Assessing critical thinking aspects involving cause and effect inquiry in the teaching of physics for engineering and technology students

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Abstract
The subject of cause and effect analysis is an important part of the foundation of epistemology. In this study, the assessment of critical thinking has been implemented in the teaching of introductory physics curricula required for technology and engineering students. In addition to the accepted critical thinking criteria, which include clarity, precision, accuracy, relevance, and consistency in each college course, the expository facet in the teaching of physics to engineering and technology students has been expanded to encompass areas concerning safety, energy efficiency, material integrity and client/customer needs. Included in the range of assessable strategies is (1) the application of specific problem solving perspectives in which situations other than those detailed in required lecture textbooks are assigned and (2) the explicit writing on cause and effect relationships in the discussion section of a lab report with emphasis on the issue of correlation and uncertainty. The critical learning assessment rubric used in this study ranked students’ abilities using the measures of Highly Competent, Competent and Needs Improvement versus Participant Deliverables. The assessment results showed that deliverables evaluating numeracy exhibited higher scores than those that addressed writing skill. The impact on General Education and ABET course objectives is discussed.

I. Introduction

One of the most important issues to a STEM student on the reason of attending college is to get a job. Recent News sources had reported the rise of robotic usage and the White House talked about robot growth replacing $20 per hour job last month. This emerging trend raises the question of critical thinking versus artificial intelligence and the number of engineers and technicians needed to build robots. Although human skills in pattern recognition, language abilities, and creative thinking are still better when compared to what artificial intelligence can do, it is important for students to build creative thinking based on critical thinking and venture beyond algorithm learning that has been found to be related to biological evolution.

Critical thinking skill could be taught in a physics class, a requirement in engineering and technology curricula. This paper addresses the critical thinking issue in three aspects, namely, the maximum and minimum conditions in physics problems and ability to extend the result using cause and effect thinking methodology, the critical step in meeting lab objective and algorithm
learning in a lecture, and the critical element in a student deliverable that crosses a failure threshold in terms of learning assessment.

A student deliverable usually could be classified as having two components, namely, a mathematical component and a writing component such as the sentences in a lab report. The root cause of a deficiency can be analyzed. Symbolic processing in algebra and nonsymbolic processing in geometry are necessary math skills. Mathematical visualization is essential when the answers are graded in terms of a mathematical expression and/or numerical content. Epistemology has traced the acceptance of a mathematical visualization as a proof over a mechanical explanation. As for the tracing of root cause in math deficiency, psychology studies revealed that the symbolic number processing is a strong predictor of arithmetic ability when compared to nonsymbolic number processing; and that a 2-minute pencil and paper test has been proposed as an effective assessment tool for primary school students. In a college setting, although arithmetic ability is well beyond the concern of a STEM student, spatial reasoning ability based on nonsymbolic number processing is an important issue in learning physics. In other words, the spatial reasoning needed in physics could have been developed in a student’s high school years, but the paradox of symbolic number processing prevalence in primary school grading over nonsymbolic number processing is outstanding. Whether this traceable reason is fundamentally responsible for the observed deficiency in mathematical visualization among the academically weaker students would deserve more investigation; not to mention that critical thinking would depend on fundamental thinking process which is an active research topic in brain scan studies.

Writing with good reasoning is expected of a critical thinker-student. Critical thinking had been described as “tends to be open ended and unpredictable, dialectical, and influenced by pragmatic and contextual considerations which are not easily assessed using the standard means of large scale testing, i.e., multiple choice tests; instruments like the California Critical Thinking Test have therefore been criticized” in the field of informal logic. Psychologist Gregory Bassham and colleagues wrote a book titled “Critical Thinking: A Student's Introduction, Fifth Edition 2012”. Philosopher Michael Austin summarized Bassham's critical thinking as having the following important elements: clarity, precision, accuracy, relevance, and consistency. In our lab class, the promotion of critical thinking using uncertainty ranking to assess the extent of meeting the lab purpose have been found to be more suitable for community college engineering and technology students, in contrary to a PNAS report last year that Chi-square statistics is a good start to develop critical thinking with physics class students at Stanford.
II. Critical thinking in physics examples

In a projectile motion understanding in terms of vector drawing and algebra is a fundamental starting point in the learning of college physics. A sketch with the initial velocity and the final velocity will automatically raise the question of a “cause” vector when the final velocity vector is the effect. Graphical vector representation of relative velocity concept is important since the algebra steps are quite cumbersome. When a boat velocity is represented as (known speed, unknown angle to be determined), the water current vector is represented as (known speed, known angle), and resultant velocity is represented as (unknown speed to be determined, known destination angle), the algebraic expressions with trigonometry terms are not easy to solve. However a graphical solution is much easier by drawing the water current velocity first with the known values, and use critical thinking to find the intersection of a line (resultant velocity and an arc (boat velocity)) would demonstrate a full understanding of relative velocity such that a boat captain would know which angle to set his/her boat. Such visualization training is crucial to all subsequent force drawings using the free body diagram concept. The contact forces must be visualized with spatial thinking. The force pair in Newton’s 3rd law visualization is crucial in building the free body diagram for each body. The momentum vector $p$ as in kinetic energy (KE) expression $p^2 / 2m$ is important to reinforce the momentum vector in collision problem solving. The integrand construction using vector concept also needs spatial thinking. The critical thinking of recognizing all these vector diagrams as equivalent mathematical entities will ensure mastery of vector application required for all engineers, if not technicians. When it comes to energy cause and effect consideration, it is KE that drives the motion against the potential energy (PE), so to speak. When it comes to the teaching of force, an Atwood machine with a negligible pulley mass has 2 parameters with delta-$m$ in PE expression as the cause and KE in summation-$m$ expression as the effect. Many of the Physics FCI (force concept inventory) items are about cause and effect because a force received by an object must have a companion force received by another object, according to Newton’s third law. One can argue that the Lagrangian via the energy concept with constraints is more fundamental since we use Lagrangian formulation in analytical mechanics and quantum mechanics. Nonetheless, a cause and effect inquiry on force or energy is equally viable to stimulate critical thinking.

A physics question asking maximum or minimum condition is a good platform to demonstrate critical thinking. A standard “Person on ladder” problem asking for the minimum ladder inclination angle for a given ground friction with a smooth wall assumption carries clarity in terms of the associated free body diagram with the acting forces, precision and accuracy in terms of the dynamic equations and their calculations, relevance in terms of the model assumptions of a rough ground and relatively smooth wall, and consistency in terms of prediction that variation of the ground coefficient of friction would yield consistent variation of the minimum incline angle for safety. Such consistency reinforces the cause and effect inquiry methodology. With such a dissection, all physics problems are critical thinking problems as long as two or three dynamics
equations are required. However algorithm learning can become routine procedural steps with the loss of cognitive sensitivity that threatens critical thinking.

A standard roller coaster problem can be reformatted so as to ask the force questions from a material viewpoint, thereby extending the textbook perspective into other engineering related situations. A client/customer could be asking for the material cost given certain velocity requirement for a joy ride. The students should show that the supporting force is lowest when the coaster is at the highest position inside an upside down looping track. Another client/customer could be asking for clean wind energy and students should know the thermodynamics efficiency. The conclusion that 59% efficiency is the best a conventional wind turbine can do in a lecture note posed on the MIT website could be used to extend the standard treatment in a textbook 21. Along the consideration of thermodynamics, computer heat dissipation is crucial for high performance computing; and it has been shown that our ultimate future based on a 2.3% energy usage growth per year would lead to a toast in 400 years 22. Such modeling approach using thermodynamics can generate examples beyond what are offered in standard textbooks to promote critical thinking via emotional learning in the affective domain 23.

A critical thinking analysis does not necessarily require a complex procedure. For example, a student could use critical thinking to understanding the tidal force phenomenon in an inertia frame without the more complex fictitious force phenomenon in a non-inertia frame. The analysis of the splitting of the Shoemaker-Levy 9 comet after a close passage near the planet Jupiter in 1992 could use a critical thinking approach in which the differential gravitational forces on the comet was able to overcome the internal forces. In other words, the front part would have accelerated faster relatively and pulled the other parts. Such pulling would require the internal forces be strong such that the other parts could follow. This explanation requires a critical understanding of Newton’s Third Law in terms of internal forces. A pair of tidal forces in opposite directions on the two outer regions of the comet, relative to the attractive force at the center of the comet, is a calculus deduction using the more complex non-inertia frame fictitious force formulation usually taught in an advanced analytical mechanics course.

III. Critical thinking in physics lab examples

A lab report is a good platform to assess student learning in the areas of knowing cause and effect, causation versus correlation, percent difference versus percent error, and which lab measurement uncertainty is critical for failing to meet the lab objective. Cause and effect writing in a lab discussion is expected in terms of the investigated parameters. When a standard value is not known readily, percent difference would be an accepted criterion to represent the achieved precision. On the other hand, when a standard value is known, percent error would be an accepted criterion to represent the achieved accuracy using the methodology of calibration. The most challenging critical thinking situation would be the learning of which lab uncertainty would contribute the most to the failure of meeting the lab objective for technology students. For
example, a standard vibrating string experiment has been identified as one of the challenging situation when the velocity equals to (1) the frequency*wavelength from the visual inspection of the number of loops, and (2) the square root of string tension divided by the mass per unit length from wave theory. The measurement uncertainty in the wavelength ($\delta \lambda / \lambda$) is equal to the velocity uncertainty ($\delta v / v$). But the measurement uncertainty in the tension ($\delta T / T$) would contribute 50% to the velocity uncertainty ($\delta v / v$). The tension values are usually generated with various standard weights and weight resolution contribution to the velocity uncertainty is still not easy to explain using hypothetical numerical values in the uncertainty assessment in a technology student class. The understanding of the concept ($\delta v / v$) certainly would require more than the symbolic number processing skill in its calculation. Engineering students with 1-year college calculus training usually would do better when compared to the technology students with less calculus training even when the formula involves only two variables.

When a technology student wrote down a wrong micrometer reading, for example 0.63 cm instead of 0.63 mm for the wire diameter in the Young’s Modules Lab, after the micrometer usage was taught in the beginning of a semester, the lack of affective learning is an obvious conclusion, rather than the lack of psychomotor learning. When an engineering student gave a mathematical explanation on the question of “Explain the non-zero intercept of the shown lab graph” in a lecture-test, he/she was not using critical thinking. For example, in the 9.8 m/s/s verification lab using an object sliding down a tilted air-track, a graph containing acceleration on the y-axis and sine of the titled angle on the x-axis is expected to have a zero intercept. A statement like “The explanation of having an uneven table shows critical thinking skill when a technician presents such data to an engineer” usually would be sufficient to re-activate the affective learning in an engineering student, not that we are advocating the use of shame and/or pride to activate their emotion.

The analysis of linear graphical data includes the technique of extrapolation where the negative intercept on the x-axis is of interest. One example is the finding of Absolute Zero using the negative x-axis intercept value when extrapolates from a linear graph of pressure (y-axis) versus temperature (x-axis) in a first year physics laboratory class. One can criticize that an extrapolation to the range of -273 C using measurement data from the range of dry ice (around -78C) to water boiling (100C) is a poor technique; and the similar method of “y-intercept divided by the slope” would not do better. A critical thinking analysis would demand a student to understand the inclusion of multiple linear graphs with different slopes by varying the number of gas molecules in a constant volume while keeping the same laboratory temperature range. In this case, a critical thinking analysis generates a relatively more complex data collection procedure for the justification of using a small temperature range values in the extrapolation.
IV. Critical thinking in assessment

Given a situation where a student scored 5 points, 21 points, 21 points and 21 points respectively in a final exam with 4 equally weighted questions and that passing was set at having scored 70 points or above. One can argue that the critical reason for failing is that the student should have studied just a little more for the 2nd or 3rd or 4th question because only 2 more points is needed to pass. A student perspective could be just being unlucky that day because the missing crucial 2 points for passing is just of random noise origin and there would be no need to reflect on what went wrong in his/her exam preparation. However for learning assessment purpose, the critical reason for failing is that the student did not understand the 1st question at all and he/she needs to study the topics asked in the 1st question. An unbalance scoring result could be interpreted as indicator of having less motivation in learning in the affective domain. However when the outlier score is on the first question on topics covered at the beginning of a semester, a critical thinking instructor could conclude that the student had focused too much on recognition training in answering multiple choice questions and thereby having poor recall for the beginning topics.

The University of Texas at Austin Learning Sciences wrote about the limitation of using multiple choice question: “Students need to process information to really learn it, so time spent studying for recognition is not as effective as time spent working with information” 24. Multiple choice questions can test critical thinking but free expression questions with logical steps can also provide an instructor a clear map of where the student algorithmic presentation needs correction. This training is related to the development of trouble shooting and debugging skills which are needed for technicians and engineers when working in their jobs.

V. Discussion

The critical thinking in terms of cause and effect has an extension to the question on “What is the origin?” Usually an origin could be conjectured from seeing a trend or pattern. The amount of knowledge would limit the number of conjectures and future experiments can be used to settle the origin question. Such an extension would satisfy Gen Ed Objectives. The problem solving skill expected in any ABET Program Education Objectives will be improved with critical thinking training.

Learning improves the ability to use past experiences to guide new decisions. Adaptive learning in transferring past experience to solve a new scenario is a measure of having critical thinking in sorting out the pertinent information in memory for that new scenario. The differences in transfer among individual students have been found to be related to intrinsic connectivity between the hippocampus and the ventromedial prefrontal cortex in fMRI study and that decision is
indicative of memory-related activation \cite{25,26}. Such intrinsic connection and memory activation could be trained with critical thinking focused pedagogy. Whether critical thinking could be eventually totally assessed with brain scan technology without the need of assessing student deliverables is an interesting question; even though fMRI scanning shows that numerical magnitude is processed by different brain areas \cite{27}. It was reported that the right hemisphere is responsible for smaller magnitudes and the left hemisphere for larger magnitudes. Given the traditional interpretation of the lateralization of brain function where scientists attribute the abilities in spatial manipulation, face recognition and processing music to be associated with right hemisphere superiority, the conjecture that calculus concepts like $\delta x$ of a variable $x$ are processed by the right hemisphere and the numerical uncertainly calculations with symbolic number processing are associated with the left hemisphere would be an interest future education project. The current policy of symbolic number processing prevalence in primary school grading over nonsymbolic number processing could require modification with future brain scan data. When a primary school report card says that a student is good in math, how would that relate to the learning of calculus remains a critical issue in STEM education.

Among the topics discussed in the pedagogy of enhancing critical thinking, the heat dissipation examples in the Linux Cluster have been receiving the least learning resistance attitude among the weaker students \cite{28}. Perhaps there is less demand on their adaptive learning skill when we are not teaching the students to understand fully the connection of Shannon entropy to the environment entropy in information processing in thermal physics; but we do expect students to understand that the heat dissipation in the computer is equal to its power consumption in operation where heat is dissipated as the current flows through the resistive elements in electricity lessons \cite{29,30}. We also observed that students like to read commercial application notes on IC chip heat dissipation rather than the textbook examples \cite{31}, and that they were surprised when we discussed how IBM uses warm water to cool the SuperMUC Petascale System in Leibniz Supercomputing Centre (Germany) but uses cool water to cool Blue Gene/Q in Livermore Lab (America) \cite{32,33}.

The student performance in critical thinking has been assessed as satisfactory (score above 75% using highly competent =1, competent = 0.8 and needs improvement = 0.6). The rubric guideline is displayed in Table 1. The assessment results showed that deliverables evaluating numeracy exhibited higher scores than those that addressed writing skill. We believe that the critical thinking learning assessment rubric design can be extended from deliverables in physics to engineering with some modifications.
<table>
<thead>
<tr>
<th>Participant Deliverable</th>
<th>Highly Competent</th>
<th>Competent</th>
<th>Needs Improvement</th>
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<tbody>
<tr>
<td>Explanation of unexpected features in a graph (20%)</td>
<td>Explained the unexpected features in a graph as related to the physical conditions and laws of physics correctly and pointed out the critical reason for getting the features</td>
<td>Made no more than one mistake when compared to a Highly Competent deliverable</td>
<td>Used the wrong physics to explain the unexpected features in a graph</td>
</tr>
<tr>
<td>Equation set up Cause &amp; Effect (20%)</td>
<td>Provided clear explanation of the cause and effect in the setting up of the physics equations in answering a critical aspect of given problem</td>
<td>Provided explanation of the cause and effect in the setting up of the physics equations but made no more than one mistake</td>
<td>Provided explanation of the cause and effect in the setting up of the physics equations but made more than one mistake</td>
</tr>
<tr>
<td>Lab Critical Uncertainty (20%)</td>
<td>Correctly identified the lab measurement uncertainties and provided the correct ranking from the most uncertain measure to the least uncertain measure</td>
<td>Correctly identified the lab measurement uncertainties but provided the wrong uncertain ranking</td>
<td>Incorrectly identified the lab measurement uncertainties</td>
</tr>
<tr>
<td>Discussion Cause &amp; Effect (30%)</td>
<td>Utilized cause and effect inquiry in lab discussion writing correctly</td>
<td>Utilized cause and effect inquiry in lab discussion writing but with one mistake</td>
<td>Utilized cause and effect inquiry in lab discussion writing but with more than one mistake</td>
</tr>
<tr>
<td>Non-symbolic thinking &amp; Spatial thinking (10%)</td>
<td>Applied non-symbolic thinking &amp; Spatial thinking correctly in the given physics problem</td>
<td>Applied non-symbolic thinking &amp; Spatial thinking correctly but with one mistake</td>
<td>Applied non-symbolic thinking &amp; Spatial thinking correctly but with more than one mistake</td>
</tr>
</tbody>
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Table 1: Physics Critical Thinking Assessment Rubric. The participants are students. Scoring could be performed when assigning Highly Competent = 1, Competent = 0.8 and Needs Improvement = 0.6.

VI. Conclusions

The learning assessment of critical thinking has been implemented in the teaching of introductory physics curricula required for technology and engineering students. The pedagogy, based on epistemology studies, has been expanded to encompass areas concerning safety, energy efficiency, material integrity and client/customer needs. The instructor would ask for explicit
writing on cause and effect relationships in the discussion section of a lab report with emphasis on the issue of uncertainty. The assessment results showed that deliverables addressing writing skill could use more practice. Whether the advances in working memory brain scan technology can help students to develop critical thinking skill is an important future development 34.

VII. Acknowledgements

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