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Critical Thinking Activities to Promote Engagement and Long-Term Retention of Learning

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CONTEXT
'Critical thinking' is a term often thrown about in educational communities, sometimes in frustration by educators who grumble that their students "don't know how to think", or "they lack the depth required to think through this problem". Worse still, some educators believe they are already teaching critical thinking simply because "it's an engineering class, of course there is critical thinking in this class!". There is a misunderstanding that critical thinking is a skill, or set of skills, rather than a long-term process. Too often, it is assumed that students already have these 'skills' and hence there is no need to *explicitly* teach them, or to demonstrate the critical thinking process.

PURPOSE OR GOAL
The motivation of this study is to highlight the current literature on critical thinking, and demonstrate how it can be applied in STEM-based undergraduate classes to promote engagement and long-term retention of the learning. Using pedagogical approaches, this paper discusses development of a theoretical framework within which educators can create authentic learning experiences that better prepare students for the 21st century workforce; equip them with explicit tools to undertake independent problem-solving tasks; and engage them in life-long learning opportunities.

APPROACH OR METHODOLOGY/METHODS
A document-based, systematic review has been conducted to develop the educational framework. This framework combines a learning continuum often discussed in differentiated learning literature, with a thinking continuum, which maps out the developmental thinking stages proposed by Piaget and others. The framework enables the educator to choose a particular thinking activity to match the intended learning, whether it be short-term over a given lesson; longer-term over a topic; or synthesis knowledge over the entire subject. Changes in teaching practice come with enhanced knowledge of how a given activity promotes key learning and thinking development.

ACTUAL OR ANTICIPATED OUTCOMES
An exploratory research study is proposed to better assess the effectiveness of this framework, but is yet to be completed. Two hypotheses are to be investigated: a) the framework, when implemented correctly into a given STEM class, will improve student outcomes (improved: engagement; confidence and ability in completing activities; depth of conceptual and technical understanding; critical thinking and learning; year-to-year retention rates); and b) detailed demonstration of this framework enables successful implementation of appropriate interventions in a given subject.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY
While a formal study is yet to be completed in this area, anecdotal observations gathered from some chemical engineering classes has shown that many of the student outcomes listed in hypothesis a) are being met. Regular implementation of class activities with open-ended questions produced lively and in-depth discussions, and over time, students' abilities in responding to in-depth questions under test conditions also improved. Many students have provided positive feedback about this subject long after its completion and have cited several learning examples. This may indicate longer-term retention due to better engagement in the class resulting from a structure focused on regular critical thinking opportunities.

KEYWORDS

Critical thinking; differentiated learning; engagement

Introduction/Background:

‘Critical thinking’ is a term frequently misunderstood within educational communities, primarily due to the misconception that it is a skill (or set of skills) rather than a long-term process. Some educators believe that critical thinking occurs by default due to the nature of their class, and fail to recognize that these skills need to be explicitly taught throughout the entire learning process (ideally from K-12 and beyond). Critical thinking tasks are known to improve student engagement with the material, leading to high-quality learning outcomes (DeWaelsche, 2015). Consequently, students unable to practice and apply critical thinking may disengage with the learning due to perceived difficulty, drop the course, or STEM altogether (DeWaelsche, 2015; Muenks et al., 2020). A popular description of what critical thinkers ‘do’ is given by Paul and Elder (Paul & Elder, 2007) (**Figure 1**), which describes a set of characteristics that an individual builds *over many years* of practice.

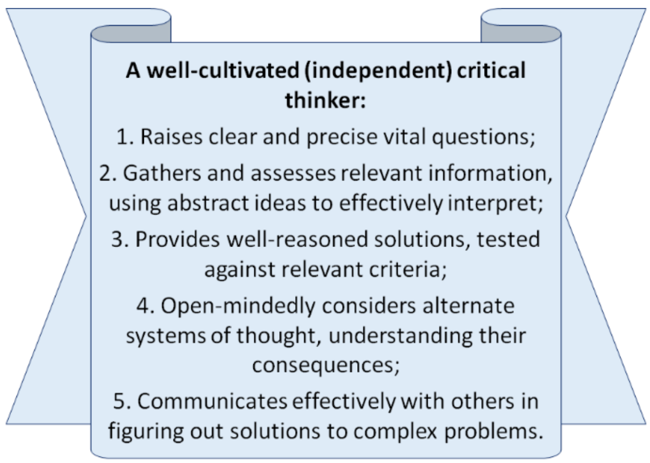

Figure 1: The five characteristics of a critical thinker (Paul & Elder, 2007).

Several developmental thinking stages are required to achieve such level of independent thought, and theorists such as Piaget and cognitive psychologists (Cuevas, 2016; Lefmann & Combs-Orme, 2013; Ojose, 2008; Schwartz, 2009) have sought to explicitly define these steps within a *continuum of thinking*. As thinking is the process by which we learn (Kadel, 2015), and learning is considered a life-long pursuit, independence of thinking and the ultimate goal of critical thinking is also a life-long pursuit. Critical thinking is defined as ‘the art of analyzing and evaluating thinking with a view to improving it’ (Paul & Elder, 2007). This definition infers an ongoing process of reflecting on present thinking abilities, highlighting a necessity by educators to explicitly teach and cultivate analysis and evaluation skills throughout all levels of education. The *process* must not be confused with the five characteristics shown in Figure 1, which are instead a *result* of cultivating improvements to one’s thinking process over many years.

In the Higher Education Learning Framework handbook (Nugent et al., 2019), there is a clear distinction made between ‘learning how to learn’ and ‘employing critical thinking strategies’ to assist with this learning. Critical and creative thinking strategies are developed through higher-order thinking (HOT) processes that can be practiced at any stage of knowledge acquisition, confirming that developmental thinking stages should be active throughout the entire learning spectrum (ideally through primary, secondary and tertiary). Students who practice HOT processes regularly can reflect on which of these promotes the best learning outcomes in a given course. Teachers can support the learning by providing scaffolded activities through to independent learning tasks. These two actions – thinking and learning – together optimize the complex process of acquiring in-depth new knowledge with an independent curiosity.

How then, does one ensure that students are adequately prepared for this thinking and learning, life-long journey? What techniques can a teacher employ that suitably enable regular practice of both teaching and learning strategies for STEM students at University (and in reality, during K-12 as well)? It is from within this context that an educational framework is proposed, which contains a thinking continuum overlaid with a learning continuum. Ideally, this framework will support teachers in choosing suitable activities that enable students to simultaneously hone their critical thinking and learning of a given topic.

Development of the Educational Framework:

Pedagogies related to the Thinking Continuum:

Piaget's theory is often criticized by those in educational research due to its dependency on biological development (particularly age) of the individual (Lefmann & Combs-Orme, 2013; Ojose, 2008). This criticism has long-proven to be valid, given that Piaget predicted 16 year-olds to have accomplished *formal operational thinking*, yet high numbers of students entering college (18+ year-olds) are still operating at the *concrete thinking stage* (Lefmann & Combs-Orme, 2013). However, what largely remains undisputed is the progression of thinking stages identified by Piaget, and the necessity of progressing through these stages in order (Lefmann & Combs-Orme, 2013).

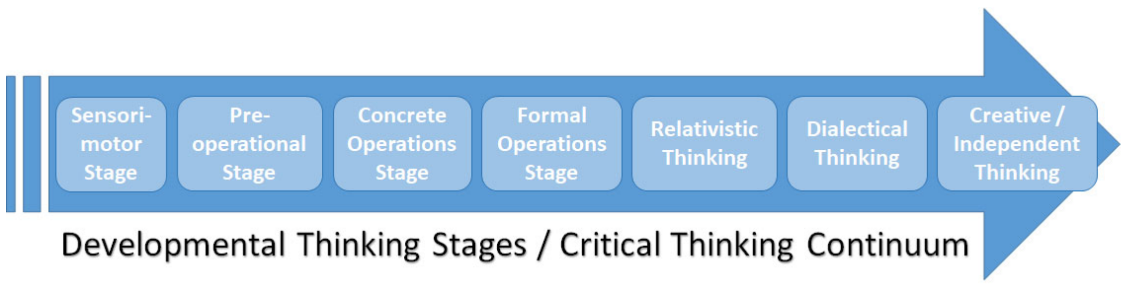

Figure 2: The critical thinking continuum map, showing developmental thinking stages proposed by Piaget (Lefmann & Combs-Orme, 2013; Ojose, 2008), post-Piagetian theorists (Chang & Chiou, 2014; Wu & Chiou, 2008)**, and creative/independent thinking theorists (Hutton-Prager, 2018; Walesh, 2017).**

Piaget's work can therefore be thought of as a useful *critical thinking continuum*, outlining progressively more difficult thinking processes that gradually develop throughout a lifetime (**Figure 2**). This is similar to many K-12 school-wide curricula (*Australian Curriculum*, 2020) that map out a student's increasing capability of science or mathematical content, for example. As with the school curricula, core skills learned in early years of school are the foundations for more difficult content taught at later year levels, and so it is with a critical thinking continuum. College-level students will still require fundamental mathematical knowledge learned many years earlier for them to succeed in engineering mathematics, just as well-cultivated critical thinkers will still require thinking skills they learned early on in the critical thinking process.

More recent theorists have expanded upon Piaget's initial four stages, to include two additional stages beyond formal operational thinking (Chang & Chiou, 2014; Wu & Chiou, 2008), commonly termed as *postformal thinking* (Wu & Chiou, 2008). While formal operational thinking masters the abstract reasoning, this rarely allows provision for alternative viewpoints and possible adjustment of a single solution to a particular problem (Chang & Chiou, 2014). *Relativistic thinking* is when an individual considers a problem from other perspectives besides his/her own, coming to the realization that more than one solution is in fact possible (Chang & Chiou, 2014; Wu & Chiou, 2008). This acceptance of other opinions or perspectives is also thought to be an important component of acceptance in diversity issues (Chang & Chiou, 2014). *Dialectical thinking* is when one comes to expect contradictory views and in fact relies on these contradictions to progress their own developmental thoughts on an issue (Chang & Chiou, 2014). Wu and Chiou (Wu & Chiou, 2008) connected postformal thinking patterns with *creative thinking*, suggesting that this was in fact necessary in scientific fields and research. Walesh (Walesh, 2017) has also formalized creative thinking characteristics and processes for engineers, confirming the importance of creativity and postformal thinking in STEM disciplines. Hutton-Prager (Hutton-Prager, 2018) connected independent and creative thinking together as another stage beyond dialectical thinking. In this stage, one has essentially mastered the art of critical thinking, is self-motivated to learn, requires little assistance in the learning process, and displays the characteristics described in Figure 1.

Piaget's and postformal thinking theories represent explicit, discrete stages of thinking progression within the continuum of thinking development over a lifetime of honing one's skills in critical thinking. Many educational theories describe similar progressive steps in thinking development, but for shorter time-periods to better assess and support student learning, such as within a lesson or topic. Some of these include Bloom's revised taxonomy (Krathwohl, 2002); Kolb's experiential learning theory (Kolb, 1984); hierarchical complexity scale (Schwartz, 2009); and cognitive load (Ischebeck et al., 2007; Willis, 2007). While each are unique, the first three rely on progressively complex thinking steps, and the last emphasizes repeated practice and reinforcement together with experience to help establish longer-term memory.

Pedagogies related to the Learning Continuum:

Differentiation is a K-12 pedagogical teaching methodology that considers student learning needs, develops depth of thinking with targeted learning activities, provides multiple approaches to the learning, and encourages enhanced engagement by the students (Bullock, 2016; Rock et al., 2008; Tomlinson, 2016). Importantly, it is a fluid process, and the teaching is constantly refined or modified throughout a topic to best match the students' needs at the time. Formative assessment is heavily relied upon to assess students' progress during a topic, and involves key questioning during class discussions and enhanced awareness of students' difficulties in order to modify teaching accordingly. Although there are several descriptions in the literature regarding differentiation, Hutton-Prager (Hutton-Prager, 2018; Prager, 2013) summarized these into five broad themes or differentiation principles (DP), which may be thought of as a *learning continuum*:

1. Understand student need and preferred learning modes
2. Focus on key concepts and provide multiple approaches to learning
3. Provide challenging learning experiences within each student's present capabilities
4. Foster collaboration between students and their faculty
5. Create independent learners and ownership of learning

This generic framework is loosely progressive, in that the educator needs to know the current knowledge base of his/her students and how they prefer to learn before starting a new topic. However, the dependence of differentiation techniques on awareness of student need (DP1) means that the educator will frequently return to the first DP throughout class activities to learn the content (DP2); challenge the students within their Zone of Proximal Development (ZPD) (Murphy et al., 2015) (DP3); and provide collaborative tasks with peers (DP4). The ultimate aim of differentiation is to create independent learners, and teach students 'how to learn' (DP5). The teacher can utilize many effective activities within the DPs, cultivating shorter-term developmental thinking stages within a given thinking capability on the continuum. This learning continuum allows the teacher to refine activities based on student need, better fostering learning independence.

An important benefit of regularly implementing differentiated teaching practices is that it models a valuable learning process for the students. As students continue to develop enhanced thinking capabilities, they will eventually approach any new topic using similar learning progressions, such as choosing the methods that allow them to learn most effectively; learning key fundamentals of a topic before attempting more challenging material; and seeking out others (or additional material) to reach a deep level of understanding.

Putting everything together:

The critical thinking continuum (on the y-axis) can be plotted against the differentiated learning continuum (on the x-axis), to come up with a conceptual framework as shown in **Figure 3**. The boxes are described in (Hutton-Prager, 2018), and represent characteristics of intersections between the two continua. They show the shift from teacher-directed tasks (lighter colour) to student-directed tasks (darker colour), as students increase their cognitive capabilities.

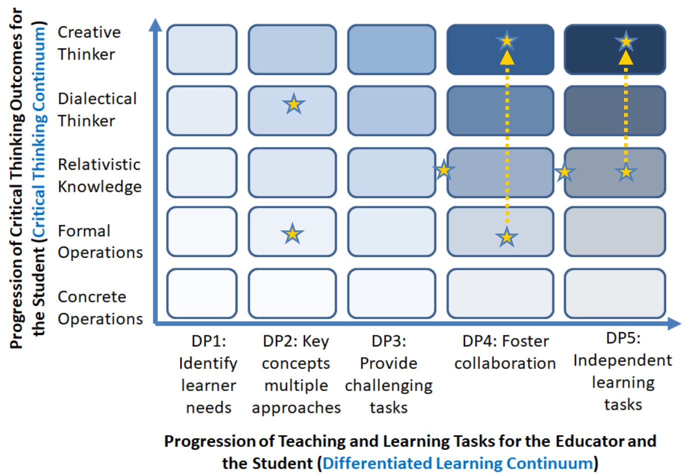

Figure 3: Representation of the educational framework (Hutton-Prager, 2018), showing the overlay of the DPs as the learning continuum with the critical thinking continuum (Hutton-Prager, 2019).
Note: stars refer to examples described in the framework demonstration.

Each of these squares needs to be populated with suitable activities for STEM-based learning and thinking, and this can only be done with buy-in from like-minded professionals, interested in developing this framework into something that can be used on a wide-ranging scale. Ultimately, the framework can be made public as a website forum, where an educator simply clicks on a particular box and has a variety of suitable activities/lesson plans freely available to spark ideas and adaptation into a particular class. This is similar to what is already available for educators in the F-10 Australian Curriculum, where suggested lesson plans/activities that match the particular point/s in the continua are freely downloadable for use (Australian Curriculum, Assessment and Reporting Authority (ACARA), 2019). At present, the framework acts as a theoretical base from which an educator may refer to design activities that address both thinking and learning practices at differing levels. An educator will plan the learning progression of a topic through DP1 – DP5 (the x-axis), and then choose suitable activities from a range of thinking levels to assist with the learning.

Evaluation and Demonstration of the Framework:

Evaluation Plans:

This framework has not yet been evaluated on a large scale. However, detailed plans for its implementation and evaluation have been prepared to address two hypotheses: a) the framework, when implemented correctly into a given STEM class, will improve student outcomes; and b) detailed demonstration of this framework enables successful implementation of appropriate interventions in a given subject. Faculty will first be trained in the framework methodology and invited to contribute to suitable learning tasks that explicitly develop critical thinking skills, hence developing a trial 'intranet framework', initially for use only to those participating in the study. Post-graduate educational researchers would also contribute and help shape the activities to align with the various pedagogical principles outlined previously, and then the framework with these initial activities would be ready to use for the implementation phase.

For hypothesis a), the variables identified include the nature of the STEM learning area (introductory; computational; fundamental theory; laboratory; final year design project); year level of subject (1^{st} – 4^{th} year); and type of students in the subject (remedial, average, exceptional).

Faculty recruited to the testing of this framework will preferably teach subjects across all STEM learning areas identified as well as year levels. The responses to be recorded during implementation of a chosen activity will include: level of engagement; overall satisfaction/confidence in ability to successfully complete an activity; depth of understanding the content (conceptual and technical); changes in critical thinking and learning abilities; and student retention rates from one year to the next. These responses will be recorded using a variety of measurement tools, ranging from survey instruments; assessments (e.g. specific homework questions; assignments, pre-/post-tests); completion of the California Critical Thinking Skills Test (CCTST); and retention year data that will be compared with previous years that did not implement these interventions. For hypothesis b), the variables include faculty from different STEM areas (e.g. engineering, science, mathematics, manufacturing); and experience of teachers (tenure-track professors, tenured professors, instructors, professors of practice). Responses will be measured using survey instruments, and will include questions to the faculty about satisfaction of the framework development; the training and preparedness for implementation; ongoing support during preparation and implementation phases; and ease-of-use of the framework.

Demonstration of the Framework and Anecdotal Observations:

The theoretical concepts of the framework have been used by the author to design and implement several class activities that address the intersection of thinking and learning. Anecdotal observations by the author have included high energy levels and enthusiasm of students in the class; positive feedback by the students on their satisfaction and interest in the subject content where these activities were regularly implemented (long after completion of the semester); and an improved ability to respond to open-ended HOT questions as the semester progressed. This 'preliminary data' suggests that a formal study of the framework implementation as outlined above is likely to result in several positive outcomes that can be further refined in the longer term.

Demonstration of some activities developed from the framework theory are presented in **Table 1**, using a graduate-level subject taught by the author at the University of Mississippi, Chemical Engineering Department. This subject also attracts undergraduates (3^{rd} and 4^{th} year students), and contains high-level calculation requirements and theoretical concepts that need to be understood to learn the content. Table 1 also describes the overlay between the learning required and the thinking levels needed to develop the learning. These activities are mapped onto the framework itself in Figure 3 (see stars and arrows), and were typical of ongoing work designed for most lessons. Key points that educators may find useful in designing their own tasks are:

- *Planning:* each activity must have a purpose that helps students achieve learning outcomes while practicing critical thinking processes. Activities must be more than time-fillers!
- *Variety:* each lesson should include at least one key activity that promotes learning and thinking, and the lesson itself should be a mix of lecturing, class discussions, small-group activities, individual response, online quizzes, etc. Activity types can be used more than once, but it is best to not over-use them.
- *Repeated practice:* regularly allowing students to engage in explicit learning and thinking activities promotes motivation, long-term retention, better in-depth understanding of material, and opportunities to cultivate one's thinking processes.

Since this class was taught to students from different year levels, it was common to see students apply differing thinking levels to each activity, resulting in varied degrees in learning outcome achievement. This in fact is typical in any class where differentiated learning principles are practiced. The activities were designed to spark curiosity in the students, and encourage them to practice higher levels of thinking, which ultimately contributed to better engagement with their learning. A preliminary Kahoot poll in the first lesson revealed the current understanding of key topics by the students. This was valuable for the teacher to know which topics needed particular attention, and also for the students to encourage them to revise certain concepts in preparation for the learning ahead (DP1). Constant, regular practice in critical thinking processes (e.g. see Table 1) provided students with many opportunities to develop their HOT capabilities. These same processes were then formally tested during examinations containing multiple choice, written response, and calculations. Several of the written response questions were designed with the same open-ended inquiry that was regularly practiced during class, and calculation tasks were occasionally followed by a justification-type question to comment on whether or not the calculated value 'made sense'. This encouraged reflection on the actual process and concepts rather than simply performing calculation steps according to a predetermined 'recipe'.

Table 1: Examples of class activities developed using the educational framework

Description of activity	Learning level; learning required	Thinking level; thinking needed
Focused free writing activity: 5 min concentrated writing response; pen does not leave paper, allow free flow of thoughts to clarify knowledge	**DP2:** Core-knowledge activity to make sense of several new concepts, and identify which areas still need additional practice to learn	**Formal:** After pre-reading and short lecture, this activity type gives another way for students to interact with the material (repetition)
Matching activity: images of surface defects need to be matched to formal descriptions of each type.	**DP2:** Core knowledge is learning about different types of defects and how they are scientifically described	**Dielectic:** Requires drawing on prior knowledge and contradictory descriptions of complex systems to complete
Open-ended class discussion questions, for example: *Imagine you are a miniscule energy detector that gets in between two atoms of a matrix. Describe energy, bonds, implications of bulk material, etc.*	**DP3 (and possibly DP4):** Newly acquired knowledge cannot be directly applied to question; understanding of concepts are critical to successfully respond	**Relativistic:** Discussion questions are deliberately ill-defined. Students need to make suitable assumptions based on information they have to adequately respond to the questions
Experimental program: students prepare composite materials; then measure bulk and interfacial properties. Series of four experiments that are written up with carefully guided questions that require critical thinking to respond	**DP4:** Practical activities performed in small groups, fostering collaborative learning. Core learning includes following experimental procedures, working scientific instruments, and analyzing / interpreting results	**Formal through to creative:** Range of thinking abilities enables procedural understanding through to cultivating considered reasoning skills and accurately communicating results
Consolidation activity: students apply consolidation theories to explain what happens to a liquid applied to a porous matrix at different times after initial application	**DP4 (and possibly DP5):** Students convert theoretical knowledge of consolidation to practical situations of a liquid that subsequently dries and consolidates on a porous matrix	**Relativistic through to creative:** Difficult scenarios require competing and contradictory theories to be discussed and compared, improving reasoning and interpretation of abstract idea
Formulation material assignment: Students come up with a material formulation of their choice, utilizing their composite components knowledge	**DP5:** Independent project requiring students to research suitable chemical components and compositions to achieve desired bulk properties, with justification	**Relativistic through to creative:** Students need to consider and assess multiple options, and make informed decisions with the information available to solve a complex problem

Conclusions / Recommendations:

An educational framework that overlays a critical thinking continuum with a differentiated learning continuum has been proposed and discussed. This framework enables the educator to develop unique and purposeful class activities with regular critical thinking practice to produce desired learning outcomes. With persistent practice of these two intersecting domains, students' motivation towards learning improves, and their critical thinking capabilities are cultivated. Several activities developed from this theoretical framework were discussed, and demonstrated in a graduate-level subject, but larger testing is needed to confirm its suitability on a wider scale. It is envisaged that this framework will become a useful resource to university-level STEM educators, where suitable activities can be regularly utilized to promote critical thinking abilities that drive learning.

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