similar results for the gains (MI: 43%, IE: 41%, TI: 29%), with post-course FCI averages of 66% for MI, 64% for IE and 54% for TI (Bourget, 2020). Some researchers do more frequent testing to show the dynamics within the semester (Sayre et al., 2012). For example, when following the traditional teaching sequence, there is a peak in understanding Newton’s 3rd law in the middle of the Mechanics semester, followed by a significant dip and a little bit of recovery towards the end (Sayre et al., 2012).

The discussed reasons of why the students struggle with this course range from inappropriate problem-solving strategies (Chi et al., 1981; Eryılmaz Toksoy & Akdeniz, 2015; Hammer, 1997; Larkin & Reif, 1979; Priest & Lindsay, 1992; M. Wilson, 2014), pre-existing misconceptions (Buteler & Coleoni, 2014; Lin & Singh, 2015; Smith III et al., 1994), the influence of motivation and attitudes (Madsen et al., 2015; Seifert, 2004), interference between vector and scalar concept topics (Sayre et al., 2012), and the presence of threshold concepts (TC).

However, other than the more present misconceptions in Mechanics and potentially, the threshold concepts, most of these reasons fail to explain what makes Mechanics different from the other Physics courses. Threshold Concepts are integrative, troublesome, irreversibly transforming how students think, and boundary defining (Meyer, 2010). The consequences of not passing a threshold could also explain the struggles in Mechanics. In addition, the list of potential thresholds for physics identified in the literature (Bar et al., 2016; Flanagan et al., 2010; Harrison & Serbanescu, 2017; Magtibay & Caballes, 2019; Meyer, 2010; Meyer & Land, 2006a; Perkins, 2006; Prusty & Russell, 2011; Psycharis, 2016; Serbanescu, 2017; A. Wilson et al., 2010) suggests that there might be more of them in Mechanics than in other physics courses.

The goal of this study was to find out if this is the case for the three compulsory physics courses of the Quebec Science Program, Mechanics (NYA), Electricity & Magnetism (NYB), and Waves & Modern Physics (NYC). The physics teachers at an Anglophone College engaged in a Delphi process to identify the concepts with typical threshold characteristics in each of the three courses, including any concept that may appear in the program's current and new versions. The results of this research are surprising. Our data suggest that, contrary to our hypothesis, there is no significant difference in the number of TC found in NYA and NYB.

With the Science Program currently undergoing revision, there is a unique chance to structure the program to help improve students' success in facing and mastering these thresholds. Possibilities include both revising the sequence of and reducing the accumulation of TC at various stages of the curriculum.

Independent of the results, participants reported that undertaking the identification process and the resultant TC lists are worthwhile, as it starts reflections among faculty about how to teach specific topics. Reflecting on both curriculum and pedagogy helps teachers understand student difficulties and instructors to improve their own teaching (Brown et al., 2021; Loertscher et al., 2014; Perkins, 2006; Timmermans & Meyer, 2019).

CHAPTER 1: PROBLEM STATEMENT

There is a well-documented problem in one physics course: Mechanics. Typically the first physics course in the curriculum, Mechanics lays the foundation for many concepts taught in the CEGEP Science Program and introduces the students to lab experimentation and proper scientific data reporting. In many cases, students do not significantly improve their conceptual understanding of Newtonian mechanics when taking this course (Hake, 1998; Lasry et al., 2014; Magtibay & Caballes, 2019). For weaker students, taking the course is even detrimental to their grasp of the concepts discussed (Lasry et al., 2014). Most students end up adopting a surface approach to learning and problem solving, meaning that they rely on memorization, focus on plugging numbers into formulas, and fail to see and understand the connections between the concepts (Chi et al., 1981; Eryılmaz Toksoy & Akdeniz, 2015; Hammer, 1997; Larkin & Reif, 1979; Priest & Lindsay, 1992; M. Wilson, 2014).

It is not surprising that this course has received much attention. Physics education research (PER) has discussed various possible causes of the problem: different problem solving-strategies, misconceptions, motivation and attitudes, interference, and memory decay. Most of those causes, however, would also apply to the other physics courses and thus fail to explain what makes Mechanics so different.

While innovative pedagogical approaches, such as interactive engagement (IE) and modelling instruction (MI), improve the results (Bourget, 2020; Hake, 1998), they still fail to bring the students to the mastery level for Mechanics. Another potential source of the problem with Mechanics is the presence of threshold concepts (TC). With their characteristics (integrative, troublesome, boundary-defining, and irreversibly transforming how students think (Meyer, 2010)), TC integrate well with the other discussed potential sources of the problem. They might also explain why Mechanics seems to cause more trouble than the other physics courses: The potential TC identified in the literature seems to imply - without evidence - that there might be a disproportional distribution of the number of thresholds across the college-level physics courses, with Mechanics having much more than the others.

The purpose of this study was twofold, first to create a list of threshold concepts for the three physics courses of both the current and the new pre-university Science Program, and second, to verify if Mechanics contains the largest number of threshold concepts. The process of identifying the thresholds and the resulting lists will help instructors understand why students struggle in this course. It will also serve as a discussion starter between faculty about curriculum and pedagogy. With the Science Program in the province currently under revision, there is a unique chance to consider thresholds across the program and disciplines. The goal should be to avoid an accumulation of TC at certain moments during specific semesters.

CHAPTER 2: CONCEPTUAL FRAMEWORK

THE STRUGGLE WITH MECHANICS

Mechanics (NYA) is different from the other physics courses. When I started teaching at our college, I was surprised to see that it had an extra hour allocated and a reduced class size. Both measures replaced the previous Science Access course (HSG), present until 2012, and the modified two-semester Mechanics (NYAX) course offered at the college in 2012-2013, designed for students at risk of failing physics in the 1st semester. With a pass rate of 81% compared the 47% of the standard NYA in the same year (Hughes et al., 2017), NYAX had provided a significant improvement in physics pass rates. Similarly, the extra hour and the lower class size together had a measurable positive impact on student success, bringing the average to 80% in 2011-2016, compared to 69% in 2007-2011 (Lenton et al., 2018). However, the measure was abandoned in 2020. Teaching the NYA course, I witnessed firsthand that many students do not seem to "get" the underlying concepts of Mechanics, are stuck in a dualistic view, fail the course, have negative attitudes towards physics and lose faith in their ability to do science.

This "struggle with Mechanics" is not just anecdotal but a phenomenon studied for decades (Hake, 1998; Hestenes et al., 1992). A standardized test, the Force Concept Inventory (FCI), is regularly used to measure gains in conceptual understanding in Newtonian mechanics. Thousands of FCIs have shown that taking the Mechanics course does not significantly improve understanding for all students (Hake, 1998). For students who did not score well (<20%) on the FCI at the beginning of the semester, a higher proportion of correct answers are changed to incorrect answers than wrong answers changed into correct answers when repeating the FCI at the end of the Mechanics course (Lasry et al., 2014). This is puzzling, as, in a constructivist view, where new knowledge builds upon previous, there should always be some improvement, even with little prior knowledge in the subject area.

WHY DO STUDENTS STRUGGLE?

Physics Educational Research (PER) describes what is going on: students lose their motivation and withhold efforts (Seifert, 2004), adopt a surface problem-solving approach (Chi et al., 1981; Eryılmaz Toksoy & Akdeniz, 2015; Hammer, 1997; Larkin & Reif, 1979; Priest & Lindsay, 1992; M. Wilson, 2014), are affected by interference between concepts (Sayre et al., 2012), and have problems with pre-existing “misconceptions” (Buteler & Coleoni, 2014; Lin & Singh, 2015; Smith III et al., 1994).

Since Ebbinghaus’ studies of 1885 (Ebbinghaus, 1885), we know that a significant amount of learning, over time, will be forgotten. Two of the reasons for this are retroactive and proactive interference. Retroactive interference or inhibition is forgetting due to learning tasks done after the initial learning, while proactive interference or inhibition is forgetting due to previous learning tasks (Pauk, 1974a; Underwood, 1957). The Ebbinghaus curve and the interference theory have been elaborated based on rote-learning tasks (Underwood, 1957) but using meaningful material also leads to a similar forgetting curve (Pauk, 1974a). Interference is causing problems with the learning of physics concepts, as shown by the conflict between scalar and vector topics (Sayre et al., 2012; Sayre & Heckler, 2009) and pre-existing misconceptions (Buteler & Coleoni, 2014; Lin & Singh, 2015; Smith III et al., 1994).

When adopting the surface problem-solving approach, the students seem to attempt to directly pass from the first cognitive level of the revised Bloom's taxonomy (Krathwohl, 2002), remembering, to the third level, application, by memorizing particular problem solutions without any understanding. This approach to problem-solving looks very similar to the distinction between the deep and surface approach to learning introduced by Marten and Säljö in 1976 (Marton & Säljiö, 1976a, 1976b). Unlike deep learning, which focuses on finding meaning and understanding, students adapting a surface learning approach try to reproduce information without any interest in its meaning (Knapper, 2010). They thus will not benefit from the transformative effect that would come with deep learning (Transformative Learning Centre 2004, as cited by (Kitchenham, 2008)).

Which approach students take can be influenced by the examination system (Watkins & Hattie, 1981), the learning environment (Entwistle, 2010), and the teaching (Kember & Gow, 1994; Lindblom-Ylänne, 2010; Ramsden & Entwistle, 1981). Already Dewey (English, 2013) critiqued that many students and teachers equate listening with learning. Traditional classroom teaching in science has been demonstrated to be ineffective in fostering the deep-learning approach (Hake, 1998; Mazur, 1997; Wieman, 2010; Woods, 1987) and further deters students with pre-existing emotional obstacles (Kubli, 2010). Physics sometimes is considered less popular and more boring than chemistry and biology, and the educational achievement in the subject less satisfactory (Ibrahim & Zakiang, 2019). Parents and friends considering physics difficult can negatively influence students (Ekici, 2016). If students do not intend to understand it, they will struggle to do so (Ramsden, 2003). Relying on extrinsic, performance-goal-oriented instead of intrinsic, mastery-goal-oriented motivation might also be detrimental to convincing students to take a deep approach for learning and problem-solving.

Changing how instructors teach and motivate their students could make a significant difference. However, a physics teacher at the college level usually teaches all three of these fundamental physics courses and would likely employ a similar pedagogy across the curriculum; results should be similar. Indeed, modern methods, such as interactive engagement (IE) and modelling instruction (MI), improve the situation (Bourget, 2020; Hake, 1998), but they still fail to bring all students to the desired level of understanding in Mechanics.

Many of the discussed issues are not limited to Mechanics as they apply to all physics courses. The main explanation for why Mechanics differs from the other courses is the conflict with “misconceptions.” We have an intuitive understanding of Mechanics: how gravity pulls objects down, forces move things and what happens when objects collide. The learning of Mechanics starts through interaction with the world in the sensorimotor stage, proposed by Piaget’s stages of development (Piaget, 1962), This set of conceptions is robust, and while adequately describing what is happening, it often conflicts with Newtonian explanations. Lasry, Guillemette and Mazur (Lasry et al., 2014) quote a student's comment regarding the FCI as: "How should I answer these questions? According to what you taught me, or according to the way I usually think about these things?" This statement sounds very familiar to Vygotsky's notions (Vygotsky, 2012) on everyday, intuitive understanding acquired through interaction with the world and academic concepts learned through deliberate instruction. The student in question seems not to have linked the two and considered what the teacher taught as separate.

For example, years of experience tell us that a constant push is needed to keep an object in motion. This view corresponds with Aristotle's outdated First Law of Motion, saying that a constant force is needed for a motion to continue. However, it turns out that an object will keep moving with the same velocity only in the absence of a net external force, as predicted in the second part of Newton's First Law of Motion. In most everyday experiences, the constant push counteracts the friction force from the surface, resulting in zero net external force. If the object slides across a frictionless surface, like a puck on ice, it becomes evident that the motion continues in the absence of any force. And here is the difference to the other fields of physics: As a baby, we spend countless hours exploring the laws of Mechanics; I doubt that many of us are allowed to gain much experience with Electricity, Magnetism, and concepts from Modern Physics during childhood. Thus, we are much less likely to have built a large set of intuitive conceptions in those fields, which would explain why there are fewer hard-rooted "misconceptions" regarding the topics of the later courses.

In the spirit of Mezirow (Taylor, 1998), many teachers try to stimulate ambiguity and doubt to remove these “misconceptions” in Mechanics. The conflict between the intuitive understanding of the Newtonian view certainly creates cognitive dissonance. While dissonance can motivate, it can also lead a person to avoid new information or convince others to support their initial views (Dawson, 1999; Festinger, 1962). Therefore it might be challenging to dispel these “misconceptions.” Some students seem to be more confused after taking the course (Lasry et al., 2014), changing their correct answers on the first FCI to incorrect ones.

Furthermore, after spending all this time and effort on removing “misconceptions”, there might not be enough time left to replace the initial conceptions with new ones. Appropriate scaffolding is vital to keep the learner within their zone of proximal development (ZPD) (Vygotsky, 2012). Maybe there are too many “misconceptions” to remove and concepts to “cover” to appropriately scaffold within a 75h, one-semester Mechanics course while keeping the students in their ZPD. After all, the two-semester version of the course and the additional hour provided significant passing grade improvement.

Concentrating on making students realize that their initial conceptions are “incorrect” could have another effect: Students will start questioning their ability to understand physics, negatively affecting self-efficacy and self-worth. Self-efficacy, however, is a critical factor of motivation (Caprara et al., 2008; Seifert, 2004). Furthermore, according to attribution theory (Greene, 1985; Seifert, 2004; Weiner, 1985), students thinking that they are not in control of their success or failure negatively affects how they approach learning physics. Social-Cognition theory (Bandura, 2012) shows that this amplifies if many students struggle and general negativity starts surrounding the classroom.

What is also different for Mechanics compared to the other courses is that it usually is one of the first college-level science courses students are taking. Often, students arrive from high school with a dualistic view of science (Markwell & Courtney, 2006). They believe that the answer is either right or wrong and thus have not advanced beyond the first stage of Perry's Scheme of Cognitive Development (Perry et al., 1970). On top of all the issues with initial conceptions, students have to transition to a more relativistic view. I do not think it is a coincidence that one of the most challenging topics students learn about in Mechanics is that all measurements and calculations based on measurements have uncertainty.

NEW INSIGHTS PROVIDED BY THE THRESHOLD CONCEPT FRAMEWORK

The learning of threshold concepts (TC) is integrative, troublesome, boundary-defining, and irreversibly transforming how students think (Meyer, 2010) and contributes to the students' struggle. The framework provides rationales for why students adopt the surface approach, lose motivation, and how some topics can interfere with the learning of others. In addition, physics seems to have many thresholds. One of the first papers I read had the title "Identifying Threshold Concepts in Physics: Too many to count!" (Serbanescu, 2017).

Most importantly, it would appear that concepts from Mechanics are listed more frequently than those of the other physics courses. An initial count revealed twice as many potential thresholds related to Mechanics as Electricity & Magnetism and Waves & Modern Physics (See Literature Review: Threshold concepts in physics). Therefore, the threshold concept framework might give a plausible reason why Mechanics is so different from the other two mandatory physics courses (Electricity & Magnetism, Waves & Modern Physics) taught in the Science Program.

The mastery of threshold concepts is critical in order to be able to continue the learning journey (Carstensen & Bernhard, 2008; Psycharis, 2016). While threshold concepts might not necessarily form the core or central ideas (Timmermans & Meyer, 2019; A. Wilson et al., 2010), they are the gateways to entire fields of knowledge. In that sense, I believe they might be part of the everlasting ideas considered in Perennialism and the essentials of Essentialism.

An open curriculum where students follow their interests and motivation could be challenging if certain thresholds have yet to be passed before progressing in the program. Following Dewey's learning model (Rodgers, 2004) and encouraging students to learn as scientists sound attractive, especially to scientists, but the time restriction of the 75 hours Mechanics course poses limits. After all, it took the scientific community several centuries, if not millennia, to develop and understand the concepts of Mechanics. Energy conservation, for instance, started with Aristotle during the Classical Greek Period and was later refined by Leibniz and Émilie de Châtelet in the 17th and 18th centuries, but it took until the 19th century to get to the modern understanding of the concept. Compared to that, many of the theories in Electricity, Magnetism and Modern Physics discovered in the 19th century took less time to establish. However, the time we give the students to go through these historical stages of development is the same for all three courses. This discrepancy might explain why modern, student-centred teaching methods, such as self-directed and discovery learning activities inspired by Progressivism and Reconstructionism, have less success in Mechanics than in the other two courses.

After abandoning the lecturing approach, some of us might have pushed the pendulum to the other extreme and overwhelmed the students with choices, leading them to repeatedly hit and fail at threshold concepts instead of helping them navigate through them and stay within their zone of proximal development. In the presence of TC, we maybe have to reconsider and vary our approaches.

To adapt our teaching to the presence of TC, we need to know where they are. Identifying them is part of the necessary pedagogical content knowledge and integrated threshold concept knowledge (ITCK) (Timmermans & Meyer, 2019). However, no comprehensive list of TC in the three main physics courses of the CEGEP Science Program exists. In the ADDIE framework (Analyse-Design-Develop-Implement-Evaluate) (Gaudet et al., 2008), identifying the gaps forms the first step of a program revision. Not being aware of the TC and not adapting the teaching creates a significant gap. In their program evaluation framework, Gaudet et al. (Gaudet et al., 2008) write that data collection without action is meaningless. However, it would appear that we are acting without data by ignoring TC. Identifying the TC of a particular program is, in my opinion, crucial. According to Gardner's practical how-to program assessment model (Gardner et al., 2010), compelling data helps get buy-in from the teachers. A list of TC could form an essential part of that data.

Finding the threshold concepts in the physics courses is only a first step. Eventually, extending the process to the entire program could be part of an ongoing, continued participatory evaluation process. These identification processes might eventually help improve the pass rates in Mechanics and the entire Science Program.

CHAPTER 3: LITERATURE REVIEW

INTRODUCTION

There is a well-documented problem in the Mechanics course: Low pass rates and, more importantly, failure to help students achieve significant gains in conceptual understanding. As discussed in the framework section, embedded in general pedagogical ideas such as motivation, interference, and student approaches to learning and problem-solving, physics education research (PER) has several possible explanations. The threshold concept framework provides additional insight into why students struggle and might explain what makes Mechanics different from the other physics courses.

This section will review the literature on students' struggle with Mechanics and the possible reasons discussed in PER. It will be followed by a presentation of the threshold concept framework and how to identify thresholds. Finally, there will be an overview of the thresholds identified in College Physics. The section will end with a reminder of why identifying threshold concepts is essential to understanding student struggles with learning.

THE STRUGGLE WITH MECHANICS

Students perceive studying physics as a challenge. Of the three courses taught in the current CEGEP Science Program in Quebec, the first one, Mechanics (NYA), is where students universally struggle most (Magtibay & Caballes, 2019; Prusty & Russell, 2011). Although the nature of the course assessments plays a pivotal role in pass rates, the main problem is that students show small gains in conceptual knowledge, an issue PER has been exploring for decades. The Force Concept Inventory (FCI), a standardized test on student understanding of Newtonian mechanics, was created almost thirty years ago (Hestenes et al., 1992). The test consists of multiple-choice questions that do not require any calculations. It thus evaluates the understanding of physics and not simply the ability to “do the math.” It is common practice in colleges and universities to have students complete an FCI at the beginning and end of their Mechanics course to measure the gain in conceptual understanding and evaluate the success of the pedagogical interventions.

Thousands of FCIs showed that not all students significantly improve their understanding of the topics covered in the FCI (Hake, 1998). Many do not achieve a mastery level of Newtonian mechanics, considered an 85% score on the FCI (Hestenes & Halloun, 1995). For students that did not do well in the FCI at the beginning of the semester, there is even a documented loss of understanding, as they perform worse on the second FCI test (Lasry et al., 2014). Some (Lasry et al., 2014) speculate that the course conflicts with previous views and confuses some students, making them question what they already knew. Others have found some interference between topics, causing a decrease in understanding Newtonian mechanics towards the end of the course if following a traditional sequence of content (Sayre et al., 2012), explaining the losses on the second FCI if administered at the end of the course. In a constructivist view, where new knowledge builds upon previous, there should always be some improvement in understanding, even with a small initial knowledge base.

While modern teaching methods, such as interactive engagement (IE) and modelling instruction, improve the situation (Bourget, 2020; Hake, 1998), the Mechanics course in general still fails to bring all students to the desired level of understanding.

EXPLANATIONS FOR THE STRUGGLE WITH MECHANICS

PER suggests that one explanation for the students' struggle with Mechanics is the different problem-solving strategies of those considered experts in the field (professors, teaching assistants, and postgraduate students) and students (novices). The "expert"-problem solvers in physics start by first identifying the major physics principles at play and then looking for connections and equations containing what is known. This approach is called the deep problem-solving approach or forward inference (Priest & Lindsay, 1992). In contrast, novices use the surface problem-solving approach or backward inference. They tend to focus on memorization, referring to previously solved problems to mimic the solution process and plug the given numbers into formulas containing the unknowns without understanding (Chi et al., 1981; Eryılmaz Toksoy & Akdeniz, 2015; Hammer, 1997; Larkin & Reif, 1979; Priest & Lindsay, 1992; M. Wilson, 2014). Thus, the novices seem to attempt to directly pass from the first cognitive level of the revised Bloom's taxonomy (Krathwohl, 2002), remembering, to the third level, application, without any understanding. As discussed in the framework, these different approaches to problem-solving, as well as the nomenclature used to describe it, resonate with the notions on the deep and surface approach to learning introduced by Marten and Säljö in 1976 (Marton & Säljiö, 1976a, 1976b).

Another difference between an expert in the discipline and many students is creativity. A researcher's success relies on divergent, out-of-the-box thinking (Klieger & Sherman, 2015). This way of thinking allows the creation of many hypotheses to be verified by experiment. It can also be helpful when confronted with an unfamiliar problem, allowing the expert to develop various possible ways to approach the problem. Very rarely are students asked to be creative. On the contrary, many physics textbooks, such as those used for Newtonian mechanics, fail to promote divergent and creative thinking (Klieger & Sherman, 2015).

Intention to remember and a positive attitude facilitate learning (Pauk, 1974b). The type of motivation might also be at the root of the students' choice to use a surface versus a deep approach. Intrinsic motivation leads to deep learning, focusing on meaning and understanding, while extrinsic motivation results in surface learning, focusing on memorization and the observed reproduction of ideas (Christensen Hughes & Mighty, 2010; Knapper, 2010). Some students have emotional reservations against science (Kubli, 2010), which can negatively impact intrinsic motivation. Material that conflicts with the students' attitudes is also more likely to be forgotten (Pauk, 1974a). Traditional classroom teaching has been shown to be ineffective in fostering the deep-learning approach (Hake, 1998; Mazur, 1997; Wieman, 2010; Woods, 1987) and further deters students with pre-existing emotional obstacles (Kubli, 2010).

Interestingly, computer programs can successfully mimic expert behaviour in solving physics problems by memorizing sample solutions (Priest & Lindsay, 1992). Thus, contrary to the prior presented deep- and surface problem-solving approaches, some think that the difference between experts and novices might only be the higher success rate and the ability to plan and solve faster (Priest & Lindsay, 1992; M. Wilson, 2014), potentially due to more area-specific information stored in long-term memory (Chi et al., 1981; St Clair-Thompson et al., 2010). The perceived relationship between math and physics could also have an influence (Priest & Lindsay, 1992; M. Wilson, 2014). While students see physics as a form of applied math, experts consider it a science based on experiments and concepts (M. Wilson, 2014). This difference in attitude could explain why students tend to perform better on problems with numbers (Lasry et al., 2014) yet have difficulty answering conceptual questions as asked on the FCI. Students with more expert-like beliefs about physics might also have more learning success or invest more efforts in learning (Madsen et al., 2015). However, all these obstacles are not unique to the Mechanics course.

Unlike other fields of physics, we all acquire a large amount of intuitive understanding of Newtonian mechanics by interacting with the environment. Those initial concepts, sometimes labelled misconceptions, alternative conceptions, naïve conceptions or pre-conceptions, change during the learning process (Brault Foisy et al., 2015; Buteler & Coleoni, 2014; Lin & Singh, 2015; Smith III et al., 1994). Because they served well during many years of real-world experience but often run counterintuitive to Newtonian mechanics, these pre-conceptions can negatively interfere with the learning process (Smith III et al., 1994). There is a disagreement on how to work with this. Some teachers and researchers focus on overcoming, transforming and inhibiting the initial concepts, calling them misconceptions (Brault Foisy et al., 2015). Others use a more constructivist approach to use and refine them (Buteler & Coleoni, 2014; Lin & Singh, 2015; Smith III et al., 1994). Some students' reduced performance on the second FCI might result from realizing that their initial conceptions are inadequate but not having fully transitioned yet to the Newtonian view (Lasry et al., 2014). The negative effect of taking the Mechanics course on students could thus be a consequence of instructors teaching based on removing "misconceptions" (Smith III et al., 1994) and working against students' initial intuitions (Buteler & Coleoni, 2014) instead of building on them.

Some argue that the level of understanding of topics is dynamically changing throughout the semester and from one semester to the other, influenced by learning gains, memory decay and the effect of learning other topics (Sayre & Heckler, 2009). For example, the grasp on Newton's 3rd law appears to peak in the middle of the first semester (when following the traditional sequence), then suffers towards the end of the Mechanics course and a few weeks into the Electricity & Magnetism course (Sayre et al., 2012), which is usually the second course in the physics sequence. In addition to memory decay, these changes might result from interference of scalar topics with vector topics (such as Newton's third law) (Sayre et al., 2012). However, this conflict is not limited to Mechanics, as the scalar and vector topic interference is also present in the Electricity & Magnetism course (Sayre & Heckler, 2009).

The conflict between initial conceptions and the Newtonian view, with the challenging transition, might also have another consequence: losing confidence. Doubting one's abilities reduces academic performance (David, 2014). It might also explain why students' attitudes towards physics deteriorate over time (Madsen et al., 2015). Furthermore, students might withhold effort as a defence mechanism to preserve their self-worth (Seifert, 2004). Fewer efforts in studying and practice could, in turn, lead to low pass rates. Figure 1 provides an overview of the traditional explanations for the struggle with Mechanics.

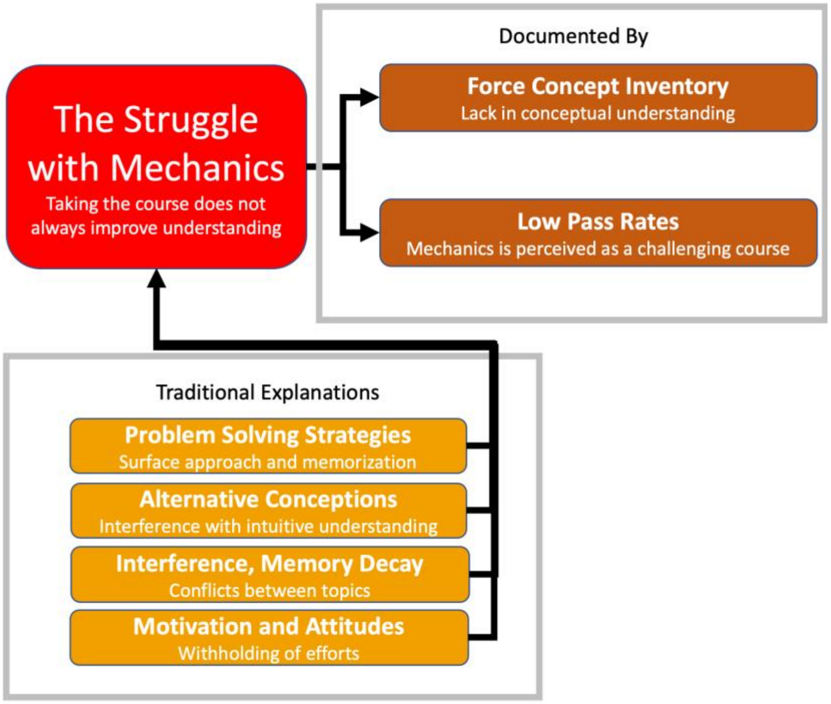


Figure 1. Summary of the traditional explanations

Note: This is the author's visual summary of the traditional explanations of the struggle with Mechanics using Problem Solving Strategies (Chi et al., 1981; Eryılmaz Toksoy & Akdeniz, 2015; Hammer, 1997; Larkin & Reif, 1979; Priest & Lindsay, 1992; M. Wilson, 2014), Alternative Conceptions (Brault Foisy et al., 2015; Buteler & Coleoni, 2014; Lin & Singh, 2015; Smith III et al., 1994), Interference and Memory Decay (Sayre et al., 2012; Sayre & Heckler, 2009), Motivation and Attitudes (David, 2014; Madsen et al., 2015; Seifert, 2004).

THE THRESHOLD CONCEPT FRAMEWORK

Some concepts are more critical than others. They act as a one-way portal, irreversibly transforming how students think (Meyer, 2010) and forming a barrier in the learning progress (Male et al., 2012). These “threshold concepts” are integrative, providing links and previously hidden connections. They sometimes define disciplinary boundaries. Often, they are troublesome, meaning that they are challenging, alien, counterintuitive, and conflicting with previous views (Perkins, 2006). Being reconstructive (changing the subjectivity), discursive (extensive use of disciplinary-specific language in the reasoning), and liminal (causing disorientation and ambiguity) are threshold concept characteristics that are sometimes added to the list (Barradell & Fortune, 2020; Reeping, 2020; Reeping et al., 2017). Figure 2 visualizes how a TC can act as a barrier in the learning process, while Table 1 provides an overview of the characteristics of a TC.

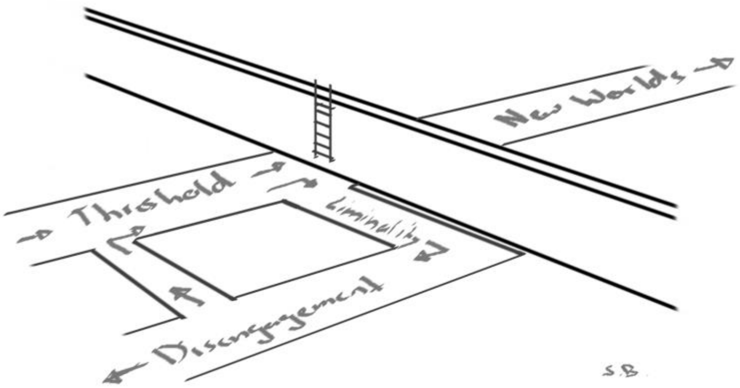


Figure 2. The threshold concept in the learning process

Note: This is the author’s visualization of a threshold concept in the learning process.

Table 1. Threshold concept characteristics

Characteristic	**Description**	**Example (Riding a bike)**
Transformative	Changing how a student thinks and views the discipline (Meyer, 2010).	Riding a bike increases the number of places one can access by oneself.
Irreversible	It can not be forgotten or being unlearned (Meyer, 2010).	It is almost impossible to forget how to ride a bike.
Integrative	Creating connections with other concepts (Perkins, 2006).	Riding a bike combines balancing with visual-motor integration.
Bounded	Being limited to the discipline or even creating a disciplinary boundary (Perkins, 2006).	The concept of riding a bike is limited to using two/wheeled vehicles.
Troublesome	Conflicting with previous views, being alien and difficult to integrate (Perkins, 2006).	Riding a bike is counterintuitive. You have to steer left first if you want to turn right.
Reconstructive	Causing a change in subjectivity (Reeping, 2020).	Distances might appear smaller once you can ride a bike.
Discursive	Using extensive disciplinary language in the reasoning (Reeping, 2020).	New vocabulary related to biking has to be learned.
Liminal	Learning the concept is not straightforward, causing ambiguity and disorientation (Reeping, 2020).	Initial failure is almost unavoidable when learning to ride a bike.

The characteristics and description summarize what was found in the literature while the author has added the examples.

An established example for thresholds in physics is vectors (Meyer & Land, 2006b; Psycharis, 2016). Without vectors, a student cannot cross a certain level of understanding. For example, Newton's Laws of Motion are limited to one dimension without vector addition of forces. However, if the concept is understood, new branches of physics open up. Vectors allow us to analyze certain phenomena that otherwise would be inexplicable, such as static equilibrium or gyroscopic motion. Learning the concept transforms the way of thinking, and it is unlikely to be forgotten. The fact that a vector does not have a fixed location makes the concept troublesome, as this is counterintuitive and entirely new for most students. The use of vectors as entities with magnitude and direction is, to some extent, limited to math, physics, engineering, and chemistry. Life Sciences also use vectors, but the definition and the underlying concept are different. In that field, vectors are unaffected hosts that transmit diseases, while for physics, math and engineering, a vector is a quantity with magnitude and direction. Thus, the definition of vectors and their use is boundary defining, and the different definitions are troublesome.

The threshold concept framework connects with the other explanations regarding students' difficulties when learning Newtonian mechanics. Repeatedly "hitting a wall" when encountering a threshold (Land et al., 2006) may result in a loss of motivation. Disengagement is a coping strategy (Davies, 2006). The troublesome nature of threshold concepts, being that they may be counterintuitive and conflicting with previous views, matches the theories on alternative conceptions and their negative impact on persistence (Chen et al., 2020). Fragmented knowledge and mimicry, as seen in the surface approach used by students, are considered consequences of not passing a threshold (Flanagan et al., 2010). Students and teachers may settle for the appearance of understanding (Davies, 2006), resulting in many students passing the Mechanics course without transitioning to the Newtonian view. Learning a threshold concept brings the risk of being stuck in liminality, a suspended state of partial understanding (Meyer et al., 2010), leaving the student more insecure, knowing what does not work but not understanding how to proceed. Being stuck in liminality reflects what can happen when the student's initial conceptions are removed but not successfully replaced by the Newtonian concepts and why some topics can negatively interfere with the understanding of others.

Forgetting is part of learning (Pauk, 1974a), but memory decay should play less of a role with threshold concepts as learning a threshold concept is considered irreversible. However, if the student did not cross the threshold, forgetting the concept might still happen. Incomplete learning leads to mental blur and forgetting (Pauk, 1974a), which might also apply to not completely mastered TC. The change in understanding during the semester (Sayre et al., 2012) and the fact that, for some students, the FCI score goes down after taking the course (Lasry et al., 2014) could therefore be the consequence of not crossing thresholds completely.

Making connections forms the base of learning (Beane, 1997). Relations to something familiar must be made to create a solid memory trace (Pauk, 1974b). The fragmented knowledge resulting from an improperly crossed threshold could prevent students from seeing the links. Not properly crossing a threshold can also be detrimental to mastering related concepts (Carstensen & Bernhard, 2008; Psycharis, 2016) due to the disruptive potential to the students' way of thinking (Davies & Mangan, 2007). Therefore, the problems created by the threshold concepts in

Mechanics could have ripple effects on other courses, explaining retroactive and proactive interference. If Gravity, for example, is not understood as a vector, the idea of a Gravity Vector Field, used to introduce Electric Fields in the Electricity & Magnetism course, is not accessible to the learner.

Table 2 provides an overview of the various consequences of not properly passing a TC, while Figure 3 shows how the TC framework integrates with the traditional explanations for the struggle with Mechanics.

Table 2. Consequences of not properly crossing a threshold

Consequence	Description	Example (Riding a bike)
Remaining stuck in liminality	Being more confused, resulting in the continued use of alternative concepts (Meyer, 2010).	Inability to learn how to bike might result in the continued use of other means of transportation.
Fragmented knowledge	Making it impossible to see links to other concepts (Flanagan et al., 2010).	If biking was never mastered, no links to biking can be made when learning to drive.
Problems learning other concepts	Limiting the ability to learn other concepts (Carstensen & Bernhard, 2008; Psycharis, 2016).	Not having learned to ride a bike will result in difficulties learning to use a motorbike.
Mimicry as a coping mechanism	Relying on the surface (memorization) approach (Flanagan et al., 2010).	An easy way out of not mastering riding a bike is to use additional support wheels. It works to some extent but is very limited.
Disengagement	Loss of motivation and withholding of efforts (Davies, 2006).	Frequent failure to learn to bike might result in abandoning biking.

Note: A summary of the consequences of TC listed in the literature, with examples added by the author.

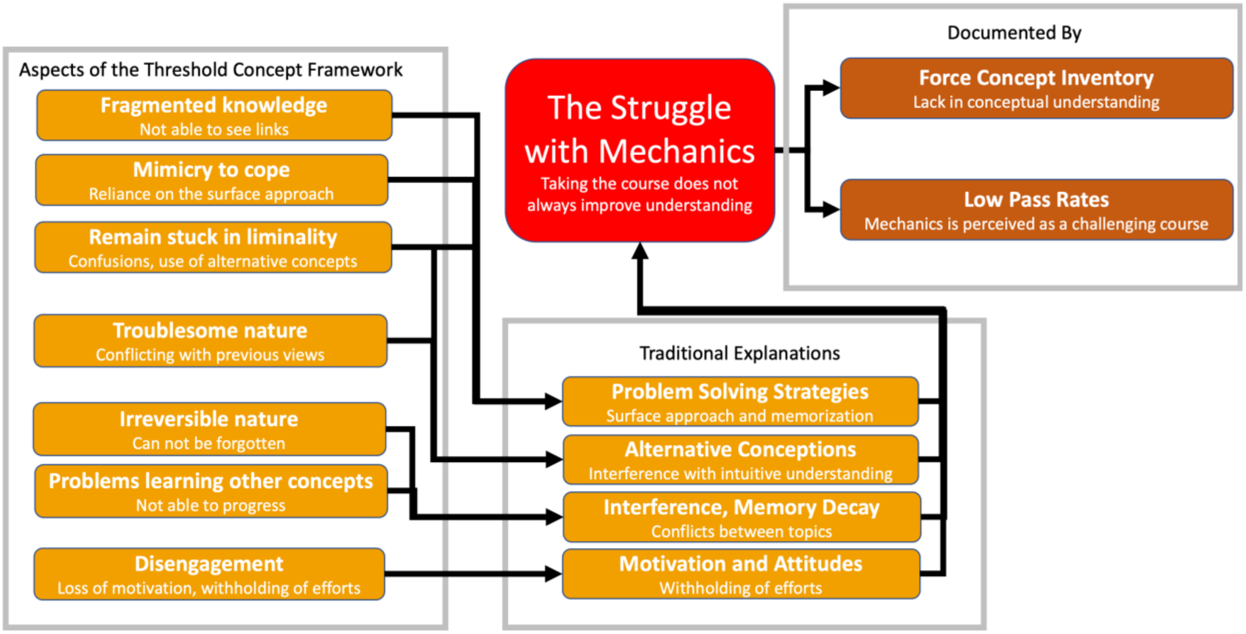


Figure 3. How TC integrate with the traditional explanations

Note: This is the author's visualization of how TC aspects (Carstensen & Bernhard, 2008; Davies, 2006; Flanagan et al., 2010; Meyer et al., 2010; Perkins, 2006; Psycharis, 2016; Reeping, 2020) (see Table 1 and Table 2) integrate with the traditional explanations (see Figure 1).

Threshold concepts are usually identified based on their characteristics, but there is some disagreement on which ones should be used (See Table 3). While some recent articles mention eight, five are more frequently used: transformative, irreversible, integrative, bounded and troublesome. Most authors seem to be in agreement that being transformative is a minimal requirement (Barradell, 2012; Barradell & Fortune, 2020; Davies, 2006; Davies & Mangan, 2007; Loertscher et al., 2014; Meyer & Land, 2006b; Quinlan et al., 2013; Timmermans & Meyer, 2019; A. Wilson et al., 2010). The irreversible and integrative characters are often deemed necessary for a concept to qualify as a threshold concept. In one case (Davies, 2006), being transformative, irreversible, and integrative are considered mutually interdependent.

Although widely recognized as a possible characteristic and sometimes even as a minimal requirement (Barradell & Fortune, 2020), being boundary defining has explicitly not been used in the identification process of some authors (Loertscher et al., 2014; A. Wilson et al., 2010). A. Wilson et al. (2010) stated that the reason for not considering boundary defining to identify TC was the difficulty of the participants to determine if a concept was boundary-defining or not.

Interestingly, Magtibay & Caballes (2019) identified threshold concepts on the troublesome nature alone. There seems to be some overlap. For example, they considered that the disciplinary language could make a concept troublesome. However, they consider all five characteristics when looking at the consequences of not crossing a threshold.

Table 3. Characteristics used to identify threshold concepts by some researchers

Author	**Transformative**	**Irreversible**	**Integrative**	**Bounded**	**Troublesome**
(Meyer & Land, 2006b)	Required	Probable	Probable	Often	Potentially
(Davies, 2006)	Required*	Required*	Required*	Required	Required
(Davies & Mangan, 2007)	Required	Required	Required	Potentially	Potentially
(Carstensen & Bernhard, 2008)			Important	Important	Base
(A. Wilson et al., 2010)	Required	Probable	Required	Not used**	Potentially
(Meyer et al., 2010)	Required	Likely	Required	-	Often
(Male et al., 2012)	Required				Required
(Loertscher et al., 2014)	Required	Required	Required	Not used**	Potentially
(Magtibay & Caballes, 2019)	Considered but not used for identification				Used
(Barradell & Fortune, 2020)	Required			Required	

* The first three criteria are considered mutually interdependent.
** Not used but considered a possibility

Legend:

Required	*A concept is not a threshold concept if the characteristic does not apply.*
Probable / Potentially	*Threshold concepts might have this characteristic, but having it is not a requirement to be a threshold concept.*
Often	*Threshold concepts often have this characteristic, but having it is not a requirement to be a threshold concept.*
Important	*Considered an important characteristic of TC but not necessarily used for their identification.*
Base	*While other characteristics are recognized, the identification is based on this characteristic.*

Various research methods are used for threshold concept identification (Hendrawati et al., 2021). Examples include self-reflection (Harrison & Serbanescu, 2017), literature review (Bar et al., 2016), workshops and focus groups (Loertscher et al., 2014; Prusty & Russell, 2011; A. Wilson et al., 2010)), interviews, questionnaires, and looking at students' work (Barradell, 2012) as well as student observation (Carstensen & Bernhard, 2008). The Nominal Group and the Delphi Technique have been used for consensus-finding (Barradell, 2012). Most methods are qualitative, and no quantitative approach seems to have been developed yet (Quinlan et al., 2013).

However, in many papers, the methodology is not mentioned, lacks rigour and transparency, and it is not clear if an identified "potential threshold" is a threshold concept (Crookes et al., 2020). As the methodology used influences the research outcome, it should be clearly stated, especially the characteristics used to identify the threshold concepts (Quinlan et al., 2013). The last point is critical, as which aspects should be used for the identification is open to interpretation (Brown et al., 2021) but dramatically impacts the result.

One difficulty of the process is that it is not easy to distinguish a threshold concept from a key- or core concept (Timmermans & Meyer, 2019; A. Wilson et al., 2010). Key concepts are at the core of a course, but they are not necessarily threshold concepts. Free Body Diagrams, for example, are central to the Mechanics course, and analyzing forces without them is almost impossible. This, however, does not necessarily make them a threshold concept. They might simply be an instrument to analyze the vector nature of forces. Sometimes, as in the case of Free Body Diagrams, it is not easy to decide what constitutes a TC or not.

Creating a list of threshold concepts has been criticized as merely producing a list of critical learning objectives, becoming so extensive that they are of limited use when analyzing the curriculum (Reeping, 2020). It appears that there is also a risk of derailment if researchers try to identify thresholds based on dialogue (Davies, 2006). Just trying to agree on what should be considered a concept can take a considerable amount of time (Timmermans & Meyer, 2019). Another problem lies in whom to ask when identifying threshold concepts. Students might not be able to recall a critical moment, realize its importance, or accurately remember an experience. On the other hand, teachers and postgraduates have blind spots, having forgotten their struggles and, as mentioned earlier, having difficulties distinguishing threshold concepts from key concepts (Shinners-Kennedy, 2016).

Related to the topics taught in the three main physics courses of the current and the new CEGEP Science Program, Mechanics (NYA), Electricity & Magnetism (NYB), Waves & Modern Physics (NYC), the literature suggests the potential (not necessarily confirmed) threshold concepts listed in Table 4. Based on the table, it appears that Mechanics has a disproportionally large amount of threshold concepts compared to the other two courses. This might explain why students struggle much more with the Mechanics course. However, it could also simply be a consequence of Mechanics getting more attention from researchers.

Table 4. Concepts discussed in the literature as potentially being threshold concepts

Common to all three courses	**Mechanics (NYA)**	**Electricity and Magnetism (NYB)**	**Waves and Modern Physics (NYC)**
1. Approximation and Modeling [(Psycharis, 2016; Quinlan et al., 2012)	1. Acceleration (Psycharis, 2016)	1. Boundary Conditions (Serbanescu, 2017)	1. Beats (tuning) (Meyer & Land, 2006b)
2. Data fitting (Serbanescu, 2017)	2. Angular Momentum (Serbanescu, 2017)	2. Charge carriers (Serbanescu, 2017)	2. Optics (Serbanescu, 2017)
3. Orders of Magnitude (Psycharis, 2016)	3. Collision (Magtibay & Caballes, 2019)	3. Circuits (Serbanescu, 2017)	3. Polarization (Serbanescu, 2017)
4. Potential Energy (Serbanescu, 2017)	4. Conservation Laws in general (Psycharis, 2016) and Conservation of Energy (Magtibay & Caballes, 2019)	4. Fields (Flanagan et al., 2010; Psycharis, 2016; Serbanescu, 2017)	4. Quantum Threshold Energy (Serbanescu, 2017)
5. Significance (Psycharis, 2016)	5. Couples and Moments (Prusty & Russell, 2011)	5. Flux (Psycharis, 2016; Serbanescu, 2017)	5. Relativity, Special Relativity, and Space-Time (Psycharis, 2016; Serbanescu, 2017)
6. Uncertainty (Harrison & Serbanescu, 2017; Psycharis, 2016; Serbanescu, 2017; M. Wilson, 2014)	6. Diagrams (Psycharis, 2016; Quinlan et al., 2012)	6. Impedance (Flanagan et al., 2010)	6. Wave-Particle duality (Psycharis, 2016)
	7. Energy (Psycharis, 2016)	7. Induction (Psycharis, 2016)	7. Waves (Serbanescu, 2017)
	8. Equilibrium (Psycharis, 2016)	8. Potential (Psycharis, 2016; Serbanescu, 2017)	
	9. Force (Psycharis, 2016)		
	10. Free-Fall (Magtibay & Caballes, 2019)		
	11. Friction (Magtibay & Caballes, 2019; Prusty & Russell, 2011)		
	12. Gravity (Bar et al., 2016; Meyer, 2010; Meyer & Land, 2006b; Psycharis, 2016; A. Wilson et al., 2010)		
	13. Hooke's Law (Prusty & Russell, 2011)		
	14. Impulse (Magtibay & Caballes, 2019; Psycharis, 2016)		
	15. Moment of Inertia (area) (Prusty & Russell, 2011)		
	16. Momentum (Meyer & Land, 2006b; Psycharis, 2016)		
	17. Newton's Laws of Motion (Harrison & Serbanescu, 2017; Meyer & Land, 2006b; Perkins, 2006)		
	18. Polar Coordinates (Serbanescu, 2017)		
	19. Projectile Motion (Magtibay & Caballes, 2019)		
	20. Reference Frames (Psycharis, 2016; Quinlan et al., 2012)		
	21. Resultant Force (Prusty & Russell, 2011)		
	22. Uniform Circular Motion (Magtibay & Caballes, 2019)		
	23. Vectors (Meyer & Land, 2006b; Psycharis, 2016; Quinlan et al., 2012)		
	24. Weight versus Mass (Bar et al., 2016)		

WHY CONSIDER THRESHOLD CONCEPTS?

The threshold concept framework provides another way of critically assessing the curriculum: Starting with identifying the threshold concepts to adapting the learning strategies to support the learning of TC by integrating the so-called integrated threshold concept knowledge (ITCK) (Timmermans & Meyer, 2019). If there is an accumulation of TC in the Mechanics course, simply lowering the expectations to improve the student pass rate might not be the best way forward. Letting students continue in the program with many improperly crossed thresholds could harm the learning of related concepts (Carstensen & Bernhard, 2008) and applying knowledge in other parts (Psycharis, 2016) of the curriculum.

Both being conscious about the thresholds and adapting our teaching accordingly (Loertscher et al., 2014; Perkins, 2006) may improve the situation in Mechanics. Changing the sequence to reduce interference between some topics might help. Although the identification process sometimes is murky and non-precise, to the point that some caution using TC to organize the curriculum, the process initiates discussions about pedagogy (Brown et al., 2021). If the number of TC is too high, there might be a limit to what adapting the teaching methods can do. That could be why the various innovations in pedagogy do not improve the results in Mechanics to the same extent as they do in other courses. Redesigning, reviewing the sequence, and reorganizing (decongesting) the curriculum (Land et al., 2006; Loertscher et al., 2014) promise to have much more impact in that case.

With the Science Program in Quebec currently in revision, there is a unique opportunity to re-evaluate the physics curriculum. For example, some threshold concepts like Uncertainty could be postponed to a later course. If the thresholds in the entire program were known, better coordination between the disciplines regarding thresholds, such as vectors and energy conservation, that are part of more than one subject, could be achieved. There is a trend towards a more holistic and interdisciplinary approach (Klein, 1990). Maybe a more coordinated program-based approach to thresholds could be beneficial. A possibility for students to have multiple attempts at crossing a threshold could be created. If students are stuck in different places, individualized learning using technology might be helpful (Prusty & Russell, 2011).

RESEARCH QUESTIONS

Students struggle (understanding and pass rate) more in Mechanics than in the other physics courses of the current Science Program. Addressing the issue with innovative pedagogy did not produce the desired outcome, and most explanations for why students have difficulties in physics cannot explain the difference between Mechanics and the other two courses.

In order to find out more about how threshold concepts might contribute to this problem, the goal of this project was to look at two research questions:

1. What are, according to physics teachers, the threshold concepts of the three main physics courses of both the current and the new CEGEP Science Program (Mechanics (NYA), Electricity & Magnetism (NYB), and Waves & Modern Physics (NYC))?
2. Does Mechanics (NYA) have the largest number of threshold concepts among the courses (NYA, NYB and NYC)?

The hypotheses are:

H_0: There is no significant difference in the number of threshold concepts among the courses.

H_1: Mechanics has a significantly higher number of threshold concepts than the other physics courses in both the current and the new Science Program.

It was anticipated that H_1 would be confirmed.

CHAPTER 4: METHODOLOGY

SAMPLE AND SETTING

The study’s target population was the physics faculty of an Anglophone College in Montreal. The sample was a convenience sample of 8 to 16 teachers depending on the round of the process (Round one: 16, Round two: 14, Round three: 16, Follow-up survey: 8).

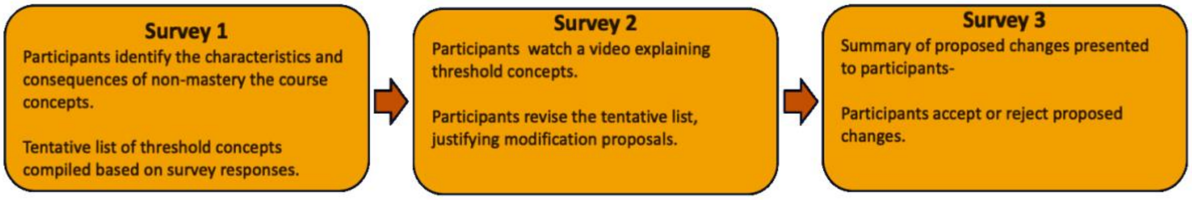
The college's physics department consisted of 12 tenured teachers and eight non-permanent teachers at the study time. Thus, 80% of faculty participated in at least one round of the process. The faculty has a diverse background, many being immigrants to Canada. All possess either a Ph.D. or a master’s in physics or a related field. The teaching experience of the participants ranges from one to 46 years. While five of the teachers in the physics department are female, the anonymized surveys make it impossible to determine the gender of the participants.

RESEARCH DESIGN

This qualitative research used the Delphi method, a group consensus finding process elaborated in the 1950s for the Army of the United States and previously used to find threshold concepts in various disciplines (Banerjee, 2020; Barradell, 2012; Townsend et al., 2016). In several rounds, three for this study, the individual group members provided written feedback on the suggestions made by the others. The moderator created a summary and sent it to the participants for further consideration. The method offered anonymity to the participants and, as it took place in an asynchronous format with written exchanges, was ideal in the context of the COVID-19 pandemic, where holding in-person group meetings was difficult.

The criteria used for a concept to be considered a threshold is that more than 50% of participants have identified it as a) transformative and b) to have at least one of the other characteristics or consequences of non-mastery usually linked to threshold concepts. Not aiming for 100% consensus, but using 50% of participants' votes to create the list of threshold concepts is similar to a previous study in a different discipline at the same college (Banerjee, 2020) that also used the Delphi technique. After the Delphi process, another survey evaluated the perceived usefulness of the process and the study results.

INSTRUMENTS



Survey 1

Participants identify the characteristics and consequences of non-mastery the course concepts.

Tentative list of threshold concepts compiled based on survey responses.

Survey 2

Participants watch a video explaining threshold concepts.

Participants revise the tentative list, justifying modification proposals.

Survey 3

Summary of proposed changes presented to participants-

Participants accept or reject proposed changes.

Figure 4. The three-round Delphi-Process

Note: This is the author's overview of the used three-round Delphi-Process adapted from (Banerjee, 2020).

Survey Round 1: Identification of concept characteristics and consequences of non-mastery

In a first survey (See Appendix A - Survey 1), the participants determined the concept characteristics and the impact of not mastering it for all concepts of Mechanics (NYA), Electricity & Magnetism (NYB) and Modern Physics & Waves (NYC). The survey included the concepts in the current Science Program and those introduced in the new version of the program.

The characteristics:

1. Transformative (changes the way the students think)
2. Irreversible (can not be forgotten)
3. Integrative (connects concepts)
4. Bounded (Is limited to the discipline)
5. Troublesome (conceptually difficult, conflicts with previous views, alien)

The consequences of non-mastery:

1. Remaining stuck (continued use of alternative conceptions)
2. Fragmented knowledge (not able to make links to other concepts)
3. Problems in learning other concepts
4. Mimicry as a coping mechanism, relying on a surface (memorization) approach
5. Disengagement, loss of motivation, withholding of efforts

While discussing the five threshold characteristics is common practice, using the consequences of non-mastery for identification has not been seen in the reviewed literature.

The participants did not receive any information about threshold concepts at this stage. Only the above lists, including the explanations in parenthesis, were provided. Concentrating on the characteristics and potential consequences in the initial round and not using the word "threshold" was done to limit the risk that respondents falsely identify every key concept as a threshold concept.

Participants were invited to ask for clarification if needed. No participant requested further explanation of the characteristics. However, clarification was requested on how to answer the questions: as perceived by the teacher or as the teacher thinks the students perceive it. Participants were informed to consider these from the student's perspective.

The moderator created an initial list of thresholds based on the survey results and distributed it at the beginning of the second round. A concept was added to the list when more than 50% of the participants considered it transformative and to have at least one other characteristic or consequence (See Figure 5).

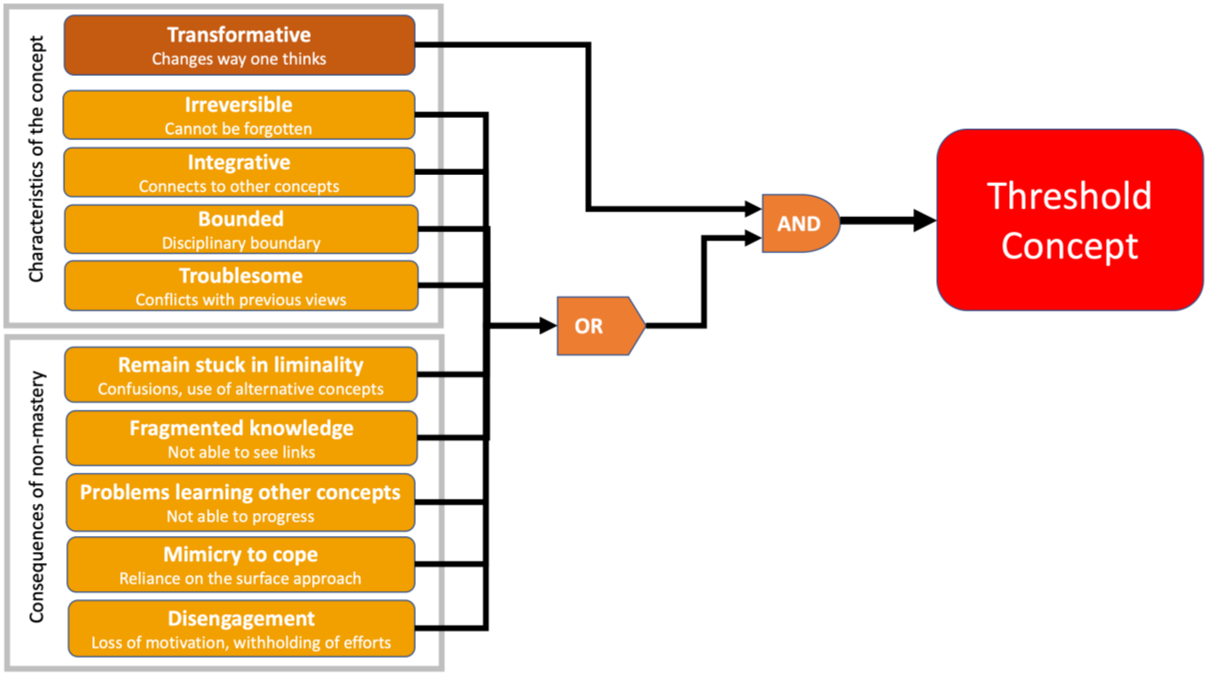


Figure 5. The used decision process for TC

Note: This is the author’s visualization of the used decision process for TC identification in this study, based on TC characteristics and consequences of non-mastery (Carstensen & Bernhard, 2008; Davies, 2006; Flanagan et al., 2010; Meyer et al., 2010; Perkins, 2006; Psycharis, 2016; Reeping, 2020) (see Table 1 and Table 2) and by extending the minimal requirement of being transformative used by many authors (Barradell, 2012; Barradell & Fortune, 2020; Davies, 2006; Davies & Mangan, 2007; Loertscher et al., 2014; Meyer & Land, 2006b; Quinlan et al., 2013; Timmermans & Meyer, 2019; A. Wilson et al., 2010).

Survey Round 2: Introduction to the TC framework and discussion of the first round data

(See Appendix A – Survey 2.)

The participants received:

- A presentation video (see Appendix D) on threshold concepts in general, prepared by the author.
- The compiled and anonymized data and the list from the first survey

A second survey then collected suggestions, with justification, to add or remove any item from the list of TC. This feedback was provided verbatim to participants, grouped by concept.

Survey Round 3: Vote on changes

The participants received a revised TC list following round two. They reviewed the suggested changes with their justifications and decided to accept or refuse the change for each item on the list (See Appendix A – Survey 3).

Follow-up survey: Usefulness and results

Four months after the Delphi process, the participants received a follow-up survey (See Appendix A – Follow-up Survey). This additional survey aimed to evaluate the perceived usefulness of the results and the process itself. Eight teachers answered this survey.

ETHICAL CONSIDERATIONS

The research project obtained approval for a year from the research ethics board of the College on September 17th, 2020. The Ethical Approval Form can be found in Appendix C.

Potential harms to the research subjects

1. Time constraints

The time investment for participants was relatively high. Each round was estimated to take about an hour, bringing the total time required to three hours.

2. The reputation of individual teachers

There could be some conflict between teachers having different views and being judged based on their contributions and comments. Making the surveys anonymous mitigated this risk.

3. Intended deception

The research title communicated to the participants initially was “Evaluation of the nature of the concepts in the physics courses of the Science Program.” The word “threshold concept” was not mentioned before the second survey. This minor deception was necessary to avoid a negative impact on the initial identification process due to the possible confusion between a “threshold concept” and an “important concept.”

Potential harms to the department, the college, and other stakeholders

As lower pass rates in Mechanics are not unique to the college, the discussion has no negative impact on the department’s nor the college’s reputation. There were no anticipated harms to the department, the college, and other stakeholders.

Potential benefits

The teachers’ thinking about the various concepts can improve students’ learning experience and help teachers plan and deliver Science Program courses. Completing the first survey on concept characteristics starts the reflection process, thus justifying the time investment required from the participating teachers. Hopefully, the process will also result in better pass rates in the future, benefitting the students, the department, and the college.

This analysis can inform the ongoing Science Program revision discussions and help the department and the college implement the new program.

Conflicts of interest

The research could lead to a call to reduce the number of concepts in some of the courses studied. Unfortunately, in the context of the Science Program revision, content appears to be directly linked to the number of hours allocated. Removing some concepts may result in fewer hours allocated to the course, thus not improving time constraints. Furthermore, anticipated impacts on the teacher workload could harm the objectivity of the participants, which, however, is mitigated as it was always clear that the results of this study will not be available before the implementation phase of the new program when course hour allocation already has taken place.

Conclusion

The potential benefits of the research outweigh the potential harms. Furthermore, participation was voluntary, and the participating teachers had the right to withdraw at any time until their data was submitted.

CHAPTER 5: RESULTS

IDENTIFIED THRESHOLD CONCEPTS IN THE THREE COURSES

The Delphi process resulted in 13 identified thresholds for NYA, 13 thresholds for NYB and eight for NYC.

Table 5. Identified threshold concepts

Mechanics (NYA)	**Electricity & Magnetism (NYB)**	**Waves and Modern Physics (NYC)**
1. Analyzing and Presenting Experimental Data, Uncertainty	1. Electric Charge	1. Index of Refraction
2. Vectors (Scalars/Vectors, Addition, Notation)	2. Conservation of Charge	2. Simple Harmonic Motion
3. 1D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration	3. Electric Force (Coulombs Law)	3. Waves and Wave Propagation
4. Inertia, Mass and Weight, Center of Mass	4. Electric Fields	4. Interference, Standing Waves, Resonance
5. Newton's Three Laws of Motion (including FBD's)	5. Electric Potential	5. Photoelectric Effect, Quantum Threshold Energy
6. Work and Power	6. Electric Current	6. Matter Waves, Particle-Wave Duality
7. Work-Energy Theorem, Conservation of Energy	7. Current and Resistance, Ohm	7. Relative Velocity (Galilean Relativity), Reference Frames
8. Kinetic Energy	8. Electric Circuits	8. Simultaneity, Time Dilation, Length Contraction
9. Potential Energy (Gravitational and Elastic), Conservative and Non-Conservative Forces	9. Kirchhoff's Loop Rules	
10. Linear Momentum: Conservation of Linear Momentum, Collisions, Explosions, Impulse	10. Magnetic Forces	
11. Uniform Circular Motion	11. Magnetic Fields, Magnetic Fields due to Current (Biot-Savart)	
12. Rotational Kinematics: Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities	12. Induction and Inductance (Faraday, Lenz)	
13. Rotation: Torque, Rotational Equilibrium, Newton's Second Law for rotation	13. AC Circuits	

(Ordered as they would appear in a "traditional" sequence)

EVALUATION OF THE PROCESS AND THE RESULTS

Only eight teachers replied to the follow-up survey. A majority either fully or somewhat agree that having a list of threshold concepts will make them more reflective on how they teach and is useful for their teaching practice. They also agree that the list can serve as a discussion starter regarding the concepts in the courses and will be useful when implementing the new Science Program.

While again, a majority strongly agrees that the resulting list is also useful for those who did not participate in the process, they recognize that having participated in the process was even more useful. They recognize that the process can initiate departmental discussion regarding the courses and that doing it ahead of the Science Program revision was useful. Indeed, a majority consider that participating in the process made them reflect on how they teach and impact their teaching.

Not a single respondent disagreed with the idea of recommending other departments and programs to engage in the process of identifying the threshold concepts.

A majority of respondents agreed or fully agreed it would have been better to have a face-to-face process instead of using online surveys. There is much less agreement on if the online format influenced the final list.

Table 6. Evaluation of the process

	Completely Disagree	Somewhat Disagree	Somewhat agree	Fully agree	I don't know / NA
Having participated in the process made me more reflective of how I teach certain concepts	12.5%	12.5%	75.0%	0.0%	0.0%
Having participated in the process will be useful for my teaching practice	12.5%	12.5%	37.5%	12.5%	25.0%
The identification process was an ideal means for initiating departmental discussion regarding our courses	0.0%	25.0%	37.5%	25.0%	12.5%
Discussing threshold concepts ahead of implementing the new Science program was a useful exercise	0.0%	12.5%	37.5%	25.0%	25.0%
I would recommend to other departments/programs to engage in the process of identifying threshold concepts in their courses	0.0%	0.0%	50.0%	37.5%	12.5%
The process would have been more useful if done face to face instead of using anonymous surveys	12.5%	12.5%	37.5%	25.0%	12.5%

Table 7. Evaluation of the resulting list of TC

	Completely Disagree	Somewhat Disagree	Somewhat agree	Fully agree	I don't know / NA
Having a list of threshold concepts will make me more reflective of how I teach certain concepts	0.0%	12.5%	37.5%	25.0%	25.0%
Having a list of threshold concepts will be useful for my teaching practice	0.0%	12.5%	37.5%	37.5%	12.5%
Having a list of threshold concepts can serve as a discussion starter regarding our courses	0.0%	12.5%	50.0%	25.0%	12.5%
Having a list of threshold concepts will be useful when implementing the new Science Program	0.0%	12.5%	25.0%	37.5%	25.0%
The resulting list of threshold concepts might have been different if done face to face instead of using anonymous surveys	12.5%	12.5%	25.0%	12.5%	37.5%

Table 8. Evaluation of results versus process

	Completely Disagree	Somewhat Disagree	Somewhat agree	Fully agree	I don't know / NA
Having participated in the process is more useful than the resulting list	12.5%	0.0%	62.5%	12.5%	12.5%
The resulting list is useful also for those that did not participate in the process	0.0%	12.5%	0.0%	37.5%	50.0%

CHAPTER 6: DISCUSSION

COMPARISON TO LITERATURE

Mechanics

Of the 13 TC identified by a majority for Mechanics, ten appeared in the reviewed literature. Only three are without a direct match: Kinetic Energy, Work and Power, and Rotational Kinematics. For two of them, this difference might be a question of topic grouping, as Kinetic Energy and Work and Power could be considered a part of "Energy and Conservation of Energy." On the list since round one, Rotational Kinematics was not mentioned in the reviewed literature.

On the other hand, several TC mentioned in the literature did not make it to the list generated in this study: Force, Free-Fall, Friction, Orders of Magnitude, Polar Coordinates, Projectile Motion, Reference Frames, and Significance. Again, this could be a question of grouping: Force could be considered part of Newton's Laws, Free-Fall a particular case of 1D Kinematics, and Polar Coordinates a subset of Vectors. Orders of Magnitude and Significance might be linked to Uncertainty. Friction and Projectile Motion had been identified by some participants but not considered a TC by a majority. Reference Frames are an interesting case. These were initially considered to be a TC of NYA by the participants. However, in round two, a suggestion, approved by a majority of participants in round three, considered them as TC in NYC instead. While introduced in NYA, the argument was that only in NYC are they discussed at a level deep enough to constitute a threshold.

Table 9. Comparison of identified thresholds for NYA with literature

Study Results	Literature
1D Kinematics: Position, Displacement, Average and Instantaneous Velocity/Acceleration	Acceleration (Psycharis, 2016)
Analyzing and Presenting Experimental Data, Uncertainty	Uncertainty (Harrison & Serbanescu, 2017; Psycharis, 2016; Serbanescu, 2017; M. Wilson, 2014), Approximation and Modelling (Psycharis, 2016; Quinlan et al., 2012), Data fitting (Serbanescu, 2017)
Inertia, Mass and Weight, Center of Mass	Weight versus Mass (Bar et al., 2016)
Kinetic Energy	
Linear Momentum: Conservation of Linear Momentum, Collisions, Explosions, Impulse	Collision (Magtibay & Caballes, 2019), Impulse (Magtibay & Caballes, 2019; Psycharis, 2016), Momentum (Meyer & Land, 2006b; Psycharis, 2016)
Newton's Three Laws of Motion (including FBD's)	Newton's Laws of Motion (Harrison & Serbanescu, 2017; Meyer & Land, 2006b; Perkins, 2006), Equilibrium (Psycharis, 2016), Diagrams (Psycharis, 2016; Quinlan et al., 2012), Resultant Force (Prusty & Russell, 2011)
Potential Energy (Gravitational and Elastic), Conservative and Non-Conservative Forces	Potential Energy (Serbanescu, 2017), Gravity (Bar et al., 2016; Meyer, 2010; Meyer & Land, 2006b; Psycharis, 2016; A. Wilson et al., 2010), Hooke's Law (Prusty & Russell, 2011)
Rotation: Torque, Rotational Equilibrium, Newton's Second Law for rotation	Angular Momentum (Serbanescu, 2017), Moment of Inertia (area) (Prusty & Russell, 2011), Couples and Moments (Prusty & Russell, 2011)
Rotational Kinematics: Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities	
Uniform Circular Motion	Uniform Circular Motion (Magtibay & Caballes, 2019)
Vectors (Scalars/Vectors, Addition, Notation)	Vectors (Meyer & Land, 2006b; Psycharis, 2016; Quinlan et al. 2012)
Work and Power	
Work-Energy Theorem, Conservation of Energy	Energy (Psycharis, 2016), Conservation Laws in general (Psycharis, 2016) and Conservation of Energy (Magtibay & Caballes, 2019)
	Force (Psycharis, 2016)
	Free-Fall (Magtibay & Caballes, 2019)
	Friction (Magtibay & Caballes, 2019; Prusty & Russell, 2011)
	Orders of Magnitude (Psycharis, 2016)
	Polar Coordinates (Serbanescu, 2017)
	Projectile Motion (Magtibay & Caballes, 2019)
	Reference Frames (Psycharis, 2016; Quinlan et al., 2012)
	Significance (Psycharis, 2016)

Electricity & Magnetism

For NYB, five of the 13 TC identified by the majority do not directly correlate with the literature. However, again, grouping might be the issue here: “Current and Resistance, Ohm,” “Electric Current,” and “Kirchhoff-s Loop Rules might be part of “Circuits.” While “Force” in general has been a TC candidate for Mechanics, Electric and Magnetic Force have never been explicitly singled out.

In contrast, only one potential TC discussed in the literature did not make it to the list: Boundary Conditions. That might be linked to how this College-Level course is taught by the participants, or simply because it was not on the initial concept list and no one thought of it as a separate item to be included.

Table 10. Comparison of identified thresholds for NYB with literature

Study Results	Literature
AC Circuits	Impedance (Flanagan et al., 2010)
Conservation of Charge	Conservation Laws in general (Psycharis, 2016)
Current and Resistance, Ohm	
Electric Charge	Charge carriers (Serbanescu, 2017)
Electric Circuits	Circuits (Serbanescu, 2017)
Electric Current	
Electric Fields	Fields (Flanagan et al., 2010; Psycharis, 2016; Serbanescu, 2017)
Electric Force (Coulombs Law)	
Electric Potential	Potential (Psycharis, 2016; Serbanescu, 2017)
Induction and Inductance (Faraday, Lenz)	Induction (Psycharis, 2016), Flux (Psycharis, 2016; Serbanescu, 2017)
Kirchhoff’s Loop Rules	
Magnetic Fields, Magnetic Fields due to Current (Biot-Savart)	Fields (Flanagan et al., 2010; Psycharis, 2016; Serbanescu, 2017)
Magnetic Forces	
	Boundary Conditions (Serbanescu, 2017)

Waves & Modern Physics

Only one of the threshold concepts identified by participants was not seen in the literature: Simple Harmonic Motion. Interestingly, the initial analysis of round one did not identify the concept as a TC. A participant suggested its addition in round two, leading to it ultimately being accepted as a TC by every participant.

On the other hand, Beats are discussed in the literature as a potential TC and identified by participants in the first round. A round two suggestion asked for their removal, which a majority approved. The rationale for doing so was that it does not form a “transformative gate” in this course. Like Relative Velocity, which was not considered to form a threshold at the level discussed in NYA, this does not mean it could not form a threshold in another course. The last related concept listed in the literature, Polarization, was identified only by a minority of participants in the initial concept analysis and thus never made it beyond the first round.

Table 11. Comparison of identified thresholds for NYC with literature

Study Results	Literature
Index of Refraction	Optics (Serbanescu, 2017)
Interference, Standing Waves, Resonance	Waves (Serbanescu, 2017)
Matter Waves, Particle-Wave Duality	Wave-Particle duality (Psycharis, 2016)
Photoelectric Effect, Quantum Threshold Energy	Quantum Threshold Energy (Serbanescu, 2017)
Relative Velocity (Galilean Relativity), Reference Frames	Relativity, Special Relativity, and Space-Time (Psycharis, 2016; Serbanescu, 2017)
Simple Harmonic Motion	
Simultaneity, Time Dilation, Length Contraction	Relativity, Special Relativity, and Space-Time (Psycharis, 2016; Serbanescu, 2017)
Waves and Wave Propagation	Waves (Serbanescu, 2017)
	Beats (tuning) (Meyer & Land, 2006b)
	Polarization (Serbanescu, 2017)

Summary of the literature comparison

In summary, one can say that there is a high degree of agreement between TC concepts identified by this study and those previously discussed in the literature. However, a different grouping of concepts can make a significant difference in the final count. Thus, one should be careful when drawing conclusions based on the total number of thresholds per course.

VARIATION AMONG TEACHERS

There is quite some variation among individual teachers. If only looking at the concepts considered a threshold by ALL participants (see Table 12 on next page), the lists shrink considerably.

Table 12. Concepts identified as thresholds by all teachers

Mechanics (NYA)	Electricity & Magnetism (NYB)	Waves and Modern Physics (NYC)
1. Vectors (Scalars/Vectors, Addition, Notation) 2. Inertia, Mass and Weight, Center of Mass 3. Newton’s Three Laws of Motion (including FBD's) 4. Work-Energy Theorem / Conservation of Energy 5. Potential Energy (Gravitational and Elastic) / Conservative and Non-Conservative Forces	1. Electric Fields 2. Electric Potential 3. Induction and Inductance (Faraday, Lenz) 4. Magnetic Fields, Magnetic Fields due to Current (Biot-Savart)	1. Simple Harmonic Motion 2. Waves and Wave Propagation 3. Interference, Standing Waves, Resonance 4. Simultaneity, Time Dilation, Length Contraction

The other extreme is when every concept considered a threshold by at least one teacher was counted (see list in Annex B - Detailed Data - Round 3). In that case, the total count of thresholds per course would be 20 for NYA, 13 for NYB and 18 for NYC.

This variation might be due to differences in personal background, how the teachers perceive the concept, and the depth teachers approach the topic in class. Regardless of the degree of consensus used to classify a concept as a threshold, Mechanics does not significantly have more thresholds than the other courses. However, in all three cases, Mechanics (NYA) is never the course with the least thresholds (100% consensus: NYB/NYC, 50% consensus: NYC, 0% consensus: NYB).

EVOLUTION THROUGH ROUNDS

Table 13. Evolution of the number of TC during the process

	Round 1	**Round 2 (suggested additions)**	**Round 2 (suggested removals)**	**Final**
NYA	16	4	11	13
NYB	4	9	0	13
NYC	11	6	9	8

Round 1 and final numbers based on majority (>50%)

After the initial round, it appeared as if the data would confirm the hypothesis of NYA having more TC: There was a significantly higher amount of concepts with TC characteristics identified by the majority of correspondents (see Table 13). Interestingly, at this stage, NYB only had four TC: Electric Fields, Electric Potential, Induction/Inductance, and Magnetic Fields. Once the participants learned about the TC framework at the beginning of round two, they suggested various additions and removals and then voted on those at the third stage. The Delphi process forced instructors to reflect on the concepts again and review the initial classification from round 1. For NYA and NYC, this reduced the overall TC number, while NYB had a significant increase.

One exciting change happened concerning Galilean Relativity. Originally a threshold concept in NYA, a participant suggested moving it to NYC. The argument proposed was that, although Galilean Relativity is presented first in NYA, its role and level of exploration in this course are not sufficient to constitute a TC. However, when discussing Special Relativity in NYC, Galilean Relativity forms the critical base and blocks students' progress if not mastered. Therefore, it should be considered a TC in NYC. Thus, the level of exploration of the concept influences whether or not participants will identify it as a TC.

COURSE COMPETENCY ELEMENTS CONTAINING THRESHOLDS

This section will analyze the number of course competencies that contain threshold concepts for the three courses in the current Science Program.

Table 14. Elements of the competency with threshold concepts in NYA

Element of the Competency	Threshold Concepts
1. To describe the translation of bodies in one dimension	1D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration
2. To describe the translation of bodies in two dimensions.	Vectors (Scalars/Vectors, Addition, Notation) Uniform circular motion
3. To describe the rotation of bodies.	Rotational Kinematics: Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities
4. To apply the concepts and Laws of Dynamics to the analysis of the translation of bodies.	Inertia, Mass and Weight, Center of Mass, Newton's Three Laws of Motion (including FBD's)
5. To measure the amount of work and energy involved in simple situations.	Work and Power, Work-Energy Theorem, Conservation of Energy, Kinetic Energy, Potential Energy (Gravitational and Elastic), Conservative and Non-Conservative Forces
6. To apply the principles of conservation in Mechanics.	Work-Energy Theorem, Conservation of Energy, Linear Momentum: Conservation of Linear Momentum, Collisions, Explosions, Impulse
7. To apply the concepts and Laws of Dynamics and Angular Momentum Conservation to the analysis of the rotation of bodies.	Rotation: Torque, Rotational Equilibrium, Newton's Second Law for rotation
8. To verify, experimentally, a number of laws and principles in Mechanics.	Analyzing and Presenting Experimental Data, Uncertainty

Table 15. Elements of the competency with threshold concepts in NYB

Element of the Competency	Threshold Concepts
1. To analyze situations in physics associated with static Electrical Charge and Electric Field	Electric Charge, Conservation of Charge, Electric Force (Coulombs Law), Electric Fields
2. To analyze situations in physics associated with static Electrical Charge and Electric Potential	Electric Potential
3. To analyze situations in physics associated with Electric Current	Electric Current, Current and Resistance, Ohm, Electric Circuits, Kirchhoff's Loop Rules
4. To analyze situations in physics associated with Charge Storage	Conservation of Charge
5. To analyze situations in physics associated with Magnetism	Magnetic Forces, Magnetic Fields, Magnetic Fields due to Current (Biot-Savart)
6. To analyze situations in physics associated with Magnetic Induction	Induction and Inductance (Faraday, Lenz)
7. To analyze situations in physics associated with Alternating Current Circuits	AC Circuits
8. To verify, experimentally, a number of laws of Electricity and Magnetism	Analyzing and Presenting Experimental Data, Uncertainty

Table 16. Elements of the competency with threshold concepts in NYC

Element of the Competency	Threshold Concepts
1. To apply the fundamental principles of Physics to the description of Vibrations	Simple Harmonic Motion
2. To apply the fundamental principles of Physics to the description of Mechanical Waves and their propagation	Waves and Wave Propagation, Interference, Standing Waves, Resonance
3. To apply the laws of Geometrical Optics	Index of Refraction
4. To apply the characteristics of Waves to light phenomena	Waves and Wave Propagation, Interference
5. To analyze a number of situations using concepts of Special Relativity	Relative Velocity (Galilean Relativity), Reference Frames, Simultaneity, Time Dilation, Length Contraction
6. To analyze a number of situations using concepts of Modern Physics	Photoelectric Effect, Quantum Threshold Energy, Matter Waves, Particle-Wave Duality
7. To analyze a number of phenomena using concepts of Nuclear Physics	
8. To verify, experimentally, a number of laws and principles associated with Waves, Optics, and Modern Physics	Analyzing and Presenting Experimental Data, Uncertainty

In both NYA and NYB, all eight elements of the competencies have at least one threshold concept. In contrast, one of the eight elements of the competencies appears to be free of thresholds in NYC. Once again, NYA and NYB are standing out for not only having more TC but also for each course competency having at least one TC. There is no significant difference in total TC number or number of competencies with TC between NYA and NYB.

IMPACT OF THE PROGRAM REVISION

None of the new concepts introduced by the Science Program Revision: Greenhouse Effect, Introduction to Thermodynamics and Heat Machines, made it to the final TC list. A majority considered them TC after round one (See Appendix B. Detailed Data) but agreed to their removal after discussion in round two.

One of the identified TC in NYB, AC Circuits, is scheduled to be removed by the program revision. A second NYB threshold: Magnetic Fields and Magnetic Fields due to Current (Biot-Savart) will lose the Biot-Savart part. A third NYB threshold: Induction and Inductance, will also be affected by the revision, with the Inductance part removed.

As a net result, the program revision will eliminate one NYB threshold and reducing two others, while not introducing any new TC.

IMPLICATIONS

With NYA and NYB having no significant difference in the number of threshold concepts, the hypothesis that simply the amount of TC in NYA is the cause for students' struggles with Mechanics cannot be confirmed. As shown in comparison with the literature, the grouping of concepts can make a huge difference, so the final "count" of TC might not hold too much value in and of itself.

EVALUATION OF THE USEFULNESS OF THE TC LIST AND THE PROCESS

The participants who responded to the follow-up survey considered the process of identifying TC in courses, and the results of the Delphi process equally valuable. In contrast, some researchers (Brown et al., 2021), while recognizing the usefulness of the process as a discussion starter, recommend not using final TC lists because they often have been elaborated with unclear TC identification criteria and different perceptions among teachers. This study implemented the suggestion to clearly state the methodology and the characteristics used to identify TC (Quinlan et al., 2013). Nevertheless, slightly different criteria, such as requiring 100% agreement, dramatically change the TC lists. Therefore, although the participants of the follow-up survey consider the results valuable, the list itself should be used with caution.

CHAPTER 7: CONCLUSION

This study has allowed us to create lists of threshold concepts for the three physics courses of the current and the new CEGEP Science Program. The reviewed literature suggested many threshold concepts in Mechanics, resulting in the prediction that an accumulation of TC contributes to the well-documented problem in Mechanics. The data refute this prediction. Surprisingly, based on the study, which considered all three courses simultaneously, the hypothesis that Mechanics has more TC than the other two courses was not confirmed, as Electricity & Magnetism and Mechanics have an equal number of TC.

The influence of concept grouping limits the usefulness of the final count of threshold concepts. Also, replacing the Covid-imposed, all online, three-round Delphi process with a more extensive process including in-person discussions could lead to larger consensus and thus better data.

Nevertheless, the study cannot rule out the role of threshold concepts. Maybe the students' struggle is more visible in Mechanics, as the other course with a high number of TCs, NYB, is taken later in the program. Mechanics might constitute the first time new CEGEP students encounter such a high number of thresholds concepts in an individual course. Maybe, some students are simply better prepared to deal with a high volume of TC later in the program, explaining why the considerable TC accumulation in NYB did go unnoticed so far. It could also be that the first semester serves as a filter, removing students who struggle. Potentially, other first-semester courses may contain a high number of thresholds concepts as well, and thus, the combination can bring students to the limit of their cognitive load capacity. Some thresholds in other courses might also interfere with the Mechanics course. If indeed it is an issue of too many TC provided to first-semester students or negative interference, perhaps moving the Mechanics course to the second semester could improve student success.

More research is needed, especially regarding the thresholds identified in NYB and the influence of the program's sequence and course interconnections. Work should start by elaborating a TC list for all the program courses. Based on that, the TC present in more than one course can be identified. At that point, discussions about the current course sequence, teaching methods, and semester schedule can be held, focusing on how well they help the students master those TC. Finally, looking at the number of TC per semester, cognitive load peaks could be identified, and measures could be taken to spread the load more evenly throughout the program.

This study makes me rethink my approach to teaching the concepts identified as thresholds. Given the students' overall workload and the program's time constraints, limiting the flipped classroom and discovery approaches to other concepts requiring less guidance and time may be better. While repeatedly hitting the wall of a TC might result in better long-term results for the strong students, we might not allow enough time in the semester for this repetition to happen for everyone. Consequently, many students could be pushed outside their zone of proximal development and lose their motivation to continue putting effort into mastering physics. Also, like many, my main focus in the past has been on Mechanics. The study indicates that we should not neglect how students learn and progress in Electricity & Magnetism.

CHAPTER 8: CLOSING STATEMENT

This research created a list of threshold concepts for the three physics courses of the current and the new Science Program. While having more TC than NYC, the Mechanics course did not have more TC than NYB. This result suggests that the number of TC alone cannot explain the students' struggles in Mechanics. Further research is needed to determine if the sequence of the TC influences their impact.

Independent of the result, the participants expressed that identifying the thresholds was a useful process. Threshold concepts are, by their nature, more difficult to learn. Learning new concepts without mastering previous TC is challenging. Thus, those thresholds require special attention, and the teachers need to be aware of their presence in the courses. Analyzing the concepts of the courses by itself did create this awareness for the teachers involved, and communicating the results will help the entire physics education community, hopefully serving as both a discussion starter and as insight for the implementation of the new Science Program. The participants of this study highly recommended that other departments and programs also try to identify the threshold concepts in their courses.

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APPENDIX A. SURVEY QUESTIONS

SURVEY 1: IDENTIFICATION OF CONCEPT CHARACTERISTICS AND CONSEQUENCES OF NON-MASTERY

Questions for each concept of the courses

Concept *Concept title*

Characteristics:

1. Transformative (changed the way the students think): yes/no
2. Irreversible (can not be forgotten): yes/no
3. Integrative (connects concepts): yes/no
4. Bounded (Is limited to the discipline of physics): yes/no
5. Troublesome (conceptually difficult, conflicts with previous views, alien): yes/no

Consequences of non-mastery:

1. Remaining stuck (continued use of alternative conceptions): yes/no
2. Fragmented knowledge (not able to make links to other concepts): yes/no
3. Problems in learning other concepts: yes/no
4. Mimicry as a coping mechanism, relying on a surface (memorization) approach: yes/no
5. Disengagement, loss of motivation, withholding of efforts: yes/no

SURVEY 2: INTRODUCTION TO THE TC FRAMEWORK AND DISCUSSION OF THE 1ST ROUND DATA

Which concepts should be added or removed from the list? In each case, justify.

SURVEY 3: VOTE ON CHANGES

Do you accept the proposed changes?

List of proposed changes

Change:

Justification:

Accept: yes/no

FOLLOW-UP SURVEY: EVALUATION OF THE PROCESS AND THE RESULTS

Part 1: The process

Using the Likert scale provided, assess your agreement with the following statements:

- Having participated in the process made me more reflective of how I teach certain concepts
- Having participated in the process will be useful for my teaching practice
- The identification process was an ideal means for initiating departmental discussion regarding our courses
- Discussing threshold concepts ahead of implementing the new Science Program was a useful

exercise

- I would recommend to other departments/programs to engage in the process of identifying threshold concepts in their courses
- The process would have been more useful if done face to face instead of using anonymous surveys

Part 2: The results:

Using the Likert scale provided, assess your agreement with the following statements:

- Having a list of threshold concepts will make me more reflective of how I teach certain concepts
- Having a list of threshold concepts will be useful for my teaching practice
- Having a list of threshold concepts can serve as a discussion starter regarding our courses
- Having a list of threshold concepts will be useful when implementing the new Science Program
- The resulting list of threshold concepts might have been different if done face to face instead of using anonymous surveys

Part 3: Results vs. Process

Using the Likert scale provided, assess your agreement with the following statements:

- Having participated in the process is more useful than the resulting list
- The resulting list is useful also for those that did not participate in the process

(Click here to jump to Methodology - Instruments)

APPENDIX B. DETAILED DATA

ROUND 1 – THRESHOLD CONCEPTS BASED ON CHARACTERISTICS

Table 17. Threshold concepts in NYA Round 1

	Identified by	
More than 75%	**Majority**	**One**
Inertia, Mass and Weight, Center of Mass	1D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration	1D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration
Newton’s Three Laws of Motion (including FBD's)	Vectors (Scalars/Vectors, Addition, Notation)	1D Kinematics: Equations for constant acceleration / Free Fall
	2D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration in 2D	1D Kinematics: Graphs
	Relative Velocity (Galilean Relativity), Reference Frames	Vectors (Scalars/Vectors, Addition, Notation)
	Uniform Circular Motion	2D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration in 2D
	Rotational Kinematics - Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities	Relative Velocity (Galilean Relativity), Reference Frames
	Inertia, Mass and Weight, Center of Mass	2D Kinematics: Projectile motion
	Common contact Forces (normal, tension, friction)	Uniform Circular Motion
	Newton’s Three Laws of Motion (including FBD's)	Rotational Kinematics - Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities
	Newton's laws of Universal Gravitation	Rotational Kinematics - Equations with constant angular acceleration
	Work and Power	Inertia, Mass and Weight, Center of Mass
	Potential Energy (Gravitational and Elastic) / Conservative and Non-Conservative Forces	Common contact Forces (normal, tension, friction)
	Work-Energy Theorem / Conservation of Energy	Hooke's Law
	Linear Momentum / Conservation of Linear Momentum / Collisions / Explosions / Impulse	Resultant Force
	Rotation - Torque , Rotational Equilibrium, Newton's Second Law for rotation	Newton’s Three Laws of Motion (including FBD's)
	Analyzing and Presenting Experimental Data, Uncertainty	Newton's laws of Universal Gravitation
		Work and Power
		Kinetic Energy
		Potential Energy (Gravitational and Elastic) / Conservative and Non-Conservative Forces
		Work-Energy Theorem / Conservation of Energy
		Linear Momentum / Conservation of Linear Momentum / Collisions / Explosions / Impulse
		Rotation - Torque , Rotational Equilibrium, Newton's Second Law for rotation
		Rotational Kinetic Energy
		Angular Momentum / Conservation of Angular Momentum
		Analyzing and Presenting Experimental Data, Uncertainty

Table 18. Threshold concepts in NYB Round 1

	Identified by	
More than 75%	Majority	One
Electric Fields Magnetic Fields, Magnetic Fields due to Current (Biot-Savart)	Electric Fields Electric Potential Magnetic Fields, Magnetic Fields due to Current (Biot-Savart) Induction and Inductance (Faraday, Lenz)	Electric Charge, Electric Force (Coulombs Law) Electric Fields Electric Potential Capacitance Current, resistance, Ohm's Law, electric Power Electric Circuits, Kirchhoff Rules, RC Circuits Magnetic Fields, Magnetic Fields due to Current (Biot-Savart) Induction and Inductance (Faraday, Lenz) Electromagnetic Oscillations, AC, RCL Circuits, Impedance

Table 19. Threshold concepts in NYC Round 1

	Identified by	
More than 75%	Majority	One
Waves and Wave Propagation	Waves and Wave Propagation	Simple Harmonic Motion
Interference, Standing Waves, Resonance	Interference, Standing Waves, Resonance	Waves and Wave Propagation
Simultaneity, Time Dilation, Length Contraction	Sound Waves, Doppler Effect, Beats	Polarity
Heisenberg Uncertainty	Simultaneity, Time Dilation, Length Contraction	Interference, Standing Waves, Resonance
	Relativistic energy and momentum	Sound Waves, Doppler Effect, Beats
	Photoelectric Effect, Quantum Threshold Energy	Thin lenses, eye or optical instruments
	Matter Waves, Particle-Wave Duality	Simultaneity, Time Dilation, Length Contraction
	Heisenberg Uncertainty	Relativistic energy and momentum
	Decay, Radioactivity	Photoelectric Effect, Quantum Threshold Energy
	Green-house effect (New Science Program)	Matter Waves, Particle-Wave Duality
	Intro to Thermodynamics, Heat Machines (New Science Program)	Heisenberg Uncertainty
		Decay, Radioactivity
		Fission and Fusion
		Green-house effect (New Science Program)
		Intro to Thermodynamics, Heat Machines (New Science Program)

ROUND 2 – SUGGESTED ADDITIONS AND REMOVALS

Table 20. Suggested additions and removals for NYA

Suggested additions	Suggested Removals
- Kinetic Energy - Projectile Motion - Resultant Force - Dot/Cross product of vectors	- 1D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration - 2D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration in 2D - Relative Velocity (Galilean Relativity), Reference Frames - Uniform Circular Motion - Rotational Kinematics - Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities - Common contact Forces (normal, tension, friction) - Newton's laws of Universal Gravitation - Work and Power - Linear Momentum / Conservation of Linear Momentum / Collisions / Explosions / Impulse - Rotation - Torque , Rotational Equilibrium, Newton's Second Law for rotation - Analyzing and Presenting Experimental Data, Uncertainty

Table 21. Suggested additions and removals for NYB

Suggested additions	**Suggested Removals**
- AC Circuits	none
- Conservation of Charge	
- Current and Resistance / Ohm	
- Electric Charge	
- Electric Current	
- Electric Force (Coulombs Law)	
- Electric Circuits	
- Kirchhoff's Loop Rules	
- Magnetic Forces	

Table 22. Suggested additions and removals for NYC

Suggested additions	Suggested Removals
- Fission/Fusion	- Radioactivity
- Geometrical Optics	- Decay
- Index of Refraction	- Green-house effect (New Science Program)
- Reflection/refraction/absorption	- Sound Waves, Doppler Effect, Beats
- Relative Velocity (Galilean Relativity), Reference Frames	- Relativistic energy and momentum
- Simple Harmonic Motion	- Photoelectric Effect, Quantum Threshold Energy
	- Heisenberg Uncertainty
	- Matter Waves, Particle-Wave Duality
	- Intro to Thermodynamics, Heat Machines (New Science Program)

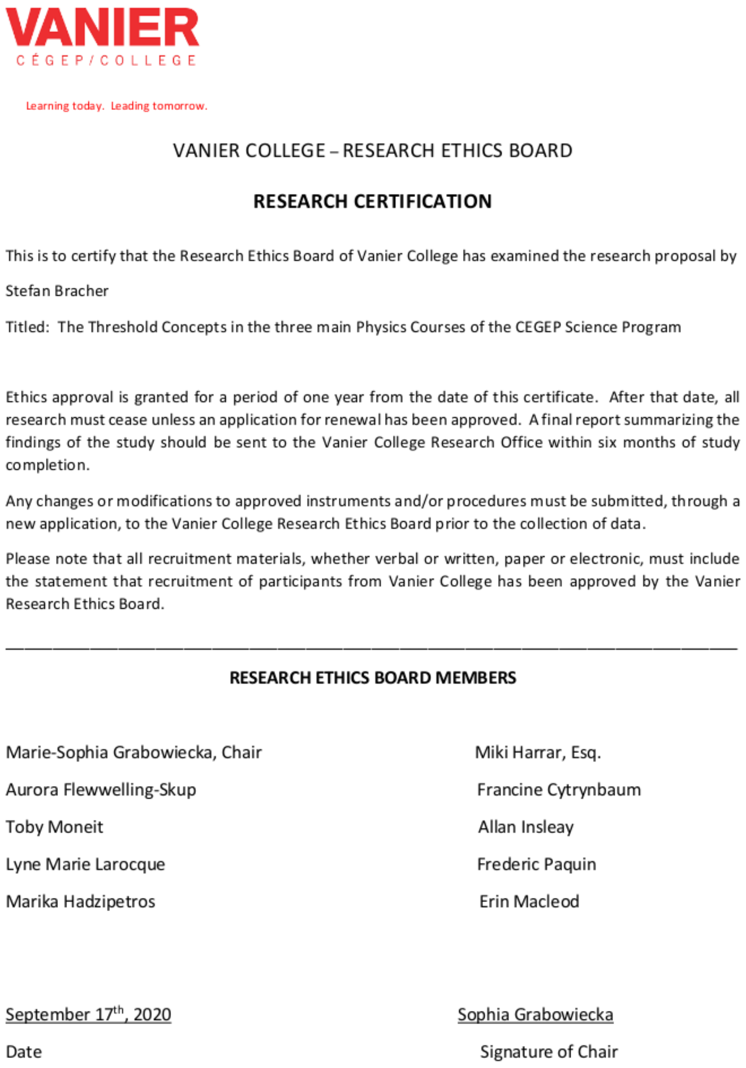
ROUND 3 – FINAL LISTS

Table 23. Identified threshold concepts (Round 3)

	Agreement			
Course	100%	> 75%	> 50%	>0%
NYA	Inertia, Mass and Weight, Center of Mass	Inertia, Mass and Weight, Center of Mass	1D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration	1D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration
	Newton's Three Laws of Motion (including FBD's)	Linear Momentum / Conservation of Linear Momentum / Collisions / Explosions / Impulse	Analyzing and Presenting Experimental Data, Uncertainty	2D Kinematics: Position, Displacement, average and instantaneous Velocity/Acceleration in 2D
	Potential Energy (Gravitational and Elastic) / Conservative and Non-Conservative Forces	Newton's Three Laws of Motion (including FBD's)	Inertia, Mass and Weight, Center of Mass	Analyzing and Presenting Experimental Data, Uncertainty
	Vectors (Scalars/Vectors, Addition, Notation)	Potential Energy (Gravitational and Elastic) / Conservative and Non-Conservative Forces	Kinetic Energy	Common contact Forces (normal, tension, friction)
	Work-Energy Theorem / Conservation of Energy	Vectors (Scalars/Vectors, Addition, Notation)	Linear Momentum / Conservation of Linear Momentum / Collisions / Explosions / Impulse	Dot/Cross product of vectors
		Work-Energy Theorem / Conservation of Energy	Newton's Three Laws of Motion (including FBD's)	Inertia, Mass and Weight, Center of Mass
			Potential Energy (Gravitational and Elastic) / Conservative and Non-Conservative Forces	Kinetic Energy
			Rotation - Torque , Rotational Equilibrium, Newton's Second Law for rotation	Linear Momentum / Conservation of Linear Momentum / Collisions / Explosions / Impulse
			Rotational Kinematics - Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities	Newton's laws of Universal Gravitation
			Uniform Circular Motion	Newton's Three Laws of Motion (including FBD's)
			Vectors (Scalars/Vectors, Addition, Notation)	Potential Energy (Gravitational and Elastic) / Conservative and Non-Conservative Forces
			Work and Power	Projectile Motion
			Work-Energy Theorem / Conservation of Energy	Relative Velocity (Galilean Relativity), Reference Frames
				Resultant Force
				Rotation - Torque , Rotational Equilibrium, Newton's Second Law for rotation
				Rotational Kinematics - Angular Position, Displacement, Velocity and Acceleration, Relation between Linear and Angular Quantities
				Uniform Circular Motion
				Vectors (Scalars/Vectors, Addition, Notation)
				Work and Power
				Work-Energy Theorem / Conservation of Energy

NYB	Electric Fields Electric Potential Induction and Inductance (Faraday, Lenz) Magnetic Fields, Magnetic Fields due to Current (Biot-Savart)	Conservation of Charge Current and Resistance / Ohm Electric Charge (Electric Fields Electric Force (Coulombs Law) Electric Potential Induction and Inductance (Faraday, Lenz) Magnetic Fields, Magnetic Fields due to Current (Biot-Savart) Magnetic Forces	AC Circuits Conservation of Charge Current and Resistance / Ohm Electric Charge (Electric Circuits Electric Current Electric Fields Electric Force (Coulombs Law) Electric Potential Induction and Inductance (Faraday, Lenz) Kirchhoff's Loop Rules Magnetic Fields, Magnetic Fields due to Current (Biot-Savart) Magnetic Forces	AC Circuits Conservation of Charge Current and Resistance / Ohm Electric Charge (Electric Circuits Electric Current Electric Fields Electric Force (Coulombs Law) Electric Potential Induction and Inductance (Faraday, Lenz) Kirchhoff's Loop Rules Magnetic Fields, Magnetic Fields due to Current (Biot-Savart) Magnetic Forces
NYC	Interference, Standing Waves, Resonance Simple Harmonic Motion Simultaneity, Time Dilation, Length Contraction Waves and Wave Propagation	Interference, Standing Waves, Resonance Matter Waves, Particle-Wave Duality Photoelectric Effect, Quantum Threshold Energy Simple Harmonic Motion Simultaneity, Time Dilation, Length Contraction Waves and Wave Propagation	Index of Refraction Interference, Standing Waves, Resonance Matter Waves, Particle-Wave Duality Photoelectric Effect, Quantum Threshold Energy Relative Velocity (Galilean Relativity), Reference Frames Simple Harmonic Motion Simultaneity, Time Dilation, Length Contraction Waves and Wave Propagation	Decay Fission/Fusion Geometrical Optics Green-house effect (New Science Program) Heisenberg Uncertainty Index of Refraction Interference, Standing Waves, Resonance Intro to Thermodynamics, Heat Machines (New Science Program) Matter Waves, Particle-Wave Duality Photoelectric Effect, Quantum Threshold Energy Radioactivity Reflection/refraction/absorption Relative Velocity (Galilean Relativity), Reference Frames Relativistic energy and momentum Simple Harmonic Motion Simultaneity, Time Dilation, Length Contraction Sound Waves, Doppler Effect, Beats Waves and Wave Propagation

APPENDIX C. RESEARCH ETHICS APPROVAL



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VANIER COLLEGE – RESEARCH ETHICS BOARD

RESEARCH CERTIFICATION

This is to certify that the Research Ethics Board of Vanier College has examined the research proposal by

Stefan Bracher

Titled: The Threshold Concepts in the three main Physics Courses of the CEGEP Science Program

Ethics approval is granted for a period of one year from the date of this certificate. After that date, all research must cease unless an application for renewal has been approved. A final report summarizing the findings of the study should be sent to the Vanier College Research Office within six months of study completion.

Any changes or modifications to approved instruments and/or procedures must be submitted, through a new application, to the Vanier College Research Ethics Board prior to the collection of data.

Please note that all recruitment materials, whether verbal or written, paper or electronic, must include the statement that recruitment of participants from Vanier College has been approved by the Vanier Research Ethics Board.

RESEARCH ETHICS BOARD MEMBERS

Marie-Sophia Grabowiecka, Chair
Aurora Flewwelling-Skup
Toby Moneit
Lyne Marie Larocque
Marika Hadzipetros

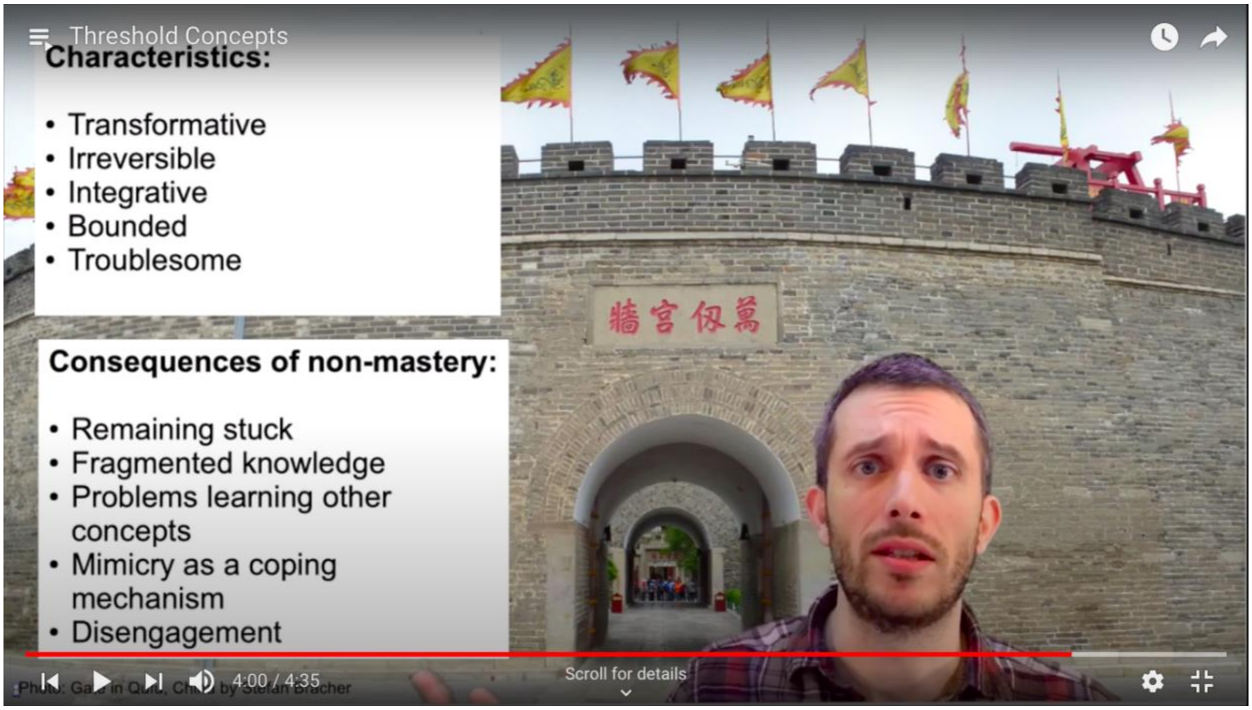
Miki Harrar, Esq.
Francine Cytrynbaum
Allan Insleay
Frederic Paquin
Erin Macleod

September 17th, 2020
Date

Sophia Grabowiecka
Signature of Chair

(Click here to jump to Methodology - Ethical Considerations)

APPENDIX D. THRESHOLD CONCEPT INFORMATION VIDEO



Characteristics:

- Transformative
- Irreversible
- Integrative
- Bounded
- Troublesome

Consequences of non-mastery:

- Remaining stuck
- Fragmented knowledge
- Problems learning other concepts
- Mimicry as a coping mechanism
- Disengagement

Video presentation on threshold concepts in general, prepared by the author to inform participants about TC ahead of the second survey.

Link: https://youtu.be/3sU3kXa81RU