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Preface

Welcome to the inaugural issue of the Research Monograph Series (RMS) – an annual publication dedicated to supporting new and emerging scholars in establishing their presence within the realm of academia through contributions to global discussions on science, technology, engineering, and mathematics (STEM) education reform. As a refereed publication sponsored by the Research and Scholarship (R&S) Committee of the Council on Technology and Engineering Teacher Education (CTETE), the new RMS aims to promote serious scholarly discussion of the connections among the Technology Education (TE), Technology and Design Education (TDE), and Technology and Engineering Education (T&EE) fields, and their place within the global discourse regarding the teaching and learning issues accompanying the steady increased focus on the integration of subjects through STEM education.

The intent for technological studies to serve as an integrator of content and practice (knowledge) from many subjects is at the core of the Standards for Technological Literacy first published in 2000 (ITEA, pp. 6-9). This pedagogical intent was made clear in the statement that "…although the study of technology may sometimes be a separate subject, it can never be an isolated subject, cut off from the rest of the curriculum" (p. 9), and which echoes that same intent by the AAAS who nearly a decade earlier recognized that "…the ideas and practice of science, mathematics, and technology are so closely intertwined that we do not see how education in any one of them can be undertaken in isolation from the others" (1993, pp. 321-322). In the nearly 20 years since the STL were published, the field has developed and implemented a plethora of programs and curricula designed specifically to integrate and intentionally teach the content and practices of the many subjects inherent within technological and/or engineering design. Through these efforts the profession developed a significant body of unique knowledge and expertise regarding sound integrative practices.

Throughout the past decade there has been a concerted effort at both elementary and secondary levels across all subjects, but particularly science and mathematics, to increasingly incorporate the use of technological and/or engineering design based learning (T/E DBL) as part of their instructional approach. Few would argue against the potential benefits for teaching and learning within such efforts. However, as potentially beneficial as they may be, there are many issues surrounding such incorporation – validity of T/E DBL as an efficacious strategy, pedagogical fidelity in how other subjects teach technological/engineering design, adequate T/E content knowledge, adequate T/E pedagogical content knowledge, etc. – and around which educational researchers all over the world and in all STEM fields are beginning to address.

The Research Monograph Series is an endeavor to provide a rigorous, peer reviewed publication platform for emerging STEM scholars around the world to address these issues by voicing new perspectives, innovative ideas, and novel approaches for researching and better understanding what are most certainly critical educational issues of the 21st century. The four chapters of this inaugural publication of the RMS address some of these very issues and provide a glimpse into those specifically concerned with the cognitive demands imposed on the learner engaged in T/E DBL.

Chapter 1

A systematic review of research around Adaptive Comparative Judgment (ACJ) in K-16 education

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Abstract

While research into the effectiveness of open-ended problems has made strides in recent years, less has been done around the assessment of these problems. The large number of potentially-correct answers makes this assessment difficult. Adaptive Comparative Judgment (ACJ), an approach based on assessors/judges working through a series of paired comparisons and selecting the better of two items, has demonstrated high levels of reliability and effectiveness with these problems. Research into using ACJ, both formative and summative, has been conducted at all grade levels within K-16 education (ages 5-18), with a myriad of findings. This paper outlines a systematic review process used to identify articles and synthesizes the findings from the included research around ACJ in K-16 education settings. The intent of this systematic review is to inform decision-makers weighing the potential for ACJ integration in educational settings with researched-based findings around ACJ in K-16 educational settings. Further, this review will also uncover potential areas for future researchers to investigate further into ACJ and its' implications in educational settings.

Key Words: Adaptive Comparative Judgment, Open-ended problems, Assessment

Introduction

The preparation of students for future employment and an emphasis on Science, Technology, Engineering, and Mathematics (STEM) education and skills has led to a larger emphasis on the integration of open-ended problems in education (Bartholomew, 2017; Dearing & Daugherty, 2004; Diefus-Dux, et al., 2004; ITEEA, 2000/2004/2007; NAE & NRC, 2014; NRC, 2009; Reeve, 2015; Sanders, 2009; Wicklein, 2006). This emphasis, often joined with problem- and project-based learning, has aimed at better preparing students for success in highly flexible and technologically-driven work environments (Dearing & Daughterty, 2004). Despite widespread efforts around open-ended problems, and their integration in education, much less has been done around the assessment strategies and techniques associated with these types of problems (Bartholomew, 2017; Kimbell, 2007, 2012a, 2012b; Pollitt, 2004, 2012; Pollitt & Crisp, 2004). Open-ended problems, with a myriad of potentially correct solutions, have traditionally been very difficult to assess with validity, reliability, and efficiency (Bartholomew, 2017a, 2017b).

Although rubrics, portfolios, technology-enabled platforms, and criterion-grading tools have all been employed towards improving the assessment of open-ended problem many of the challenges (e.g., reliability, efficiency) have remained. Research and experience continue to affirm that a teacher's ability to assess open-ended problems with fidelity using traditional forms of assessment is poor at best—past experiences, personal preferences, time in the profession, and a variety of other factors all "muddy the waters" and contribute to difficulty in assigning grades reliably (Alkharusi, 2011; Bartholomew, 2017; Crossman, 2004; Dietrich, 2010; Kimbell, 2007, 2012a, 2012b, 2016; McMillan & Nash, 2000; Pollitt, 2004; Rice, 2010; Westerman, 1991). However, a recently revisited approach to assessment titled Adaptive Comparative Judgment (ACJ) has been increasingly utilized in recent years with success in addressing many of the challenges associated with open-ended problems (Bartholomew, 2016; Bartholomew, Strimel, & Jackson, 2017; Hartell & Skogh, 2015; Kimbell, 2007, 2012a, 2012b; Kimbell, et al., 2007; Newhouse, 2011; Seery, Canty, & Phelan, 2012; Steedle & Ferrara, 2016).

ACJ was originally conceptualized as Comparative Judgment (CJ) in the 1920s by psychologist Louis Thurstone (1927) who presented several alternative methods of constructing measurement scales for assessment. Comparative Judgment is a process where a judge/assessor views two items and chooses the better of the two items. This process assumes that as judges/assessors view items they assign an instinctive value to each item based on their expertise, past experiences, and the item's quality. Thurstone posited that when two phenomena are placed in comparison with one another, an individual is able to use their own instinctively-assigned values for each item to compare and identify which of the two phenomena are 'better' with great levels of fidelity. Thurstone demonstrated that by repeatedly comparing pairs of items a rank-order could be produced of all the items assessed with very high levels of reliability. This approach to assessment, which demonstrated highly-reliably results, was largely unused for decades—largely as a bi-product of the arduous time-requirements associated with the repetitive comparison process.

Decades later, Thurstone's work was revisited by Pollitt and Murray (1996) who saw the opportunity to utilize technology as a means of optimizing this process. Pollitt and Murray (1996) used Thurstone's ideas, in conjunction with Georg Rasch's mathematical models for educational tests (Rasch, 1993), to further develop the idea of comparative judgment as a tool for assessment. Initial piloting of this approach demonstrated markedly more reliable results than traditional approaches to assessment (Kimbell, 2007; Pollitt & Whitehouse, 2012), especially in relation to open-ended problem assessment (Kumar & Natarajan, 2007).

In addition to the use of technology for facilitating the comparative judgment process, work was done to develop an algorithm which adaptively paired similarly-ranked items and worked to further reduce the time required for completing the assessment process (Kimbell, 2012a, 2012b; Pollitt, 2012). The addition of the algorithm—which adaptively pairs similarly-ranked items for assessment—to the process led to the concept of *adaptive* comparative judgment (ACJ). With the applied algorithm, improved reliability can potentially be achieved after fewer comparisons than traditional comparative judgment which relies on random pairings (Bramley, 2015; Steedle & Ferrara, 2016).

This approach to assessment, although markedly different from other assessment techniques, has been implemented by a variety of individuals in different locations, subject areas, and with different age groups (Bartholomew, 2017a). However, not all reviews have been positive with Bramley (2015) offering the harshest critique of the approach. Bramley (2015) challenged the reliability of the rank-order produced through ACJ explaining that the adaptive aspect of ACJ inflates the reported reliability. However, Pollitt (2015) countered Bramley's arguments, explaining that the demonstrated inflation is trivial and that "errors that appear only in the third decimal place of an alpha coefficient are of no practical importance at all" (p. 8). Continued efforts towards investigating the reliability, validity, and feasibility of ACJ, as an approach to assessment in open-ended problems, are ongoing in a variety of settings with the dominant technology tool for implementing ACJ being marketed by *DigitalAssess* as internet browser-based platform titled *CompareAssess* (DigitalAssess, 2017).

Although ACJ appears to be gaining traction in educational settings, the body of research related to ACJ in these settings has not been synthesized. Therefore, we sought to perform a systematic review of literature related to ACJ in K-16 settings which may serve as a starting point for understanding this process, its' implementation into educational settings, and the potential benefits and challenges of utilizing this approach. We intend this piece to be a useful tool, with research-based conclusions, for decision-makers weighing the potential for ACJ's implementation in educational settings. The guiding question for this review was:

> What are the key findings related to research around the implementation of Adaptive Comparative Judgment in K-16 education settings?

Method

Systematic Literature Reviews

Consistent with our intent, the guiding research question, and recommendations of Borrego, Foster, and Froyd (2014) around systematic reviews of literature, we investigated the current literature around ACJ in K-16 settings. This effort involved collecting studies conducted on the topic, refining and narrowing the results, and highlighting key findings related to the research question. This work is not intended to include every item of work related to ACJ; rather, this work is intended to serve as a starting point for individuals interested in ACJ and its' implementation in K-16 education (ages 5-18). Indeed, as Petticrew and Roberts (2008) suggest in relation to systematic literature reviews, we aim to provide a "general overall picture of the evidence in a topic area" (p. 21). As such, this work will highlight articles, related to ACJ and its' implementation, which work to inform our guiding research question and may serve useful in future efforts around ACJ in K-16 settings.

Search Parameters

To begin the process of identifying relevant literature and related search parameters several prominent articles, centered on ACJ for assessment, were reviewed. Prominent articles were selected based on their citation in numerous (>5) ACJ-related publications. These publications and the accompanying cited works were used to establish initial search parameters for investigation. Following the review of these articles an additional search was conducted using the key words "adaptive comparative judgment" and "ACJ" in academic journal search engines related to education (e.g., GoogleScholar, ERIC, EBSCOhost, and Education Full Text). Additionally, as ACJ is highly-connected, and often confused with "comparative judgment," both "comparative judgment" and "CJ" were also used in the search engine efforts.

These efforts yielded 133 total results on "Education Source," with "ERIC" producing 97, "Education Full Text" providing 65, and Google Scholar producing about 1,400,000 results. Review of these results showed that the vast majority of these articles were not relevant to adaptive comparative judgment or its' implementation in education settings. Further focusing our search results we constrained the search to "Adaptive Comparative Judgment" as a key search phrase. Utilizing this as the key search phrase, "Education Source" returned eight results (with two of the results referring to the same article), "ERIC" produced four results, "Education Full Text" yielded two results, and "Google Scholar" produced 40 results. After removing duplicates 46 total articles were collected; all of these articles were published after 2012.

In addition to the literature search, contact was made with leading researchers and publishers of research related to ACJ. Through these efforts an additional 35 sources (e.g., items such as conference papers and/or unpublished works) were added resulting in a total of 81 articles and papers for further review and analysis. One of these papers was removed because it was not written in English which resulted in a total of 80 papers for review.

The next step in the process involved classifying, and then removing, items based on several predetermined criteria. This was done by reviewing the abstracts, introduction, methods, and findings sections for each work. Articles that did not show to meet the criteria were removed. The classification categories and the criteria for inclusion are listed here:

1. **Seminal papers:** highly-cited papers around ACJ which were influential in the development or implementation of ACJ approach to assessment.
   Not Included: papers focused solely on comparative judgment (comparative judgment is similar to ACJ but does not involve the use of the adaptive algorithm to selectively pair items for judgment), rather than *adaptive* comparative judgment. Papers focused on development of "escape" (a large-scale project in the UK which provided the first widespread implementation of ACJ at the outset). Papers focused on the development of the software platform for ACJ assessment rather than research around using ACJ. Papers solely focused on the process of training assessors in an ACJ setting.
2. **Context**: the context of the paper should be limited to studies around ACJ in education settings (K-16).
   Not Included: papers with research founded in settings outside of education or postgraduate studies such as medical school, graduate school, or uses within the workforce. Papers related only to the feedback of judges in ACJ settings or papers dealing solely with self-efficacy and student confidence.
3. **Original Research:** included works should reflect original findings and research around ACJ.
   Not Included: papers from the same author without new findings or explanations.

Following the systematic removal process (see Figure 1) a total of 31 papers remained for further analysis. The majority of the articles which were removed were eliminated in response to criteria 2: the context of the paper should be limited to studies around ACJ in K-16 education settings (K-16). Additionally, many of the papers, which were removed, revolved around *comparative judgment*, rather than *adaptive comparative judgment*.

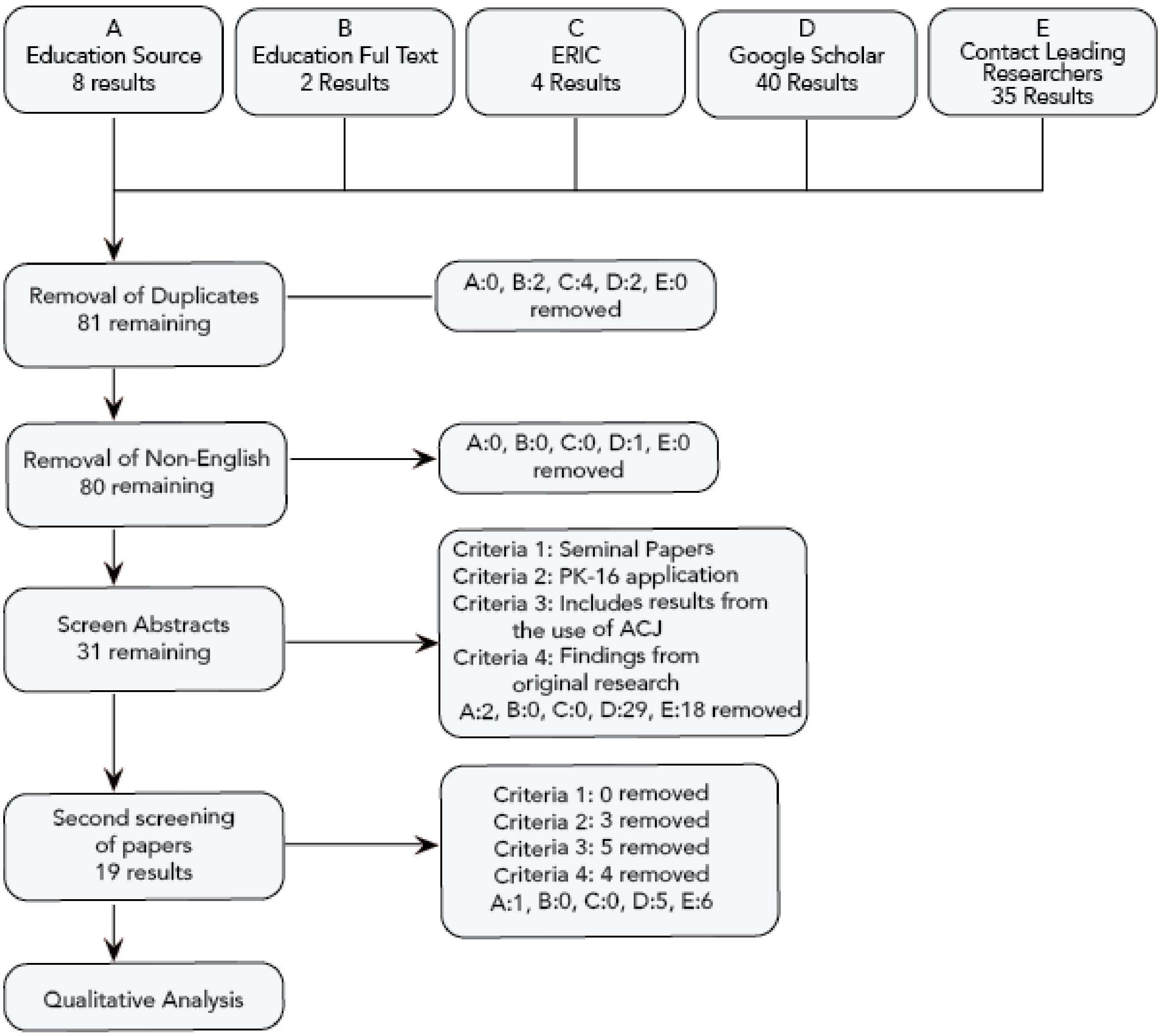

Figure 1. Overview of Systematic Literature Review

Following the screening of abstracts there remained 31 papers that were separated and analyzed again at a deeper level to ensure the criteria were met. This further review revealed that while the abstracts of these papers showed potential for the meeting of the criteria, many of these were duplicates or missing key criteria for inclusion. This second-level sifting resulted in 12 additional papers, out of the 31, being removed for a new total of 19 articles (see Table 1). These 19 articles will serve as the guiding literature for this review.

Table 1

Final Articles for Inclusion in the Synthesis of ACJ-related Literature at the K-16 Education Level

ID**	Title	Author(s)	Source	Year
A	Let's stop marking exams*	Pollit, A.	IAEA Conference, Philadelphia	2004
B	Investigating a judgmental rank-ordering method for maintaining standards in UK examinations*	Black, B., & Bramley, T.	Research Papers in Education, 23(3), 357-373.	2008
C	The validity and value of peer assessment using adaptive comparative judgment in design driven practical education	Seery, N., Canty, D., & Phelan, P.	International Journal of Technology and Design Education, 22(2), 205-226.	2011
D	Summative Peer Assessment of Undergraduate Calculus using Adaptive Comparative Judgement	Jones, I., & Alcock, L.	Mapping university mathematics assessment practices, 63-74.	2012
E	Evolving project e-scape for national assessment*	Kimbell, R.	International Journal of Technology & Design Education, 22, 135-155.	2012
F	The origins and underpinning principles of e-scape*	Kimbell, R.	International Journal of Technology & Design Education, 22, 123-134.	2012
G	The method of adaptive comparative judgment*	Pollitt, A.	Assessment in Education: principles, policy & practice, 19(3), 281-300.	2012
H	Using adaptive comparative judgment to obtain a highly reliable rank order in summative assessment	Pollitt, A., & Whitehouse, C.	AQA: Center for Education Research & Policy.	2012
I	Using digital representations of practical production work for summative assessments	Newhouse, C. P.	Assessment in Education: principles, policy & practice, 21(2), 205-220.	2014
J	Investigating the reliability of Adaptive comparative judgment*	Bramley, T.	Cambridge Assessment, Cambridge, 36.	2015
K	On 'Reliability' Bias*	Pollitt, A	Cambridge Exam Research Technical Report	2015

(continued)

ID**	Title	Author(s)	Source	Year
L	Evaluating comparative judgement as an approach to essay scoring	Steedle, J. T., & Ferrara, S.	Applied Measurement in Education, *29* (3), 211-223.	2016
M	Validity of comparative judgment to assess academic writing: examining implications of holistic character and building a shared consensus	van Daal, T., Lesterhuis, M., Coertjens, L., Donche, V., & De Maeyer, S.	Assessment in Education: Principles, Policy & Practice, 1-16.	2016
N	Relationships between access to mobile devices, student self-directed learning, and achievement	Bartholomew, S.R., Reeve, E., Veon, R., Goodridge, W., Stewardson, G., Lee, V., & Nadelson, L.	Journal of Technology Education, *29* (1), 2-24	2017
O	ACJ: A Tool for International Assessment Collaboration	Bartholomew, S.R., Hartell, E., & Strimel, G.	PATT34 Millersville University, Pennsylvania, USA 10–14 July, 2017.	2017
P	A Comparison of Traditional and Adaptive Comparative Judgment Assessment Techniques for Freshman Engineering Design Projects	Bartholomew, S.R., Strimel, G.J., & Jackson A.	International Journal of Engineering Education, *34* (1), 20-33	2017
Q	Illustrating Educational Development Through Ipsative Performance in Design Based Education	Seery, N., Delahunty, T., Canty, D., & Buckley, J.	PATT Conference, Philadelphia.	2017
R	Using Adaptive Comparative Judgment for Student Formative Feedback and Learning During a Middle School Open-ended Design Challenge	Bartholomew, S.R., Strimel, G., & Yoshikawa, E.	International Journal of Technology & Design Education, https://doi.org/10.1007/s10798-018-9442-7	2018
S	Examining the Potential of Adaptive Comparative Judgment for Elementary STEM Design	Bartholomew, S.R., Strimel, G., & Zhang, L.	Manuscript submitted for publication	2018

Note: * denotes a paper determined “seminal” by the authors
** identifiers to be used through the duration of the paper

Mapping Results

The results of our systematic review revealed several important findings related to the state of ACJ-related research in K-16 education. These key areas of synthesis include: context, approach, assessor characteristics, and results; each of these areas will be presented here.

Context. The first step in mapping our results was to identify basic information around the identified research articles. Mapping the results across time (see Figure 2) and by grade-level (see Figure 3) helps to establish the background for the state of current research around ACJ in K-16 education settings. Since 2011, 17 studies around ACJ in K-16 education have been conducted which fit the identified criteria for this systematic review (see Figure 2). There appears to be an upward trend in number of research efforts related to ACJ in K-16 education settings but this should be taken with caution as there are relatively few years for comparison.

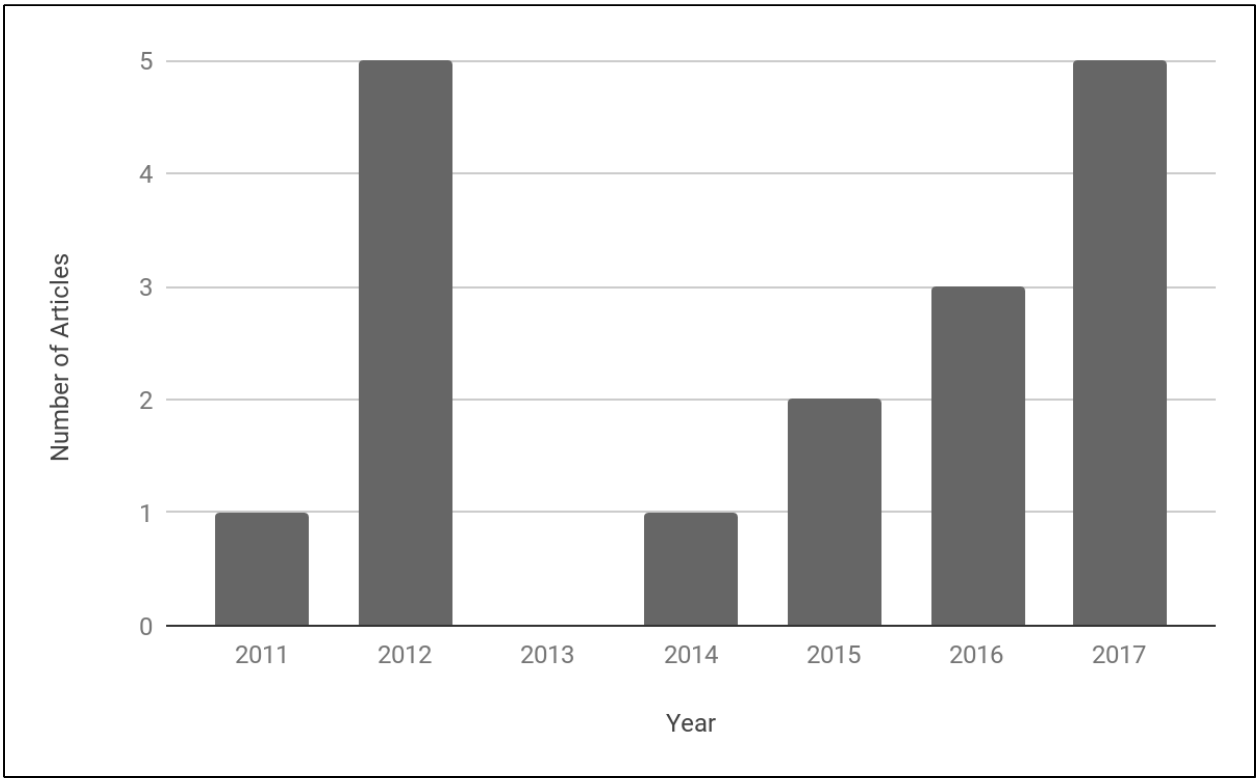

Figure 2. ACJ in K-16 Research Articles by Year

In terms of grade-level research efforts around ACJ our results revealed one study at the elementary level, three at the middle-school level, three at the high school level, and five in the context of undergraduate education (see Figure 3). The majority of early work around K-16 ACJ implementation was conducted at the University level with more recent efforts around the middle school and high school levels (Bartholomew, 2017).

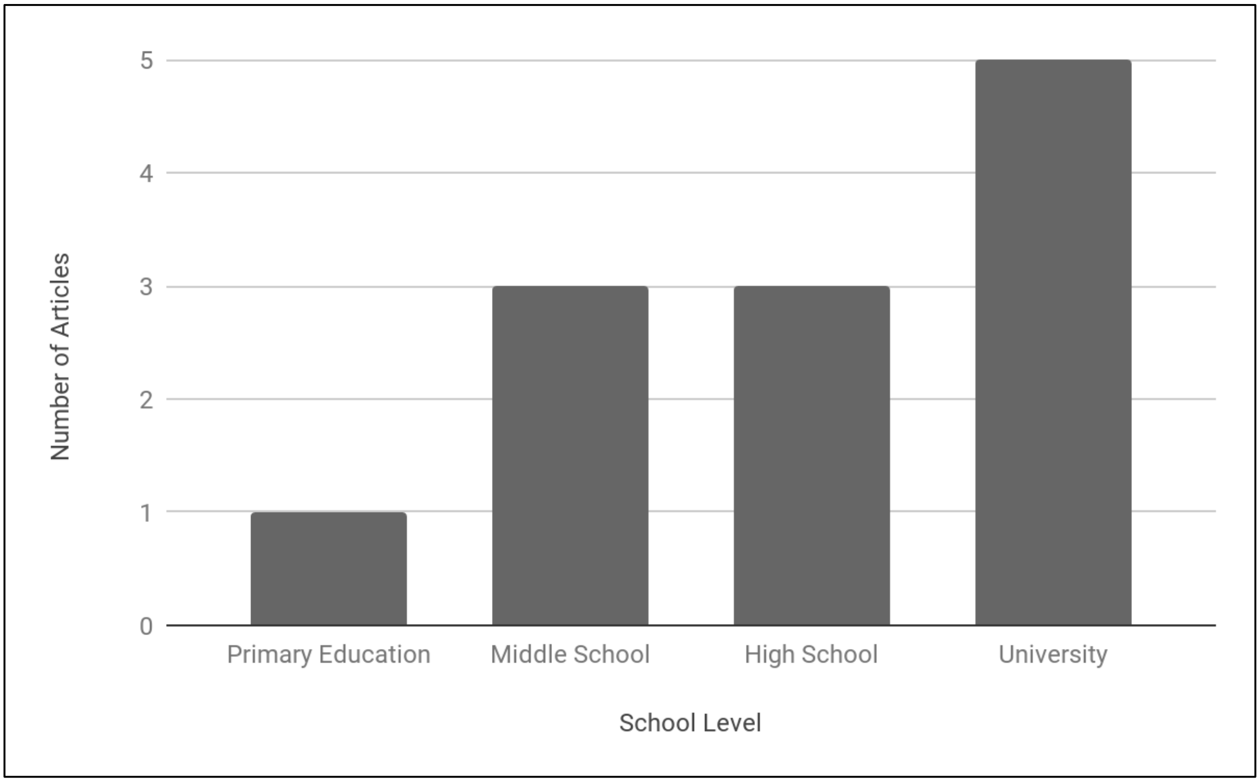

Figure 3. Grade Level of ACJ-Related Research

Beginning in 2004 with the presentation by Pollitt, Elliot, and Ahmed the majority of implementation of ACJ in K-16 settings has continued to employ ACJ in summative settings (D, I, L, P, & Q). These studies have not been confined to one content area but have included English writing (N), design and technology (C, I, N, O, P, Q, & S), human development (N), math (N), social studies (H & P), and teacher-preparation programs (D & I).

Table 2

K-16 ACJ Integration: Settings, Assessors, and Participants

ID	Author (year)	Participants [*n*] & Artifacts	Assessor demographics	Research location	Subject area
B	Black, & Bramley (2008)	University students [10] Compulsory scripts	Assessors	United Kingdom	Psychology
C	Seery, Canty, & Phelan (2011)	University students [137 participating with 63 as judges] Student portfolio	University teachers	Limerick, Ireland	Engineering and Technology Teacher Education
D	Jones, & Alcock (2012)	University students [168] Math scripts	College students	Loughborough University	Calculus
H	Pollitt, & Whitehouse (2012)	High school students [564] Writing Essays	Teachers and Examiners	Greater London Area	Physical and Human Geography
I	Newhouse (2014)	Year-12 students [75 visual arts & 82 design] Design & visual arts projects	External assessors	Western Australia	Design and Visual Arts
L	Steedle, & Ferrara (2016)	High school students [200] Writing responses	Secondary school English teachers	Florida, United States	English
M	van Daal, et al. (2016)	University Students [41] Writing essays	Academic audience, professors, and researchers	Belgium	Academic writing
N	Bartholomew, S.R., Reeve, E., Veon, R., Goodridge, W., Stewardson, G., Lee, V., & Nadelson, L. (2017)	706 middle school students (age 12-13 years old) 200 design portfolios 200 design products	Educators with experience in technology, engineering, and design education	Western United States	Technology & Engineering Education

(continued)

ID	Author (year)	Participants [*n*] & Products	Assessor demographics	Research location	Subject area
O	Bartholomew, S.R., Hartell, E., & Strimel, G. J. (2017)	200 middle school design portfolios and 200 design products (age 12-13 years old)	Educators with experience in technology, engineering, and design education from the United States, Sweden, the U.K., and Ireland	U.S.A., Sweden, U.K., Ireland	Technology & Engineering Education, Design & Technology Education, Teknik
P	Bartholomew, Strimel & Jackson (2017)	University students [16] (average age of 20) Engineering design portfolios	Educators with experience in technology, engineering, and design education	University in Appalachian region	Engineering
Q	Seery, Delahunty, Canty, & Buckley (2017)	University students [128] (Year 3) 128 design tasks	University students	Limerick, Ireland	Initial Technology Teacher Education
R	Bartholomew, Strimel, & Yoshikawa, (2018)	Middle school students [65] (12-13 years-old) Middle school teacher [1] Graphic design projects	Middle school students	Midwestern United States	History
S	Bartholomew, Strimel, & Zhang (2018)	Primary students [92] (age 5-10 years old) Kindergarten teachers [2] Fourth grade teachers [2]	Primary school teachers	Midwestern United States	Elementary school STEM

Approach. Thurstone (1927), who is credited with the original concepts behind ACJ was silent regarding the timing for implementation of ACJ as an assessment tool. The majority of early efforts in ACJ integration centered on summative assessment—mainly for end of year assessment by awarding bodies (M. Wingfield, personal communication, August 29, 2017). Pollitt, Elliott, and Ahmed presented their plans at the University of Cambridge Local Examinations Syndicate (2004) where ACJ was posited to be a replacement for the end-of-year rubric-based approach then employed by the major exam bodies in charge of overseeing the high school examinations.

In addition to several studies around summative assessment through ACJ, recent efforts in utilizing ACJ for formative assessment have also been undertaken. These efforts have largely been confined to design settings with students using ACJ, as a tool for assessment, in the midst of a design project (formative) and then again at the conclusion (summative).

ACJ for Summative Assessment. The majority of K-16 ACJ integration has been aimed towards utilizing ACJ as a tool for summative assessment of open-ended projects. Specifically, the majority of these studies using ACJ for summative assessment (C, O, P, Q, & R) have been conducted in Technology, Engineering, and/or Design classrooms. A brief synopsis of each of the studies in Technology, Engineering and/or Design classrooms is included here:

> **C.** Seery, Canty, & Phelan (2012) implemented ACJ with University students studying Engineering and Technology Education engaged in design scenarios and found that using ACJ for peer judgment allowed students to demonstrate their ability to make critical judgment. They also recognized that by having peer evaluations, the assessor was more fully able to empathize with the work having just gone through the design process. Seery, Canty, & Phelan also reported that "Student confidence in a democratic approach to the assessment formed the basis for unrestricted engagement. As a result, the relationship between student and assessor (their peer) was relaxed" (p. 224).
>
> **O.** Bartholomew, Strimel, & Hartell (2017) employed ACJ for the summative assessment of student work by panels of judges from four different countries. They found high reliability levels for each group of judges with significant correlations across panels from different locations. Their findings suggest ACJ may be a uniquely situated tool for international collaboration in/through summative assessment.
>
> **P.** Bartholomew, Strimel, & Jackson (in press), who used ACJ for summative assessment of college freshman engaged in open-ended engineering problems, demonstrated high levels of reliability and validity by comparing the traditional markings from the instructor with the resulting rank order from the ACJ results. However, they found no significant correlation between the ACJ results and the actual effectiveness of the student designs.

Other subject areas with summative ACJ-related research have included English (L& M), human development (B), math (D), and social studies (H & R). A brief synopsis of each of these studies is included here:

> **D.** Jones and Alcock (2012) employed ACJ in a University level calculus class. In this study, the students participated in peer feedback without given criteria. They looked at

the inter-rater reliability between the peers compared to experts and novices. They found that expert to peer had a 0.63 correlation coefficient, expert to novice had a coefficient of 0.55, and peer to novice had a coefficient of 0.67. Through the process of peer evaluation, students reported recognition of needed self-improvement.

H. Pollitt and Whitehouse (2012) implemented ACJ in high school human and physical geography classes. ACJ was used on 564 high school written essays and the results indicated that ACJ was a valid assessment when compared to traditional marking methods.

L. Steedle and Ferrara (2016) studied the use of ACJ as an assessment for High School English classes from two separate writing prompts. This study found that the total time it may take to use ACJ is greater than traditional methods to reach a suitable reliability level.

M. van Daal, et al. (2016) studied the use of ACJ as a summative assessment for academic writing at a University level. They reported finding ACJ as a valid assessment when grading writing assignments holistically in their study.

R. Bartholomew, Strimel, & Yoshikawa (2017) utilized ACJ for summative assessment with an open-ended design challenge involving middle-school students and found the resulting rank order to be both reliable and valid.

ACJ for Formative Assessment and Learning. In addition to summative assessment, efforts towards using ACJ as a learning tool for students in formative settings have shown great promise in terms of student learning, achievement, and peer-feedback (P). Students who engaged in ACJ formatively have reported increased recognition of areas for improvement, benefits from exposure to peer work, and increased ability to improve their work (P). Efforts in the area of K-16 ACJ for formative assessment include:

Q. Seery, et al. (2017) found that learning gains associated with ACJ were not confined to individual students; rather, they posit that the entire class of students involved in ACJ, for formative learning, will improve significantly over time. Their exploratory data and research has revealed very promising findings to this effect.

R. Bartholomew, Strimel, & Yoshikawa (2017) conducted research with middle school students (age 12-14) engaged in an open-ended design problem. These students utilized ACJ for peer-formative feedback and assessment at the midpoint of their design experience. When compared with the control group of students, the students engaged in ACJ for formative learning performed significantly better than their peers at the conclusion of the assignment ($t(100) = -4.28$, $p < .001$).

Assessors: Training, Selection, and Experiences. In the ACJ process the items being compared are uploaded to a web-based portal which facilitates the pairwise comparisons. In many of the initial implementation settings ACJ was performed by professional assessors or experts (A, E, F, G, H, & K). However, in recent year's movement towards ACJ assessment by a variety of individuals including teachers, industry partners, and students, have all been employed (L, Q, R, & S). Although all the included articles did not provide background on the chosen assessors the information that was provided is synthesized here:

B, I, & L. Three studies (Black & Bramley, 2008; Newhouse, 2014; Steedle & Ferrara, 2016) all used educators or professional assessors for looking at student work.

C, D, &R. Three other studies (Bartholomew, Strimel, & Yoshikawa, 2017; Jones & Alcock, 2012; Seery, Canty, & Phelan, 2011) used the students in the participating class as the judges participating in the ACJ sessions.

M. van Daal, Lesterhuis, and Coertjens (2016), who looked at the assessment of academic writing, utilized professionals with varied expertise in the writing department for their assessors. Each of these individuals had background and experience in assessment writing products.

O. Bartholomew, Hartell, and Strimel (2017) used judges with design, technology, and engineering education backgrounds from several different countries to compare the assessment similarities and differences across location. While all the judges have design, technology, and/or engineering backgrounds the USA-based assessors all held K-12 teaching licenses. The UK-based judges were composed of those with K-12 and college-level backgrounds and the Sweden-based judges were teachers, professors, and graduate students in technology fields.

P. Bartholomew, Strimel, and Jackson (in press) compared engineering design portfolios with assessors who all came from backgrounds in teaching the engineering design process. These included practicing teachers, researchers, and graduate students.

In addition to the training, background, and experience of judges several of the research studies have recorded the time required for judges to make the necessary comparisons for the ACJ process. These times were often recorded to compare with traditional grading approaches and the times required have varied greatly between studies (see Table 3), locations, judge background, and subject-area.

Table 3

Judgment Statistics for Assessors

ID	Author	Judge Background	Time (traditional grading)	Time (ACJ)
I	Newhouse (2014)	External assessors	6.4 min for Design 9.9 min for Visual Arts	5.6 min. for Design 5.4 min. Visual Arts
N	Steedle, & Ferrara (2016)	Secondary English teachers	Prompt 1 M = 121.2 min. Prompt 2 M =116.4 min.	Prompt 1 M = 116.7 min. Prompt 2 M = 70.5 min.
P	Bartholomew, Strimel, & Jackson (2017)	Educators with experience in technology, engineering, and design education		Average time per judgment ranged from 0:55 to 3:26
S	Bartholomew, Strimel, & Zhang (2018)	Primary Teachers	Project 1 M = 6.48 min. Project 2 M = 6.87 min.	Project 1 M = 11.92 min. Project 2 M = 9.80 min.

ACJ Implementation Results. The results from ACJ implementation in K-16 settings have revolved largely around reliability and validity. A detailed discussion of the research around, and statistical approaches to, the ACJ reliability is beyond the scope of this work (see Pollitt, 2012 for a more detailed discussion on these ideas), but several key findings from the included research articles will be presented here related to efficiency, validity, and reliability.

Efficiency. The research included here seems to suggest that ACJ is not a more efficient method of assessment when compared with traditional approaches. However, efforts towards improving the algorithm, and the associated efficiency, have been underway for the past several years by companies such as *Digital Assess* (DigitalAssess, 2015), and some research has suggested that the time required for ACJ is not significantly different from that of traditional assessments (H, L, & S). It should be noted that the time recordings, derived from the ACJ-platform around judge decisions, may not be completely accurate as these times reflect the total time a paired comparison is present before a judge—regardless of how actively focused the judge may be on making the judgment.

Speaking about efficiency, and the ACJ algorithm that guides the process, Steedle and Ferrara (2016) laid out a synthesis of studies that involved comparative judgments of student performance and concluded that the assessment process could become more efficient using *adaptive* comparative judgment and the associated algorithm for determining pairs (L). This argument for ACJ over CJ, in terms of efficiency, resides in the pairs for comparative judgment being paired more optimally and efficiently—instead of having random comparisons, there are controlled, intentional pairings that makes the process more efficient in obtaining high levels of reliability (C. Rangel & M. Wingfield, personal communication, August 29, 2017). Bartholomew, Strimel, & Zhang studied the time required for teachers to make assessments through traditional approaches and through ACJ for open-ended assignments and found that the ACJ process took significantly more time than traditional approaches. However, they pointed out that these findings were not universal to all teachers in the study and the assessment tendencies of the teachers, in both ACJ and traditional assessment, were significantly different by teacher and grade. Overall, they concluded that between 8-10 rounds of judgment was required for a steady rank-order of student products to emerge in ACJ given the participants and artifacts in their research (S).

Pollitt and Whitehouse (2012) explored the rounds of judgement necessary for a reliable rank order. Their research showed that with the adaptive algorithm a reliability coefficient of 0.97 was reached after 12 rounds of judgment with additional rounds not contributing to a significantly higher reliability.

Validity and Reliability. Efforts towards determining the assessment validity, which refers to how closely the assessment actually measures the identified construct (Messick, 1992), of the ACJ output (e.g., the rank order of the artifacts included in the judgment session) have revolved largely around comparing the rank order with the results (e.g., scores) from traditional approaches to assessment (see Table 4).

Consistently, across the studies included, ACJ has produced high levels of reliability in the resulting rank order. The majority of studies included demonstrated levels of reliability $r \geq .8$ (see Table 4). The reliability coefficient produced in conjunction with rounds of ACJ assessment refers to the confidence of a subsequent session producing similar results given the session parameters. Many of the arguments in favor of using ACJ as an assessment tool for open-ended problems have largely centered on the high levels of reliability achieved through this approach (H, I, L, N, Q, R, &S).

Synopses of validity and reliability from the included research are included here:

H. Pollitt and Whitehouse (2012) looked at essays written from physical and human geography writing prompts. These results showed a correlation of 0.63 when compared to traditional marking with a reliability coefficient of 0.97.

I. Newhouse (2014) implemented ACJ in both Visual Arts and Design classes at a University level. They compared ACJ rankings with analytical marking and found a correlation coefficient of about 0.5. Additionally, they found reliability levels of 0.95 for Design and 0.93 for Visual arts.

L. Steedle & Ferrara (2016) looked at the validity and reliability of two writing prompts. When compared with traditional test scores, they found a correlation coefficient of 0.78 on Prompt 1 and 0.76 on Prompt 2.

N. Bartholomew, Reeve, Veon, Goodridge, Stewardson, Lee, & Nadelson (2017) used ACJ for the assessment both the portfolios and products of a middle school open-ended design challenge. A high interrater reliability was found for both the portfolios (r = 0.97) and the products (r = 0.96).

P. Bartholomew, Strimel, & Jackson (in press) compared the rank order of student portfolios, as obtained by a panel of judges with engineering and design background, with the scores obtained by student through traditional assessment approaches. Their analysis revealed a significant correlation.

Q. Seery, et al. (2017) implemented their study in an Initial Technology Teacher Education and showed high reliability on four separate assignments. The reliability on the four separate assignments was 0.97 each time.

R. Bartholomew, Strimel, & Yoshikawa (2017) compared the final rank order of middle school student design projects with the scores received by the students from their teacher using traditional assessment approaches. The results demonstrated a significant correlation suggesting validity around ACJ as an assessment approach.

S. Bartholomew, Strimel, and Zhang (2017) looked at the assessment of two open-ended design projects at an elementary level. Each teacher assessed the work of the students in their own class. All four teachers recognized the comparable results of rank order to traditional grading methods, however, because their study explored the use of a solitary judge no reliability was obtained/reported.

In addition to comparing the rank orders with traditional marking Bartholomew, Strimel & Jackson (in press) compared the ACJ rank order with the actual effectiveness of student prototypes in accomplishing the designed task. In this research the students were tasked with producing a water filtration device; the final turbidity levels of the provided water to each of the students were recorded as a representation of the effectiveness of their actual design. The analysis revealed that, while the rank order and the student scores received from their teacher were highly-correlated, the final turbidity level of the students' designs (e.g., the design effectiveness) and the ACJ rank order were not significantly correlated. This suggests potential issues with assessment validity as the actual effectiveness of the student designs were not represented in the final ACJ-produced output.

Table 4

Reliability and Validity Results across Studies

ID	Author	Validity (i.e., comparison with traditional grading)	Reliability level
C	Seery, Canty, & Phelan (2011)		*r* = .96
H	Pollitt & Whitehouse (2012)	*r* = 0.63 (with traditional marking)	α=0.97(interrater reliability)
I	Newhouse, C.P. (2014)	r ≈ .5 (with analytical marking)	*r* = .95 (design) *r* = .93 (visual arts)
L	Steedle & Ferrara (2016)	*r* = .78 (prompt 1) *r* = .76 (prompt 2)	*r* = . 89 (prompt 1) *r* = .78 (prompt 2)
M	van Daal, Lesterhuis, & Coertjens (2016)	SSR=.84	
N	Bartholomew, S.R., Reeve, E., Veon, R., Goodridge, W., Stewardson, G., Lee, V., & Nadelson, L. (2017)		*r* = .96 (design products) *r* = .97 (design portfolios)
P	Bartholomew, Strimel, & Jackson (2017)	No significant correlation between ACJ rank or traditional rank and turbidity score. *r* = -.79 (ACJ rank and rubric score)	*r* = .95
Q	Seery, Delahunty, Canty & Buckley (2017)		*r* = . 0.974 (Assignment 1) *r* = . 0.973 (Assignment 2) *r* = . 0.965 (Assignment 3) *r* = . 0.971 (Assignment 4)
R	Bartholomew, Strimel, & Yoshikawa (2018)	*r* = -.56 (midpoint rank and rubric score) *r* = -.61 (final rank and rubric score)	*r* = .93 (midpoint) *r* = .97 (conclusion)
S	Bartholomew, Strimel, & Zhang (2018)	*r* = -.42	

The reliability level of the ACJ output is contingent on the rounds of judgment completed (G, I, & L). Pollitt (2012) suggested 12 rounds as a target for achieving a reliable rank order while Bartholomew, Strimel, & Zhang's (2017) suggested that a reliable rank order may be achieved as early as 6 rounds if ACJ were utilized by a solitary assessor (P). Steedle and Ferrara (2016) reported that reliability was above 0.8 by 9 rounds of judgment and slowly increased with further judgments (L).

Conclusion

Our analysis focused specifically on findings from studies on the recent uses and practices of ACJ in K-16 settings. Based on our synthesis we believe that ACJ demonstrates great potential for improving, informing, and potentially revolutionizing open-ended problem assessment in K-16 settings. With markedly higher reliability than other forms of assessment, coupled with other benefits in formative feedback, peer-review, and collaboration, ACJ is a potent tool in it's infancy of K-16 implementation. However, issues related to increased time investment requirements and assessment validity must also be noted and research into these topics will clarify the future potential for ACJ in educational settings.

This review outlined the research and findings around ACJ in K-16 education with the intention of informing decision-makers regarding the benefits, challenges, and research-based conclusions related to ACJ. Further, this review serves to highlight necessary future research areas related to settings, content areas, populations, and contexts within which the implications of ACJ-integration have not yet been explored. As the majority of ACJ research has taken place in college settings and in the areas of design, technology, and engineering education, we maintain that efforts towards broadening the context and samples included in ACJ-related research would further strengthen the understanding around the potential and implications for ACJ integration into K-16 education. Furthermore, the majority of ACJ research has emphasized summative assessment techniques and has shown positive results. Preliminary efforts into utilizing ACJ as a formative tool for assessment and feedback has shown promise and further efforts in both summative and formative applications of ACJ will strengthen arguments related to ACJ's potential for educational transformation.

From our review it was clear that the majority of research into ACJ for K-16 assessment has been conducted by a select group of researchers in a small sample of locations—most notably in the United Kingdom. We contend that future work into integrating ACJ in new settings, content areas, and with diverse samples will shed additional light and prove valuable in the conversation moving forward around ACJ for K-16 education.

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Chapter 2

Framework for the Development of a Study on Authentic Problem Solving Skills in K-12 Grades

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Abstract

Collectively identified as one of the 21st century skills, critical thinking and problem solving skills (CT and PS) involved in solving authentic design problems are not assessed in traditional science and mathematics standardized testing or in most technology education K-12 classrooms. 21st century learning outcomes are realized when students are able to gain deep understanding of science and math concepts, and, use the content and practices of these disciplines with the content and practices of technology and engineering to solve problems situated outside the classroom. For this to occur, integration of the disciplines in the instructional approach is essential (NRC, 2009; Sanders, 2012). Researchers have argued that the integrative STEM education (I-STEM ED) pedagogical approach (with its roots in technology education) promotes active learning through student discovery of using science and mathematics content and practices in novel situations.

This paper presents the results of the literature review conducted to develop a framework for characterizing and defining CT and PS skills. Specifically, this paper is organized around the following four themes: 1) the foundations of STEM education and theories of learning that underpin the I-STEM ED pedagogical approach, 2) the need for CT and PS skills among students to meet the 21st century educational goals, 3) the relationship of CT and PS skills to the T/E DBL approach used in I- STEM ED, and, 4) gaps in the research focusing primarily on studies within the 21st century. Furthermore, a potential framework for a rubric for assessing CT and PS skills is proposed.

The Problem

The shortfall in the intended outcomes for students' achievement of the implied higher order thinking skills, characterized by one of the five C's of the 21st century skills – critical thinking and problem solving (P21, 2015a), is a focus of STEM education reform. Specifically, outside the confines of traditional classroom settings, students are not able to recognize, recall, and utilize the science and math content needed for solving authentic design-based problem solving (Song, et al., 2016).

One reason for this inability to recognize, recall and utilize the needed science and math content could be that students are not learning and practicing the utilization of multidisciplinary content in the context of designing solutions to authentic problems. The technology education (Tech-ED) framework has traditionally been geared toward student learning through the content and practices of technological and engineering design. However, not all students are able to access Tech-ED coursework, and not all Tech-ED teachers are prepared with the science and math content knowledge to do justice to the pedagogical approach needed to integrate the disciplinary content areas and practices (Wells, 2010). The practice of an integrative science, technology, engineering and mathematics education (I-STEM ED) pedagogical approach is defined as:

> the application of technological/engineering design based pedagogical [T/E DBL] approaches to *intentionally* teach content and practices of science and mathematics education through the content and practices of technology/engineering education. Integrative STEM Education is equally applicable at the natural intersections of learning within the continuum of content areas, educational environments, and academic levels. (Wells & Ernst, 2012/2015)

Viewed from this design-based learning context, the absence of such pedagogical practices presents a key problem for promoting student development of higher order thinking skills necessary for critical thinking and problem solving (CT and PS) in the context of the 21st century needs. As Wells (2008) explains, I-STEM ED "fosters a blended pedagogical approach and establishes the curricular foundations that have long been supported by cognitive research" (p. 11).

The lack of research to support the benefits of T/E DBL as a signature pedagogical approach of integrative STEM education, for "conceptual attainment" (Zuga, 1995, p. 67) and "problem solving" (Zuga, 2000, p. 2) skill development as outcomes of technology education hinders the promotion of more widespread use of this integrative pedagogical practice (Cajas, 2000; Kolodner, 2000; Zuga, 2000). To investigate the benefits of the I-STEM ED pedagogical approach in promoting the development of CT and PS skills it is essential to identify those student abilities that contribute to CT and PS skills. Furthermore, an assessment instrument and scoring rubric would be required to quantify those abilities.

A literature review was conducted to investigate the pedagogical framework within which development of students' CT and PS skills are situated. This paper is organized around five distinct areas: 1) foundations of STEM education, 2) learning theories underpinning I-STEM ED, 3) the pedagogical approach of I-STEM ED, 4) development of CT and PS skills, and 5) the relationship of CT and PS skills to the T/E DBL approach used in I- STEM ED. Results of these investigations are summarized, followed by conclusions and implications regarding future research on this topic.

Foundations for Integrative STEM Education

The rapid pace of change, the complexity of human problems, and the ease of global access to technologies and human resources have created the demand for education to help develop the next generation of STEM literate workforce (Friedman, 2005; NAE & NRC, 2014). Efforts to reform science and mathematics K-12 education to meet the challenges of the coming decades have been ongoing since the 1960s. The individual disciplines in STEM – science, technology, engineering and mathematics have distinct pedagogical approaches and educational goals that address literacy in those disciplines (NGSS Lead States, 2013; ITEEA, 2000/2002/2007; NCTM, 2000). Despite these reforms, the way in which STEM education has been interpreted and practiced in K-12 has been a "siloed" (NAE & NRC, 2009, p. 12) approach which has resulted in students' lack of ability to utilize their knowledge in real world applications, sometimes called transfer of learning (Wiggins & McTigue, 2005). Furthermore, STEM education has been largely interpreted as an emphasis on science and mathematics education in most classrooms, with those subjects being taught without any relationship to the other disciplines (Wells, 2013). With the lack of technology education programs in most schools, students do not even experience the interconnectedness of the STEM disciplines in the technological design applications of the curriculum (NAE & NRC, 2009).

More recently, engineering design has been introduced within some science and technology education classrooms. In *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (NAE and NRC, 2009) a multidisciplinary committee of experts noted that engineering is a way to increase student achievement in technological literacy, increase student achievement in science and mathematics literacy, and also, to act as a catalyst in integration of STEM education in K - 12 grades. Uniform standards for engineering education in K-12 are not adopted by all states due to overburdened curricula in secondary education, and the lack of teacher preparedness for teaching an engineering curriculum in K-12 (NAE & NRC, 2009). Instead, science, technology and mathematics curricula have included design instruction (ibid). *A Framework for K-12 Science Education* (NRC, 2011b) created a new directive among science educators when it announced that the teaching of engineering concepts would be a part of the Next Generation Science Standards (NGSS). However, as stated before, these approaches are limited by teacher knowledge and preparedness for teaching engineering design within their disciplines (Wells, 2008; Zubrowski, 2002).

Literacy as defined within science, technology and mathematics is the ability to understand information or claims in the context of the disciplines, evaluate the validity of the same, and, communicate evaluations and predictions with a vocabulary that is consistent within that discipline (NGSS Lead States, 2013; NCTM, 2000). This definition inherently separates the content and practices of each of those four disciplines in STEM, and is not representative of authentic or real world situations where it is necessary to devise solutions or problem-solve within the intersections between the disciplines (Sanders, 2012; Pope, Brown and Miles, 2015). For students to succeed in college or in the workforce, they need to be able to function in the continuum of the four disciplines, and this necessitates STEM education to be intentionally integrative in its approach (Huber & Hutchings, 2004).

Learning Theories underpinning the I-STEM ED pedagogical approach

Learning is a cognitive process that involves conceptual growth and reasoning. External input is processed in the brain by encoding and storing information in long term memory in a meaningful manner from which it can be recalled and utilized when needed (Greeno, Collins, &

Resnick, 1996). While this is a simplistic explanation, the processes involved are complex and require more intentional teaching and learning.

A widely-used model of the process of learning is that human senses receive new input, which are held in a sensory register for a fraction of a second and passed on to working memory. In working memory, the information is processed and immediately stored in long-term memory or lost. Information is stored in long-term memory, only if it has some strong emotional associations for the learner or makes sense to the learner and has a connection to some previously stored information from past experiences (Bransford, Brown & Cocking, 2000; Brown, Collins & Duguid, 1989). Furthermore, learners' construction of knowledge is linked to the activity, context and culture in which it is learned (Brown, Collins & Duguid, 1989).

Although most learning occurs in a collaborative or social context, such construction of knowledge requires an individual to be engaged as the sole constructor of his/her knowledge, uniquely related to his/her previous knowledge. Retrieval of stored information repeatedly strengthens the interconnectedness of stored information and its future recall at appropriate times is enhanced. This intentional teaching and learning process, where information is repeatedly retrieved and used in different ways, supports the development of cognitive connections required for integration (Huber & Hutchins, 2004). In alignment with constructivism as originally proposed by Jean Piaget (1968) and later supported by cognitive science research (Bransford, Brown & Cocking, 2000), it becomes the responsibility of educators to design instruction in a manner that enhances students' knowledge construction in an integrated and sense-making manner. Furthermore, repeated and consistent experiences are needed to enhance the robustness of interconnectedness of concepts, and create habits of mind.

The I-STEM ED pedagogical approach promotes active learning through student discovery of using science and mathematics content and practices in designing solutions to identified problems, and active construction of understanding by doing (Wells, 2017, 2016b). Within engineering design, the predictive nature of designing a solution and testing the model or prototype in an iterative fashion, are opportunities (with instructional guidance) to refine one's understanding due to inconsistencies observed known as cognitive dissonance (Festinger, 1962; Puntambekar & Kolodner, 2005). The central tenet of education is to increase students' understanding, and many researchers have argued that the T/E DBL approach is effective in increasing students understanding through such cognitive dissonance (Cajas, 2001; Wells, 2010; Puntambekar & Kolodner, 2005; Barlex, 2003). Although there is an acknowledged lack of evidence to support this claim (Zuga, 1995), there is potential for cognitive growth in the I-STEM ED pedagogical approach.

Despite recognition of the need for integration, historically the focus has remained on increasing students' proficiency in the individual disciplines. It has only been in the last decade that there has been a recognition that US students' performance in assessments outside the classroom lags behind (Pope, Brown & Miles, 2015). Researchers have noted that using an instructionally independent approach, or the silo approach, to teaching the disciplines has resulted in students' lack of success in science and math performance outside the classroom (NRC, 2009). When students understand and experience the interconnectedness between the disciplines, their performance and literacy are likely to improve (NRC, 2009; Drake & Burns, 2004). The intentional integration of the content and practices of the disciplines as a pedagogical approach helps develop STEM literacy, rather than focusing on literacy in the individual STEM disciplines (Sanders, 2012). Effective use of grade-appropriate science, technology, engineering & mathematics disciplinary concepts and practices in designing and implementing solutions to authentic problems would help provide meaningful experiences for students to understand the relevance of learning in the real world. The *Standards for Technological Literacy* published in 2000, and revised again in 2002 and 2007, promoted the integration of various content areas using technological and engineering design as the vehicle to deliver multiple disciplinary content in an engaging and integrative manner.

The widely accepted definition for I-STEM ED suggests the *intentional* teaching of content and practices of science and mathematics through the content and practices of technology and engineering education (Wells & Ernst, 2012/2015).

T/E DBL as the pedagogical approach of I-STEM ED

The pedagogical approach in I-STEM ED supports knowledge construction through intentional hands-on experiences to engage students to achieve minds-on learning outcomes (Wells, 2017, 2016a). The intentional design of learning experiences within I-STEM ED addresses deeper learning through scientific inquiry, engineering design, predicting and testing, all encapsulated in the T/E DBL pedagogical approach. Within the existing school infrastructure and curriculum framework, the T/E DBL approach is best suited to Tech-ED courses and programs. However, these courses are in most states electives, lack importance in terms of graduation or college admission, and lack teacher preparedness to teach the needed science and math content within the T/E design-based approach.

As John Dewey (1910) noted and others have since confirmed, hands-on experiences are better than learning by hearing or through demonstrations (Wiggins & McTighe, 2005; Felder & Brent, 2016). However, the interpretation of hands-on learning for instructional purposes has primarily been project-based learning (P_jBL inclusive of technology education classrooms. Specifically, students are provided an end-goal for a project, some criteria and constraints, instruction on how to accomplish the end-goal, detailed instruction on the hands-on aspects, and informed that assessment is directly tied to the various parts (what one can see, hear, and touch) of the project.

As Felder and Brent (2016) note, the PjBL approach is teacher-centered and does not imply learning has occurred. For learning to occur, not only do the students have to engage in the hands-on activities, but they have to be “caused” to learn (p. 6). One method is to engage students in learning experiences that are inquiry based and embedded in a challenge that is relevant to their lives. To successfully design a solution, students need to research and learn the content areas related to the embedded problem, design a solution, and build and test a prototype or a model. Researchers have also found that learning improves when the content is relevant to students’ lives (Drake & Burns, 2004; Fennema, 1992), and this can be satisfied with the use of relevant and appropriate authentic design problems. One instructional model named PIRPOSAL© for T/E DBL (Wells, 2016b) exploits “the full spectrum of complex learning processes” (p. 15) that are associated with the definition of the I-STEM ED pedagogical approach.

The T/E DBL approach engages students in a design challenge that is central and the focal point for a “convergent and divergent” questioning process within which students engage in learning and designing (Wells, 2016b, p16). Design, a process that is inseparable from innovation, is a collaborative activity within which a group of people tackle an ill-defined (or authentic) problem that is constrained by resources available and the constraints of real-world conditions. Most real-world problems are ill-defined and can have multiple solutions (Ormrod, 2012). The optimal solution involves the optimization of constraints and benefits. The

ITEA/ITEEA (2000/2002/2007) regards design as "an iterative process that produces plans by which resources are converted into products or systems that meet human needs and wants or solve problems" (p. 237).

The design challenge in the T/E DBL approach is central to students' learning experience. Construction of knowledge occurs within the relevant context of the design challenge and within the culture of peer-to-peer questioning and researching in a collaborative environment, and this is how students learn (Brown, Collins & Duguid, 1989; Bransford, Brown & Cocking, 2000). This student-centered instructional style has been found to be superior to the traditional teacher-centered instructional style (Felder & Brent, 2016). Using a process of 1) identifying and defining the problem that must be solved, 2) defining criteria for the solution, and 3) identifying the disciplinary content areas that relate to the problem, students engage in a collaborative process of questioning, researching and ideating to design, build, evaluate and re-iterate until an acceptable solution is created. Instructional strategies used in the T/E DBL pedagogical approach are intentionally designed based on Gagne's events of instruction (Gagne, Wagner, Golas, & Keller, 2004) to promote students' knowledge construction in the procedural, declarative, schematic and strategic knowledge domains (Wells, 2016c). The iterative and repeated design process requires students to reflect on their existing knowledge in all relevant subject areas in order to construct new knowledge and this is an important aspect of developing habits of mind (Jonassen, 1997).

From the perspective of a cognitive approach, the four types of knowledge constructed by students from the (intentionally placed) cognitive demands of design-based problem solving are:

- declarative knowledge, which includes definitions, concepts and principles of a subject,
- procedural knowledge, which is the practice used within the subject or discipline,
- schematic knowledge, which is the reasoning and relationship between concepts, and,
- strategic knowledge, which is knowing the appropriate utilization of concepts (NAGB, 2009; Shavelson, Ruiz-Primo & Wiley, 2005).

These types of knowledge are hierarchical and reflect deeper learning when students are able to exhibit the interconnections between concepts and disciplines and demonstrate the use of the knowledge in developing a solution to the posed design challenge (Webb, 1997). However, isolated experiences of T/E DBL where students may learn in this manner in a Tech ED class will not achieve the goal of developing habits of mind and habits of hand. As discussed previously, Tech-ED is not mandatory as part of the K-12 curriculum (for graduation) in most states. Only repeated experiences in T/E DBL within an integrative STEM educational program would help students develop these habits, and most students do not have opportunities for these experiences.

The potential of I-STEM ED for improving student achievement

The Partnership for 21st Century Skills (P21) argues that for students to succeed in college and careers in the 21st century, development of five essential skills are necessary – 1) critical thinking and problem solving, 2) communication, 3) collaboration, 4) citizenship and 5) creativity in innovation (P21, 2015a). In addition, the fast changing technological environment of the 21st century requires students to be competent in transferring their learning to new situations and new problems (NRC, 2012b). These competencies require interconnected disciplinary content knowledge, and knowledge of how, why and when to apply this knowledge to answer complex questions or solve problems (ibid). In a recently published info-graphic by The

Chronicle of Higher Education (http://results.chronicle.com/C2C-IG-2017), the most important skill employers look for in new employees, is the ability to make decisions (to problem-solve) in a complex multi-faceted technical environment. Making decisions in a multifaceted technical environment implies that workers should have not only technical skills in their discipline, but also be able to recognize the content of other disciplines, evaluate the usefulness of the identified content, and be able to create a strategy for making an informed choice on how to proceed. Without the knowledge of interdisciplinary content areas and knowledge of how, why and when to apply this knowledge, this is hard to do. Problem solving and critical thinking go hand-in-hand, where achieving the end-goal or solving the problem requires decision-making about disciplinary content to be used, discarding irrelevant information, devising a strategy and evaluating progress (P21, 2015a).

In the traditional Tech-ED classroom, design skills are assessed through achievement of competencies specified in select Career and Technical Education (CTE) courses, where disciplinary content in science and math are not the focus of instruction even in the STEM cluster. For example, in Virginia, the competencies listed in the CTE (2015) website for most of the courses start with workplace readiness skills, identified as: 1) personal qualities, leadership and people skills, 2) professional workplace skills, 3) examining aspects of industries, 4) historical overview of technology or engineering, and, 5) knowing the design process. In some of the engineering courses, managing real-world problems is explained as researching the context of a local problem and interviewing professionals on the various aspects of the problem (CTE, 2015). While these competencies are only the bare minimum required, it is worth noting that there is a lack of focus on solving authentic or real-world problems. Therefore, as traditionally implemented, the Tech-ED classroom is an opportunity for students to experience P_jBL, but not fully utilized as an opportunity to promote the higher order thinking needed in solving authentic problems.

In the traditional secondary educational classroom, the required core subjects of science and math are taught separately, and assessed using standards of learning assessments. Therefore, students with high scores in their science and math assessments, and high levels of proficiency in the competencies measured by the CTE courses, do not develop the interdisciplinary literacy that is necessary for real-world problem solving in situations outside the confines of their classrooms. The lack of integration skills hinders critical thinking when a problem solver is engaged in a multidisciplinary context and faced with an authentic problem. An example of such a situation is evidenced by the poor performance of students in assessments that are not within the confines of the classroom, such as the PISA and the TIMMS.

In the report on Discipline Based Education Research (DBER) (NRC, 2012a), the board on science education and the division of behavioral and social sciences and education summarized their recommendations regarding future directions of DBER. Included in this report is the recommendation for more studies on the K-12 students' transition to college to better understand the acquisition of important interdisciplinary cross-cutting concepts in STEM their influence on retention and persistence of students in the STEM disciplines. Furthermore, with respect to students' success in college especially in STEM disciplines, students switch out of these disciplines due to their inadequate high-school preparation for challenging math or science courses (Seymour & Hewitt, 2000, Haag, Hubele, Garcia & McBeath, 2007). Among other reasons for students' failure to persist in college STEM programs, Haag, et al. (2007) note that students' under preparation is caused by deficiencies in content and domain specific depth of knowledge, and lack of students' skills and habits in problem solving within science and mathematics topics (p. 932). Students' SAT scores and high-school standardized test scores do not reflect these types of deficiencies.

In an integrative STEM education program, all five of the 21st century skills mentioned before are learned and practiced within the context of the T/E DBL pedagogical approach. Students learn science and math concepts and practice their utilization in authentic problem-solving through the content and practices of T/E DBL. The T/E design challenge is appropriate for students to work together in a collaborative manner, with the teacher facilitating and providing guidance on teamwork skills. Intra-team communication is inherently essential and once again, the teacher helps students learn better ways to communicate with each other. External communication involves presenting the solution using visual presentations (posters, PowerPoint presentations), audio-visual (by making oral presentations or video presentations), and in writing by preparing reports and abstracts. Students are challenged to create unique solutions by engaging in friendly competition with their peers. Citizenship, which is a recent addition to 21st century skills, is addressed by having students interact with the connected computing technology in a responsible and reflective manner. Critical thinking and problem solving are addressed by having students grapple with complex criteria within the design context, to make decisions about the selection of relevant information and processes. Through the T/E DBL pedagogical approach, educators can help students learn the 21st century skills and "help students construct scientific understanding and real-world problem-solving skills" (Fortus et al, 2004, p. 1082).

By introducing the engineering design requirement in science and math standards, there has been an attempt to include the 21st century skills in every student's experience (NGSS Lead States;2013; NCTM, 2000). However, without assessment strategies for all these skills within the curriculum, there is no mandate for instruction to focus on teaching all these skills. Furthermore, including engineering design within science and mathematics instruction only introduces students to the design process without experiencing the integrative and inter-disciplinary approach embedded in I-STEM ED.

Characterizing Problem Solving

Researchers agree that problem solving is a decision making process (Reeff, 1999; Hayes, 1989; Martinez, 1998). Explicitly, problem solving is a goal driven process that requires recognition of the nature of the problem, identification of the end-state that implies success, creation of a strategy to go from the current-state to the end-state, execution of the strategy and adaptation of changes in strategy based on difficulties encountered along the way (Martinez, 1998; Hayes, 1989).When a problem is based in a real world context, the recognition and understanding of the problem in a solver's perception is key to devising a process to solve the problem, and this implies that no two authentic problems can be solved using the same knowledge or exact process (Reeff, 1999).

Not all problems are the same, specifically the two types may be characterized as: 1) well-structured, where all information needed to solve the problem are provided, and, 2) ill-structured, where there are many unknowns, many conflicting goals and multiple approaches to solve the problem (Jonassen, 1997). Well-structured problems are typical of problems practiced and assessed in the traditional science and mathematics classrooms. The other, ill-structured problems, which are typical of real-world situations, are much like what professionals see in the workplace. Solving such problems require a multiple disciplinary approach, often have multiple conflicting or vague goals, and not all information is even known. In the engineering educational setting, a design challenge, which will be referred to as an authentic problem in this study, with or without model making, is closer to the ill-structured end of the spectrum of problems (Heywood, 2005). It is important to know the process involved in solving such problems in order to develop an effective assessment of students' PS skills.

For solving authentic problems, methods can be algorithmic or heuristic or a combination of both (Martinez, 1998; Jonassen, 2000; Ormrod, 2012). Algorithmic methods are typical of mathematical problem solving in the context of a classroom, where students learn step-by-step procedures on how to work out factoring for quadratic functions or long division. Heuristic methods are more like general strategies or rules involved in an engineering design-based iterative problem that can only be solved through execution and testing. While algorithmic methods are not useful in authentic problem solving, general heuristics alone are also not reliable in authentic problem solving without deep understanding of the content areas within which a problem is embedded (Perkins & Solomon, 1989). In an authentic design problem situated in the context of science and mathematics, heuristics may help in creating the general strategies for solving the problem, but algorithmic methods may be used when it comes to utilizing specific mathematics and science knowledge to solve the problem. Furthermore, frequently practiced and accessed pathways to stored content in long-term memory help solvers with recognition of content areas relevant to the problem, and to think and reason forward in order to evaluate the results of any particular action to progress logically towards a solution (Perkins & Solomon, 1989).

From a cognitive perspective, the mental processes involved in problem-solving are based on knowledge and prior experiences of the solver (Ormrod, 2012; Newell & Simon, 1972). The prior knowledge is stored in long term memory and information gleaned from the problem are stored in short term or working memory. The latter has limited capacity and therefore can become overloaded during problem solving. This cognitive overload can hinder the solver's ability to successfully complete the solution. Therefore, the science, mathematics and engineering methods of problem solving recommend identifying and writing down (symbolically and visually) identified information (Heywood, 2005; Jonassen, 1997; Jonassen, Stroebell & Lee, 2006). This relates to the first phase of solving an engineering design based problem: identification of the problem parameters, such as useful information given, and unknowns. Metacognition is involved in mental activities such as identifying and selecting appropriate conceptual knowledge, planning a strategy to use the conceptual knowledge, monitoring one's progress towards a goal (Jonassen, 1997; White & Fredrickson, 1998). When the problem is encountered in a situation not within the confines of the classroom where the content was learned, the authentic problem demands the solver's ability to recognize the subject and specific content involved in the problem. Repeated experiences in solving such problems create the strong interconnected organization of information within a solver's long term memory and practiced habits of mind (Jonassen, 1997; Perkins & Salomon, 1989).

Based on various researchers' work on problem solving skills, the specific skills that can be associated with solving design problems that are not well-structured (not quite ill-structured, but authentic as previously described) can be identified as – 1) recognizing and identifying the problem, 2) recalling and organizing specific subject content relevant to the problem, 3) carrying out the procedural steps that are common practices within the subject, 4) looking back to see if the progression is logical, and, 5) stating the solution to the identified problem (Newell & Simon, 1972; Polya, 1973; Perkins & Salomon, 1989; Heller & Reif, 1984; Reeff, 1999). To develop a method of assessment would require specific ways to measure students' acquisition of these skills.

Review of Previous Techniques of Student Assessments on Problem-solving

A review of published research between 2000 and 2015, using the keywords "student achievement", "engineering", "STEM education", "problem-solving" and "design-based", and specifically targeting student participants from secondary and postsecondary programs, provided an initial count of 82 papers. Upon reviewing the abstracts, several papers were rejected from further review because they were either too narrowly focused within a specific discipline of STEM, or were too broadly focused on overall program assessment and thus, did not fit into the purpose of this review. As shown in Table 1, only six studies explicitly focused their investigations on students' problem solving skills.

Table 1

Summary of types of programs and measures of student achievement previously researched

Type of Student Achievement Measured	Self-Efficacy	Design Skills	Problem Solving	Spatial Analysis	GPA	Math-Sci Scores	Retention in STEM	Persistence in program	Interest Development	**Total**
Type of Program										
K-12			1		1				3	5
4-year college	2	3	5	1					1	12
Summer camp or short experience						1				1
Total # of studies by type	**2**	**3**	**6**	**1**	**1**	**1**	**0**	**0**	**4**	**18**

Of the six studies, only one was using high-school students as their participants, which suggests a void in the research on problem solving skills among students in secondary education. For purposes of this study however, among these six, there were four research studies that focused on problem-solving skills and were relevant (see Table 2) for methods used to assess students' problem-solving skills.

Eseryel, Ifenthaler and Ge (2013) focused on evaluating 9th grade students' ill-structured and complex problem solving skills using an experimental automated reasoning tool. The study tested and validated the developed tool using an adapted protocol analysis method (APAM). The researchers found that the automated tool and the APAM did not measure problem solving on an identical conceptual level. Steif, Lobue, and Kara (2010) examined problem solving and promotion of thinking about conceptual knowledge in the subject of engineering mechanics (Statics). The conclusions of this study were that when instructional strategies emphasize metacognitive processes to seek and describe useful information in the initial stages of solving a problem, students are generally more successful in solving the problem.
Describing and generating explanations are indicators of deeper understanding of content and successful problem solving. Taraban, Craig, and Anderson (2011) also focused on engineering mechanics, and designed their study to identify solvers' skill levels using specific indicators in their paper and pencil solutions.

Table 2.

Relevant research studies focused on measuring students' problem solving skills

Previous research	**Type of program**	**Specific usefulness for assessing problem solving skills.**
Docktor & Heller, 2009	Physics for science & engineering - 1st year students	Strong rubric developed. Construct validity established. Reliability across different problems also established. Context of problem: physics domain.
Eseryel, Ifenthaler & Ge, 2013	9th grade students	The automated tool developed, and the protocol analysis method used did not measure problem solving on an identical conceptual level.
Steif , Lobue & Kara, 2010	2nd or 3rd year engineering students	Concluded that describing and generating explanations are indicators of deeper understanding of content and successful problem solving.
Taraban, Craig & Anderson, 2011	2nd or 3rd year engineering students	Reliable evidence for PS ability indicators were found in the paper & pencil solutions. Use of metacognitive prompts were important to elicit student responses to show CT.

The specific indicators hypothesized were, 1) symbolic representation and diagram to describe the context of the problem, 2) specification of assumptions and principles applicable, 3) devising a strategy and executing the plan, and, 4) checking equations and solutions. Using a video recording of students thinking aloud with prompts, and students' paper and pencil solutions, the researchers confirmed that reliable evidence for problem solving ability indicators were found in the paper & pencil solutions when supported by using data from the video recordings. The use of prompts was important to elicit student responses on specific thinking about why certain decisions were being made in the process of solving the problem.

These studies confirmed that students' thinking processes and skills in problem solving can be revealed when appropriate question prompts are asked. The significance of this contribution for this study is best presented with an example. When working on rewriting a formula to solve for a variable, a solver will often skip steps because of familiarity with that technique. As a result, when substituting numerical values in the formula there is a strong potential that the solver could make an arithmetic error and get an incorrect answer. Therefore, when confronted with an incorrect answer and without seeing all the steps that were used in rearranging the formula and substituting the values, the solver is not able to ascertain whether the error was simply arithmetic or a deeper problem based on not knowing how to correctly rearrange a formula to solve for the unknown. Instructionally it is therefore necessary to require all the steps to be shown in order to diagnose the mistake and identify the skill that needs remediation. For purposes of this study, in order to reveal CT and PS while students solve a design challenge, specific questions prompts were used to elicit responses that are directly related to the identified skills in problem solving stated in the research sub-questions.

The study conducted by Docktor and Heller (2009) was designed to develop and test an easy to use physics-specific problem-solving assessment rubric for paper-and-pencil solutions when used with context-rich (or authentic) problems. The rubric was determined to be reliable, valid and useful to assess authentic problem solving skills in the physics domain. Key categories of assessment were identified for successful problem solving measures within the context of a physics based problem. These categories are - 1) useful description (symbolic and descriptive), 2) selection of physics content and use in solving the problem, 3) selection of mathematical content and use in solving the problem, and, 4) logical progression towards a solution. As previously discussed, these categories can be mapped onto the problem-solving process identified by several researchers (Newell & Simon, 1972; Polya, 1973; Perkins & Salomon, 1989; Heller, 1992; Reeff, 1999).

A review of three years (2013 to 2015) of published articles in Journal of Engineering Education (JEE) and the International Journal of Engineering Education (IJEE), revealed sparse research conducted with K-12 students as the primary participants. This review, and other research reports (NRC, 2010) confirm the need to focus on K-12 student achievement in CT and PS to better understand the benefits, and the potential for integrative STEM education. When K-12 students were participants in the research, the data collected were mostly related to either short summer camps where students were exposed to some specific instructional strategy, or the focus was regarding interest development among students through motivation based or self-efficacy based techniques. The glaring shortcoming is that none of the researchers focused on student achievement using acquired skills over a multi-year instructional program using the I-STEM ED pedagogical approach.

Implications for Designing Research to Assess CT and PS in K-12 Engineering Classes

Three studies from the review described earlier have strong influence on a potential research design to assess CT and PS in K-12 engineering classes and in a multi-year I-STEM ED instructional program. They are those studies conducted by Docktor & Heller (2009), Steif, Lobue, Kara & Fay (2010), and, Taraban, Craig, & Anderson, (2011). In these three studies, the common theme was assessment of student problem-solving skills in the discipline of physics or the sub-discipline of mechanics (Statics). The participants in the 2009 study were first year science and engineering students registered for the introductory calculus based mechanics course. The 2010 and 2011 studies were situated within the context of engineering students engaged in the first course in engineering mechanics: Statics. Methodological details, specifically the design of an instrument used to collect data, the researchers' assessment of the extent to which their study was successful in achieving the goals stated, and the relevance of the research to the current focus, of the three above-mentioned studies are discussed in the next sections.

Development of a PS rubric

The research conducted by Docktor & Heller (2009), was aimed at developing, testing and validating an easy-to-use problem solving rubric to assess students' problem solving skills in the physics domain. Specifically, their intent was to develop an easy to use method to assess the quality of the procedures and reasoning, in addition to the more commonly assessed correctness of end-results. The problem tasks used in the 2009 study were characterized as authentic and context-rich. Context-rich problems are short stories where the statement is not explicit about what variable is unknown, the problem may present more information than necessary or some information may be assumed as known to all, and solvers would need to make some reasonable assumptions prior to solving the problem (Heller and Keith, 1992). These types of problems may have one or more of the above mentioned features in common with real-world problems and may be also be called authentic problems (ibid). The 2009 study was also intended to make sure that this rubric was "applicable to any problem solving format used by a student, and to a range of problem types and topics typically used by instructors" (Docktor, 2009, p. 1).

The research conducted by Docktor and Heller (2009) is important because of the rubric that was developed to score any type of physics-based authentic problem. The rubric has five main categories that relate to established definitions of problem-solving and critical thinking (Newell & Simon, 1972). Established for this rubric was validity for generalizability across different populations and contexts, including those similar to traditional text book problems as well as those that are context-rich. The five broad categories (using a Likert scale from zero to five for assigning point values) addressed by this rubric are organizing problem information into a useful description, selecting and applying appropriate physics principles, selecting and using mathematical procedures appropriately, and the overall communication of an organized reasoning pattern (Docktor & Heller, 2009).

Use of Metacognitive Prompts

As previously discussed, conceptual knowledge is not sufficient for solving authentic problems, recognizing the relevant content in the context of the problem, and knowing when and how to apply the relevant knowledge. Metacognitive strategies of identifying useful information and the approach to solving the problem are thinking processes that need to be explicitly demonstrated in order to assess solvers' PS and CT skills. The two studies conducted by Steif, et al. (2010) and Taraban, et al. (2011), demonstrated the use of metacognitive prompts to elicit deeper thinking and explanations of specific PS skills. Using sketching (also known as free body diagrams in physics and mechanics) and descriptive language to explain understanding of the problem given both are important to successful problem-solving, and as indicators of solvers' ability to select and apply appropriate conceptual knowledge in physics (Steif, et al., 2010). Reliable evidence of solvers' problem-solving skills can be found in paper-and-pencil solutions when appropriate metacognitive prompts for the specific PS skills indicators are provided to solvers' in order to elicit explanations of their thinking (Taraban, Craig, & Anderson, 2011).

Potential for Assessing Key Student Abilities with a Scoring Rubric

To assess the five key student abilities contributing to CT and PS, a modified version of a rubric previously developed by Docktor & Heller (2009) to "provide a minimal measure that can be used to assess problem-solving independent of instruction or type of problems used" (p. 1) can be used.

Modification of the Rubric

The 2009 rubric developed by Docktor & Heller had five categories as described below:

1) Useful Description - refers to the process of summarizing information from a problem statement in an appropriate and useful form, such as assigning mathematically useful symbols to quantities and visualizing the situation with a sketch.
2) Physics Approach - is the demonstration of knowledge of physics concepts and principles associated with the problem and showing an understanding of those concepts.
3) Specific Application of Physics - is the process of selecting and linking appropriate physics concepts and principles to the specifics of the problem.
4) Mathematical Procedures - are the mathematical operations used to obtain the desired physics quantity.
5) Logical Progression - is the extent to which the solution is focused and consistent.

For purposes of developing a modified rubric, "useful description" can be separated into two parts – the descriptive aspect of the category was separate from the graphical representation of the useful description. Researchers have identified both these skills as essential components of problem identification, and therefore, separating the two skills into separate prompts would ensure that all students respond to both those skills (Heywood, 2005; Jonassen, 1997; Jonassn, Stroebel & Lee, 2006). Furthermore, the second and third items (Physics Approach and Specific Application of Physics) could potentially be combined in the selection and utilization of the science content and practices.

It would be necessary to align and validate the modified rubric through a study using I-STEM ED experts. Through an iterative process of consensus building among the experts, the modified rubric can be finalized. For conducting a study, using a sample of students from an I-STEM ED program and administering a design-based assessment, researchers have shown that when using rubrics, inter-rater reliability can be achieved through training and having no more than two raters (Jonsson & Svingby, 2007; Moskal & Leydens, 2000).

Conclusions

In an integrative STEM education program, all five of the 21st century skills (Creativity, Collaboration, Communication, Critical Thinking and Problem Solving, Citizenship) are learned and practiced within the context of the T/E DBL pedagogical approach. From a perspective of learning theories, the T/E DBL approach provides the context for student engagement (and motivation) through a design challenge. The design and testing of a solution involves an iterative approach to student learning and utilizing content and practices of the STEM disciplines. Specifically, CT and PS are involved in predicting, designing, testing and re-iterating, which are not practiced in traditional classrooms. CT and PS skills are also not assessed in traditional science and mathematics standardized testing. When students are tested for their problem solving abilities in the traditional classroom the focus is on the extent of correctness of the end-result, and rarely, if ever, on the reasoning or procedures leading to the result (Docktor & Heller, 2009; Shavelson, Ruiz-Primo, Li & Ayala, 2003; Steif & Dantzler, 2005). Furthermore, the content knowledge tested is directly related to what has been recently taught in the classroom, which does not require the solver's demonstration of metacognitive processes involved in CT that require selecting the discipline specific content knowledge.

Research into the nature and characterization of problem solving over several decades has identified a set of student abilities requisite of success for solving authentic problems outside the confines of a typical classroom (Newell & Simon, 1972; Polya, 1980; Perkins & Salomon, 1989;

Martinez, 1998; Jonassen, Stroebell & Lee, 2006). Specifically, these student abilities are: 1) Useful description, both symbolic and descriptive, 2) Recognition and selection relevant science and mathematical content applicable to the problem, 3) Use of the principles and practices of specific content identified to solve the problem, and 4) adherence to a devised logical strategy for solving the problem.

Implications

The need for further research within technology education has been well documented by several researchers (Zuga, 1995, 2000; Cajas, 2000; Kolodner, 2000). Specifically research on how students select and utilize science principles previously learned in solving T/E design-based problems, using a qualitative approach would provide additional insights into student learning and transfer of their learning. The development of authentic design challenges and assessment instruments are needed for demonstrating the benefits of the integrative STEM ED pedagogical approach in developing CT and PS skills among students. In traditional Tech-ED classrooms, assessments lack specific focus on the CT and PS skills. The development of an assessment and rubric will provide opportunities to introduce these skills in the classroom and further, provide opportunities for further research on the benefits of I-STEM ED pedagogical practices. Furthermore, the availability of assessment instruments for CT and PS will create opportunities for more widespread use of the T/E DBL approach in science and math classrooms and provide a way for demonstrating student achievement.

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Chapter 3

Toward a Matrix of Situated Design Cognition

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Abstract

Design is commonly associated with cognitive frameworks for teaching and analysis. However, the nature of design extends beyond cognition to social and dynamic contexts. Situated cognition, which posits that knowing cannot be separated from doing or social contexts, may be an appropriate perspective with which to analyze design teaching and learning. This monograph summarizes dimensions of design from the work of Crismond and Adams (2012) and distills five dimensions of situated cognition from Driscoll (2005). These two concepts are compared, with similarities identified and implications for design teaching and learning described. A matrix of situated design cognition is presented for further investigation and theory building.

Keywords: design, design cognition, situated cognition, design pedagogical content knowledge (PCK)

Toward a Matrix of Situated Design Cognition

Design is the process of forming plans and developing products to solve a problem or address an opportunity to meet human needs or desires. It is a distinct type of problem solving (Jonassen, 2000) that appears in many fields of study. For example, “instructional,” “interior,” “engineering,” and “web” can all be appended with the word “design” and produce a coherent meaning. Though design appears in many disciplines, it can be considered a distinct domain with ways of acting and knowing (Cross, 1982). The study of design in this way involves a “unifying core” that spans these disciplines and subsequently informs practice in each (Goel & Pirolli, 1992, p. 397). Developing an understanding of how designers think and behave in the face of uncertainty is important for improving practice—both for designing and teaching design.

These patterns of thinking have been subject to much investigation, being called *design cognition*. As Dym, Agogino, Eris, Frey, and Leifer (2005) state, the process of problem formulation and solution generation is a complex cognitive process. Yet, the breadth of design activity includes aspects unaddressed by many of the available cognitive frameworks. And if we hope to effectively teach design, we must teach its full nature and how it is enacted by designers (International Technology Education Association, 2007; Todd Kelley & Rayala, 2011).

Therefore, we have synthesized dimensions of design and situated cognition to offer a reoriented perspective on design cognition that accounts for the highly-situated nature of design practice. The resulting perspective is presented as a matrix of situated design cognition. In the subsequent sections, the dimensions of design cognition and situated cognition are described, methods for comparing situated cognition theories and design activity are presented, and the matrix of situated design cognition is discussed. This emerging connection of design and situated cognition holds implications for design teaching and research.

A Focus on Design Cognition

Design has been characterized as a cognitive task because it generally involves the external representation of mental structures: forming a mental picture of a situation and bringing it about (Goel & Pirolli, 1992). More specifically design involves forming an understanding of problems, potential solutions, and making judgments and decisions about what ideas to pursue—all mental activities (Daugherty, Mentzer, & Kelley, 2011). Todd Kelley and Rayala (2011) describe several motives for studying and understanding design cognition: as a means for establishing interventions to improve design teaching and evaluating current design curricular efforts. Both of these aims, and the intent of design cognition research generally, are to establish better methods to prepare future designers (Adams, Turns, & Atman, 2003). Moreover, Wilson-Lopez, Smith, and Householder (2013) claim it is essential to examine design cognition at all levels—from adolescents to advanced practitioners—in order to identify strategies for fully supporting adolescents as they develop the habits of mind practiced by professional designers, such as engineers.

A variety of design cognition taxonomies have been established and employed in design cognition research. Taxonomies have been derived from the actions of design practitioners, design process models presented in design curriculum, analyses of engineering textbooks, or cognitive science frameworks. Grubbs and Strimel (2016) categorized these taxonomies based on their foundations as either a general design process, practitioner design process, or cognitive science taxonomy of design. Examination of design cognition studies conducted between 1996 and 2016 revealed eight different taxonomies used to define the cognitive tasks associated with design work (Grubbs, Strimel, & Kim, 2018; Strimel & Grubbs, 2017). Each of these cognitive activity taxonomies was found to have a distinct foundation and intent. The eight identified design cognition taxonomies and their originating source are provided in Table 1.

Since cognition is, by definition, unobservable, these lists of activities represent various attempts to uncover what designers are doing while designing. This representation of cognitive tasks during design is important for design educators to understand so that instruction can effectively instill expertise; similarly, the underlying modes of design thinking are important for learners to understand so that observations can be instructional. Investigations of design cognition are numerous (Cross, 2001) and span grade levels from elementary to undergraduate (Lammi & Gero, 2011). Among the results are insights regarding how long designers with varying levels of expertise spend on design, how frequently they switch tasks and iterate, how often they seek out information about the problem, and how they visualize their work (Atman et al., 2007; Cardella, Atman, & Adams, 2006; Mentzer, 2014).

Because each of these design cognition findings may be meaningful for design education, Crismond and Adams (2012) put many of these findings together in an attempt to inform design teaching. Their scholarship of integration identified core dimensions of design, and produced a matrix of behavioral patterns and how they intersect with each dimension. Each specific behavioral pattern included novice to informed designer comparisons and instructional recommendations. In contrast to other problem-solving investigations which made novice–expert comparisons (e.g., Chi, Feltovich, & Glaser, 1981), informed design was chosen as a more meaningful school-based outcome than expert design—informed designers have some training but not the accumulated experience that an expert does. While Crismond and Adams (2012) based their matrix on design cognition research, they noted that “the social aspects of design, including the challenges of helping students develop their abilities to collaborate and cooperate

Table 1.
Design Cognition Taxonomies in Prior Literature from Strimel and Grubbs (2017).

General Design Process		**Practitioner Design Process**		**Cognitive Processing for Design**				
Technology Education Design Process Model (Welch, 1996)	**High School Engineering Design Process Model** (Hynes et al, 2011)	**Mental processes for technological problem solving** (Halfin, 1973)	**Engineering Textbook Design Process** (Moore et al., 1995)	**Cognitive Procedures in Solving Problems** (Middleton, 1998)	**Problem Domain: Degree of Abstraction** (Purcell, Gero, Edwards, & McNeill, 1996)	**Strategy Classification Scheme** (Purcell, Gero, Edwards, & McNeil, 1996)	**Function-Behavior-Structure** (Gero & Kannengiesser, 2004)	
Reading the Design Brief	Identify Need or Problem	Analyzing	Problem Definition	Generation: Retrieval	System	Analyzing the Problem	Design Requirement	Formulation
Discussing Performance Criteria	Research Need or Problem	Communicating	Gather Information	Generation: Synthesis	Subsystems	Consulting Information about the Problem	Function	Synthesis
Discussing Constrains	Develop Possible Solution(s)	Computing	Generating Ideas	Generation: Transformation	Detail	Evaluating the Problem	Behavior Expected	Analysis
Generating Possible Solution	Select Best Possible Solution(s)	Creating	Modeling	Exploration: Exploring Constraints		Postponing the Analysis of the Problem	Behavior from Structure	Evaluation
Sketching / Drawing a Possible Solution	Construct a Prototype	Defining Problem(s)	Feasibility Analysis	Exploration: Exploring Attributes		Proposing a Solution	Structure	Documentation
Planning the Making of a Mock-up	Test and Evaluate Solution(s)	Designing	Evaluation	Executive Control: Goal Setting		Clarifying a Solution	Description	Reformulation type 1
Manipulating Materials	Communicate the Solution(s)	Experimenting	Decision	Executive Control: Strategy Formulation		Retracting a Previous Design Decision		Reformulation type 2
Making a Mock-up	Redesign	Interpreting Data	Communication	Executive Control: Goal Switching		Making a Design Decision		Reformulation type 3
Refining a Mock-up	Completion (leaves the cycle)	Managing		Executive Control: Monitoring		Consulting External Information for Ideas		
Copying a Mock-up		Measuring		Executive Control: Evaluation		Postponing a Design Action		
Checking Available Resources and Materials		Modeling				Looking Ahead		
Abandon Current Solution		Model/Prototype Constructing				Looking Back		
Plan Making		Observing				Justifying a Proposed Solution		
Making a Prototype		Predicting				Analyzing a Proposed Solution		
Identifying a Problem with a Prototype		Questions/ Hypotheses				Postponing an Analysis Action		
Modifying the Prototype		Testing				Performing Calculations to Analyze a Proposed Solution		
Evaluation of a Possible Solution		Visualizing				Evaluating a Proposed Solution		
Evaluating of a Sketch or Drawing						Explicitly Referring to Application Knowledge		
Testing a Mock-up						Explicitly Referring to Domain Knowledge		
Evaluating a Mock-up						Explicitly Referring to Design Strategy		
Testing Prototype								
Evaluating Prototype								
Recording Results from a Mock-up								
Recording Results from a Prototype								

in design teams and learn through their interactions with peers…have not been articulated in this version of the framework" (p. 778).

The Borders of Design Cognition

As noted in the previous quotation, design is inherently social (Bucciarelli, 2003) whether that is through interactions with clients, stakeholders, or other team members. "Designs do not exist in a vacuum" (Todd Kelley & Rayala, 2011, p. 201). Depending on the context of the design problem, background knowledge in a variety of domains is useful; design educators also encourage students to cultivate knowledge through interviews and observations with potential users. By its social connections, design is also linked to societal and ethical issues (Jasanoff, 2016; Purzer & Chen, 2010), suggesting that the situation in which design occurs is important.

An analogy used in design literature gives another way that design is unaddressed by cognitive theories: the problem space and solution space. As designers work, they define what the problem space is—the task environment. Effective design traverses the boundaries of this problem space into the solution space—an area of potential solutions to the problem—and as these solutions are explored, the understanding and nature of the design problem space is changed (Cross, 1997; Dorst & Cross, 2001; Salustri, Eng, & Rogers, 2009). This dynamic representation of design spaces emphasizes that the situations of design, and designer perceptions and understanding of these spaces, make a great deal of difference in the generated solutions. The representation also illustrates that the approaches taken in design are determined by whether or not designers observe salient details of the design environment (Daly, Adams, & Bodner, 2012; Goel & Pirolli, 1992).

Adams et al. (2003) posed the question "what does design learning look like?" For example, they acknowledge design cognition investigations mentioned previously, and note that more experienced designers tend to lengthen the process, dig deeper into each phase, and flow through phases of design. However, the type of design problem provokes a different cognitive response and the authors give more complex windows on what design learning might look like including adaptive expertise and learning as a dynamic system. There is a present recognition that design expertise involves flexibility for different situations and effectively dealing with complex situations by using available resources.

Exploring Design as Situated Cognition

Given the mental nature of design activity and its simultaneous contextual dependence, situated cognition may be an appropriate framework for investigating design activity and learning. Situated cognition integrates knowing and doing and argues that environmental and sociocultural contexts impact learning (Driscoll, 2005). Therefore, our investigation explored the overarching question "What might design education and learning look like from a situated cognition perspective?" The objectives of the research included 1) identifying similarities between design practices and situated cognition and 2) synthesize implications for design education as a result of these similarities.

Method

To identify similarities between the concepts of design practice and situated cognition, a set of key dimensions was identified for each concept. Based on the descriptions of each dimension, areas of similarity were described on a matrix. Then, further information searching and synthesis were done to describe teaching and learning implications for the integration of design and situated cognition as *situated design cognition*.

The integration work of Crismond and Adams (2012) formed the dimensions of design used in this synthesis. After reviewing articles from more than 170 peer reviewed design journals, as well as books and anthologies on design, seven key design performance dimensions were identified as being central to doing design. The work of Crismond and Adams (2012) was selected for our integration effort because it involved a broad search and synthesis of design practice. Additionally, the dimensions represented are overarching characteristics of doing design and are supported by patterns of design cognition.

Next, the overview of situated cognition by Driscoll (2005) was selected to inform dimensions of situated cognition because it also provided comprehensive coverage of the concept. Situated cognition stems from the belief that "what people perceive, think, and do develops in a fundamentally social context" (p. 157). If we are not able to *do* as a result of what we know, or are not able to transfer what we have learned to new situations, the learning is not meaningful. The dimensions of situated cognition are organized around two overarching ideas provided by Driscoll (2005) to describe the nature of situated cognition: "knowledge is conceived as lived practice" and "learning is participation in communities" (p. 153). Beneath these two ideas are five ways in which situated cognition is realized.

Dimensions of Design Practices

Learning while designing. Effective design is a process of learning. Each phase of the design process (e.g., problem definition, brainstorming, prototyping, testing) is informational and should inform deliberate iteration. Supporting this dimension, a study of high school student design cognition by Strimel (2014b) found that participants who enacted more iterations for testing their solutions, making observations, interpreting the outcome data, and using the resulting data to make design optimizations achieved better solution performance results. Furthermore, Wankat and Oreovicz (1993) state that expert problem solvers often evaluate any mistakes or failures in the design process to learn what should have been done and then develop new problem solving methods, while novices will often ignore the failures or mistakes made.

Making and explaining knowledge-driven decisions. Building on information obtained through research in the design process, effective designers conduct tests and generate insight as a foundation for their decisions. Additionally, effective designers give rationales for their decisions (Jackson, Mentzer, & Zissimopoulos, 2015). For example, Strimel (2014b) found that high school participants who conducted tests to assess different design ideas, and interpreted the resulting data to inform design decisions, developed more effective solutions.

Working creatively to generate design insights and solutions. Creativity and innovation are key objectives of design education. Facione (2011) describes that "creative or innovative thinking is the kind of thinking that leads to new insights, novel approaches, fresh perspectives, and whole new ways of understanding and conceiving of things" (p. 14). The National Academy of Engineering and National Research Council (2009) state that creativity is inherent in the engineering design process and therefore, include creativity as one of the engineering habits of mind. In addition, this dimension of effective design includes being able to deal with ambiguity or uncertainty in the design process.

Perceiving and taking perspectives intelligently. As designers collaborate with team members and potential users, the skill of empathy can broaden their understanding of the problem and help identify greater potential solutions. Fila and Hess (2014) posit, "empathic skills such as understanding user needs within their own surrounding context are seen as essential to developing appropriate and innovative designs" (p. 2). These interactions with people provide an opportunity to learn from others, which effective designers will use to their advantage in developing successful design.

Conducting sustained technological investigations. Much of design is object-based and therefore, the analysis of resulting design artifacts is important. As a result, effective design can involve the use of conjectures or propositions, and rigorous testing of design artifacts and their potentials. As stated by Orr and Flowers (2014), sustained investigations are the way in which people learn and inform their future problem solving judgments.

Using design strategies effectively. Given the wealth of information and possibilities in design, effective designers know how to manage, synthesize, and apply a range of techniques. They have an understanding of the design process beyond the needs of any one project (Lawson & Dorst, 2009) and are able to manage constraints or criteria of the given situations.

Integrating and reflecting on knowledge and skills. Effective design enables and is enhanced by reflective practice (Schön, 1983). This type of metacognition can help designers foresee and overcome roadblocks in design. Therefore, metacognitive thinking skills are considered essential for success as a technical problem solver (Todd Kelley, 2008).

Dimensions of Situated Cognition

Knowledge as lived practice. The first overarching characteristic of situated cognition is that it involves lived practice. "One learns a subject matter by doing what experts in that subject matter do" (Driscoll, 2005, p. 156); said again, our "understanding is embodied through [our] actions" (Daly et al., 2012, p. 210). Dall'Alba (2009) similarly notes, "Becoming a professional, then, involves transformation of the self through embodying the routines and traditions of the profession in question" (p. 37). Part of the learning process, and a simultaneous demonstration of learning, is the use of expert behavioral patterns and resources. In the context of design, as we learn effective design we begin to mirror the behavior of experts. Situated cognition is focused on this applied—instead of inert—knowledge.

Anchored instruction. Situated cognition implies that instruction is grounded in real-life contexts. Learning tasks are based on practical situations (even if they may not be encountered by the students) and embedded data which is used to solve the problem (Choi & Hannafin, 1995). The authenticity of these contexts enables students to do and apply knowledge, rather than recite (Strimel, 2014a).

Assessment in-situ. Like anchored instruction, situated assessment is based on real situations, evidence of doing, and evidence of participation in a community. Instead of tests, which are limited in their realism and interactivity, assessment methods could include portfolios, process data, or performances. These alternative methods are more in line with the situated learning processes of doing and interacting.

Learning as participation. The second overarching characteristic is that learning is a reciprocal connection with community. On the one hand, we learn through interaction with experts and by adopting their behavior; these experts are the core members of the community. On the other hand, learning co-constitutes the community (Driscoll, 2005, p. 159), every member is changed; our interactions can help in "defining and redefining the very nature of the profession" (Lawson & Dorst, 2009, p. 66). Throughout these interactions, learning is evidenced by increasing participation—a beginner might observe the community while someone with more practice can engage with the community.

Communities of practice. Choi and Hannafin (1995) stated that effective situated learning tasks should be "coherent, meaningful, and purposeful activities that represent the *ordinary practices of a culture*" (p. 56, emphasis added). Practitioners and experts are bound by their common engagement with these activities, called a community of practice (Barab & Duffy, 2000). Communities of practice collaborate to solve problems. Importantly for newcomers, communities govern access to resources; membership in the community is obtained by participation.

Apprenticeships or cognitive apprenticeships. The focus on apprenticeships in situated cognition is based on the real-life learning of many professions. Learning happens through incipient participation with a master, even in menial tasks, and observation of the situation. The role and responsibilities of the apprentice eventually grow, demonstrating learning.

Semiosis. As communities grow and shift, the language and iconic representation of the community will develop. Semiosis, or sign-making and interpreting, is based on the inner-group communication that emerges and affords distributed intelligence of the community. Understanding the language of the community further enables access to community knowledge and resources.

Identifying Intersections of Design and Situated Cognition

Areas of overlap between design and situated cognition were identified by placing the dimensions orthogonally. Similarities, or areas where situated cognition might offer a new insight to design, were marked in the matrix. The Matrix of Informed Design, created by Crismond and Adams (2012), is intended to be used as a point of reference for future research, it is representative of key dimensions of design, and its descriptions are sufficiently ambiguous to afford new perspectives on design. We followed this model when describing the intersections of design practice and situated cognition: our matrix is a point of reference, representative of key aspects of the intersection of design and situated cognition, and open to new perspectives on design. To substantiate the areas of intersection between design and situated cognition, themes from prior literature were identified and implications for teaching practice were collected. Unpacking these intersections works to complete an image of situated design cognition.

Results

The overlapping dimensions of design and situated cognition are marked in Table 2 with a description of how situated cognition might enable or facilitate design practice. We took each element of situated cognition and envisioned what design might look like as enacted through that lens. The nature of situated cognition—that learning "is a natural by-product of individuals engaged within contexts" (Choi & Hannafin, 1995, p. 53)—supports the use of situated cognition elements to facilitate engagement in design and, consequently, effective design practice. Learning occurs as students integrate knowing and acting and being (Dall'Alba, 2009, p. 43); by embedding students in design situations to be solved, design students will learn through their practice of design. And the structures of situated design cognition are related to design or design-based strategies. Following the brief synopsis in Table 2, the intersection of situated cognition and design practice is described further. Empirical evidence and recommendations are provided where possible, though the completion of this vision is an opportunity for future research.

Anchored Instruction

Anchored instruction is similar to problem-based learning (Choi & Hannafin, 1995); this makes anchored instruction highly relevant for design education, since design- and problem-based scenarios are also similar. Among aspects of anchored instruction, the information-rich and meaningful context it provides might be effectively leveraged for design instruction. *Making Knowledge-Driven Decisions*, *Working Creatively to Generate Design Insights*, and *Perceiving and Taking Perspectives Intelligently* were all identified as areas of overlap for anchored instruction because an anchored approach brings embedded information and assumptions suitable for the design process. These anchored situations enable students to bring their own perspective on the problem, or reframe the problem as necessary, to generate different design approaches and solutions (Daly et al., 2012).

Table 2.

Intersection Matrix of Design and Situated Cognition.

	Knowledge as Lived Practice		Learning as Participation in Communities		
Dimensions of Informed Design	**Anchored Instruction**	**Assessment In-Situ**	**Communities of Practice**	**Apprenticeships/Cognitive Apprenticeships**	**Semiosis: Sign Interpretation and Production**
Learning While Designing	Refer to and learn from the design context while designing	Formative and summative feedback on design should improve practice	Peer collaboration informs design; learning is interactive	Effective design behavior is modeled by experts or peers	Comprehension of the evolving language of a community enables access and use of community knowledge and resources
Making Knowledge-Driven Decisions	Decisions are based on authentic problem contexts and users	Continuing evaluation of design decisions and gathered information; using decision rationales in assessment	Leverage the knowledge and resources of the community for decision-making	Observe experts or peers to understand value structures used in decision making and rationales	Language informs making and communicating decisions
Working Creatively to Generate Design Insights and Solutions	Evolved understanding of the problem can be used to generate insights	Feedback can be incorporated to generate and improve design solutions	Build off of the insights of others to generate and improve design ideas	Ideation and creative thinking processes can be learned through observation	Sketching ideas using the proper language and symbols can help a community envision new solutions
Perceiving and Taking Perspectives Intelligently	Design should be informed by the perspectives of authentic users/customers	Design should be shaped by user testing and feedback	Design should be informed by the standard practices of the culture in which it is situated	Observing experts can showcase the coherent, meaningful, and purposeful design activities that represent the practices of a profession	Community language can enable effective design communication among stakeholders; language provides access to the distributed intelligence of the community
Conducting Sustained Technological Investigations	Examinations of authentic design artifacts can inform design decisions	Rigorous and authentic evaluations of design concepts or artifacts can enable design optimization	Information sharing among the community can afford deeper investigations into innovative design solutions	Design critiques should be informed by the specific practices or standards various professions hold for evaluating design performance	The language of the community is used to effectively share design concepts and artifacts
Using Design Strategies Effectively	Experiences in authentic design tasks build a repertoire of knowledge and skills to be used in future design work	Understanding the outcomes of previous design experiences can build associations between design situations and effective strategies	Professional mentor guidance and peer feedback can aid in the selection of an effective design strategy	Expert critiques of designs can provide suggestions for both solution and process improvement	Design strategies that use community language can help to leverage the distributed intelligence of the community
Connecting and Reflecting on Knowledge and Skills	Metacognitive regulation can enable the acquisition of knowledge and skills necessary to complete a design task	Design assessment incorporating self-reflection can identify the knowledge and skills necessary to better solve a problem	Analysis of peer design performance can be used as learning and self-reflection tool	Observing experts can highlight common design attributes such as creativity, focusing on the end user, metacognition, collaboration, and intellectual curiosity	Notebooks, design artifacts, and design process visualization can be used as reflective tools

Young (1993) outlined four steps for setting up authentic, anchored instruction: pick an appropriate set of situations, determine necessary scaffolding, find supports to track student progress and guide students, and define the role of assessment. These steps are also useful for design—the small design challenges or large design projects in a course should be grounded in realistic scenarios that enable multiple perspectives of analysis. The instruction might be scaffolded so that students grow in confidence during the design projects, as they experience success on the initial ones (Jobst et al., 2012; Tom Kelley & Kelley, 2013).

Several guiding activities related to design have recently been proposed. For example, Atman, McDonnell, Campbell, Borgford-Parnell, and Turns (2015) tasked students to analyze their own design process timeline as a reflective tool to foster understanding of the design process. Also, Purzer (2011) similarly proposed the analysis of other design teams as an opportunity for team reflection the design process. Reflection like this may enable students to guide their own progress throughout the design challenge. Because the reflection is based on authentic situations, learned design strategies can be applied to similar situations in the future. Young (1993) finally recommended ongoing, integrated assessment for situated learning; this approach for design might require frequent design checks with the instructor, teacher access to design journals (which can easily be done through electronic design notebooks), or assessment of engagement and interaction with the design situation.

Assessment In-Situ

Assessment remains a challenge in design (Strimel, Bartholomew, Jackson, Grubbs, & Bates, 2017). The ambiguity of the process, availability of multiple correct approaches, and potential for multiple solutions can lead to unreliable results. Approaches to assessment from a situated cognition perspective may address some of these assessment challenges for design educators. Several types of assessment are mentioned for situated cognition and the focus is on realistic connection between enacted knowledge. Multiple choice tests, for example, are not part of many professions. Options for assessment include diagnostics, summary statistics, and portfolios (Driscoll, 2005); self-referencing information, performance assessment, and concept maps (Choi & Hannafin, 1995); or log files showing engagement with content (Jonassen & Land, 2000).

As a design educator it is important to ask what is emphasized for design assessment. Design education may help enable critical thinking and communication skills (Cross, 1982), but does the focus need to be on these skills? creativity? design performance? Assessment methods should align with these priorities; be based on design performance, not esoteric knowledge; and enable students to reflect and improve their design practice. Feedback from assessment procedures and testing conducted while designing can provide deeper insight into designed ideas. Substantive improvements to the design product should also develop from the instructor's and users' feedback—a form of assessment beyond the design classroom.

Communities of Practice

Community classrooms require a shift in the nature of our classes, decentralizing decision-making from a teacher-centered to a student-centered approach. Participants in a community of practice include those who are inbound, insiders, outbound, or boundary members (Driscoll, 2005). Insiders are especially able to shape the culture of the community, though it is influenced by the participants as a whole.

Community of practice approaches in design education provide access to a central set of stakeholders and shared resources. With regard to information searching and benchmarking, important design steps, community of practice teaching would imply information sharing rather than everyone repeating the same steps (Collins, Joseph, & Bielaczyc, 2004). Depending on the design situation, the learning community may rely on boundary members who are able to bridge the classroom and the design domain of interest. For example, certain stakeholders might enable access to users or domain specific knowledge.

Treating collaborative groups within the class as design communities of practice may also yield new insights for situated design cognition. For example, grouping students based on interest in a design problem may be a benefit if they are able to form an effective community (and instructional design may be set up to facilitate such a community formation). Inter-group check-ins between the classroom learning communities, or design teams, may also allow students to give one another feedback and guidance in the design process.

Apprenticeship

Apprenticeship models are familiar for design education because effective design behavior is often modeled by expert instructors or peers during design critiques. Cross (2006) stated

> What designers know about their own problem-solving processes remains largely tacit knowledge—i.e., they know it in the same way that a skilled person ‘knows’ how to perform that skill. They find it difficult to externalize their knowledge, and hence design education is forced to rely so heavily on an apprenticeship system of learning. (p. 9)

Because design is ambiguous, design education has often relied on apprenticeships of sorts. This helps uncover the reason for design decisions and makes apparent the salient feature of a design problem in case the student had missed them.

A dialogue observed by Schön (1983) demonstrates the ways that design instructors might model behavior: the design teacher thinks-aloud, modeling decision-making for the student in response to constraints of the design situation. This thinking-aloud demonstrates knowing in action and tacit knowledge, potentially touching on an array of design motives and skills.

Semiosis

The final element of situated cognition involves the language used by designers. Several types of communication are evident at various stages of design: verbal, graphical, mathematical, or even physical models are used to communicate the features of design (Dym et al., 2005). Sketching is an important part of design and can be used in many phases of design, including problem definition, brainstorming, and communication (Cardella et al., 2006). Simple sketches, with eliminated detail, present ambiguity and enable the design team to envision new solutions as they go (Tversky & Suwa, 2009).

The nature of community language suggests that in order to have a deep understanding of design artifacts or sketches, one needs to be part of the community—or at least have access to the resources of the community. This has implications for design assessment, since the ideas embedded in a sketch or representation can never be fully unpacked. Design educators should keep this in mind when attempting to interpret design journals or documentation. Sketching also has implications for reflection during design; if ambiguity is preserved and sketches are revisited, it may lead to new insights in design.

Conclusion

Much of design education and practice already demonstrates the belief that designers' actions are grounded in situations, contexts, or frames of thinking, and that designers' interactions with the environment and others fundamentally change the design problem and solution spaces. "Design Thinking reproduces knowledge through action with the goal of changing existing situations into preferred ones. These challenges are tackled in interdisciplinary teams with a clear focus" (Noweski et al., 2012, p. 79). Existing perspectives on design cognition have enjoyed a strong discourse and further support through empirical inquiry. The perspective presented in this framework should be further triangulated by similar discourse and experimentation related to each element of situated design cognition. The five situated cognition elements are main elements drawn from a limited portion of rich literature on instructional design; therefore, this matrix might be expanded in the future to encompass more facets of situated cognition.

Nonetheless, this paper has distilled situated cognition to five key elements and described its alignment with design practice. Each dimension of situated cognition represents a lens by which we might view design education for enhancement, bringing the strengths of learning theories to our field. Whether in design education courses, or for instructors using design-based learning, aspects of the emergent *situated design cognition* seem to point the structure of our learning environments toward authentic and collaborative problem-solving. The implications of situated design cognition hold promise for fostering engaging contexts for learning. While some of these implications are found from previous literature, there are many starting points in this matrix that can be expanded by further literature searching, empirical investigation, and theory building, hopefully leading to new implications in design teaching and learning.

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Chapter 4

Promoting 21st Century Skills in Problem-Based Learning Environments

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Abstract

This paper investigates the relationship between problem-based learning (PBL) environments and the promotion of 21st century skills. Programs like STEM education and technology and engineering education (TEE) that promote PBL are also explored. Various print and electronic sources were examined and the literature selected from review comes from experts in fields of education, 21st century skills, PBL, STEM education, and technology and engineering education (TEE). The review of literature suggests that 21st century skills are best developed through hands-on and problem-based activities. Since STEM and TEE incorporate many hands-on activities focused on solving problems, both programs are recognized fields that teach 21st century skills in addition to science, technology, engineering, and math content knowledge. However, STEM and TEE classrooms and labs need to be carefully designed in order to accommodate collaborative and hands on activities. Some specialized PBL environments like Makerspaces, Tinkering Studios, and STEM Labs already exist, but the need for additional dedicated PBL environments continues to increase as the focus on teaching 21st century skills through PBL becomes more widespread and prevalent in the educational system.

Keywords: 21st century skills, problem-based learning, STEM education, technology and engineering education

Introduction

Education plays an important role in preparing students for the society in which they live. In the past, students were equipped with the skills necessary to fill the roles that involved routine manual or cognitive labor. However, today's economy and industries are very different. Computers and machines are able to do the jobs that once employed a large part of the population and, as a result, greater numbers of people are employed in jobs that require higher-level thinking and communication skills – tasks that computers and machines cannot perform autonomously (Dede, 2010).

If students are expected to survive and thrive in a technology driven world and "navigate the complex life and work environments in the globally competitive information age," they must be given opportunities to "[develop] adequate life and career skills" (Morrison, Roth McDuffie, & French, 2015, p. 245). In other words, schools need to prepare students to meet the challenges of working in an ever-changing, technology driven society by helping them to develop the higher-level thinking and communication skills that they will need when they enter the workforce. These higher-level thinking skills will also allow students to adapt when they meet challenges and changes due to the development of technology. As John Dewey once said:

> It is impossible to foretell definitely just what civilization will be twenty years from now. Hence it is impossible to prepare the child for any precise set of conditions. To prepare them for the future life means to give them command of [themselves]; it means so to train them that they will have the full and ready use of all their capacities; that their eye and ear and hand may be tools ready to command, that their judgement may be capable of grasping the conditions under which it has to work, and the executive forces be trained to act economically and efficiently. (Gomez & Albrecht, 2014, p. 15)

Due to the rapid improvement of technology, the world is changing more quickly than ever before, so the future Dewey describes is even more uncertain. As a result, it is important to equip students with not only academic content knowledge, but also with general skills that will enable students to face any situation with confidence. It is no longer enough for students to be proficient in math, reading, and writing; students need to have more tools at their disposal. These tools generally come in the form of various higher-level thinking and communication skills, often referred to as 21st century skills.

21st Century Skills

21st century skills consist wide range of skills and abilities that are necessary for success in a technological world (Dede, 2010). 21st century skills promote lifelong learning, which allows students to adapt and be more responsive as the world around them changes and as they, themselves grow and change (OECD, 2005). Since today's workplace and society is constantly changing, the ability to adapt to the fast-paced life of the global community becomes increasingly significant to success in the global workplace. Therefore, it is important that students to have adequately developed 21st century skills so that they are able to be flexible and change with the world around them.

Although different conceptual frameworks for teaching 21st century skills vary slightly, common themes and skills listed in these frameworks include critical thinking, problem solving, collaboration, communication, and creativity (Dede, 2010). Once developed and mastered, this collection of skills will go with the students for the rest of their lives. Students with these abilities are better able to adapt to new situations, solve their own problems, share their ideas, and reflect on how their actions affect others. As adults, they will be able to react positively to inevitable changes in the world around them and solve problems that arise because of these changes (Lemke, 2002).

In the 20th century, during the peak of the Industrial Age, high importance was placed on students' and workers' abilities to follow explicit directions from teachers and supervisors. However, due to changes in industry, the economy, and technology, there is a need for today's workers to not only follow directions, but also to adapt to the changing world (Lemke, 2002). Students must be prepared to enter a workforce that is drastically different from that of the 20th century. As Dede noted:

> Declining portions of the labor force are engaged in jobs that consist primarily of routine cognitive work and routine manual labor – the types of tasks that are easiest to program a computer to do. Growing proportions of the nation's labor force are engaged in jobs that emphasize expert thinking or complex communication – tasks that computers cannot do. (2010, p. 51)

As a result, today's students need to be proficient in not only reading, writing, and mathematics, but also in areas like critical thinking, problem solving, creativity, communication, and collaboration so that they are prepared for a workforce that requires higher-level thinking and communication skills (Dede, 2010). In other words, students need to have various 21st century skills in addition to basic content knowledge of subject matter in order for success in the modern world.

"Major shifts in the ways people communicate and access information" has also had an impact on the skills students need to develop (Prettyman, Ward, Jauk, & Awad, 2012, p. 7). With the ease of access to information through the Internet, it is no longer a matter of remembering information, but knowing how to use the information available to us. Students need to be able to use the fundamental subjects taught in school and know how to apply these subjects in new and creative ways to solve problems and communicate their ideas to others.

Why Our Students Still Lack 21st Century Skills

Although it is generally agreed that certain 21st century skills are necessary to be successful, business leaders have reported that students have "deficits" in these skills, and the lack of these skills in our society will "significantly impact the future economic growth in the United States and abroad" (Mosier, Bradley-Levine, & Perkins, 2016, p. 13). What is more, American students are also falling behind in traditional areas of math, reading and science as well. A study conducted by the Organization for Economic Cooperation and Development (OECD) shows just how far behind American students are compared to their international peers. The results of this study, which are based on the Programme for International Student Assessment (PISA) – a test that measures reading, math, and science abilities of students in developing and developed countries – show that the United States ranks 38th out of 71 countries in Math and ranks 24th out of 71 countries in both science and reading. With rankings falling in the middle of the pack, the United States clearly is not preparing its students to compete with top global academic performers like Singapore, Hong Kong, Ireland, South Korea, Japan, Canada, Germany and the United Kingdom (Desilver, 2017). Therefore, in order to keep up with the global economy, America's schools need to do a better job of developing their students' 21st century skill sets in ways that enhance and enrich standard math, science, and reading curriculum.

Since the era of the Space Race in the 1950's, there has been a growing need for innovation and creative thinking in order to keep America on the top of the world's educational ladder. Money from the government has been "poured" into educational initiatives and reforms in order to increase the development of 21st century skills, which can help to create a more innovative society (Bartholomew, 2015, p. 14). Although the goal was to improve education and preserve America's position as a global leader, schools and teachers today are still struggling to instill 21st century skills in students.

The main challenge when teaching 21st century skills is finding the time to teach these skills in an already full curriculum. Teachers and students are often confined to learning and testing environments that are limited by curriculum and assessments imposed by the school or state (Strimel, 2014a). Many teachers already have difficulty teaching the entire required curriculum for their content area in order to enable their students to pass standardized tests. Adding additional curriculum – even necessary curriculum that includes the teaching of crucial 21st century skills – would create more difficulties for teachers who are trying meet standardized testing requirements.

However, according to Dole, Bloom, and Kowalske (2016), 21st century skills cannot be properly measured through current standardized testing methods. In other words, skills like critical thinking, problem solving, creativity, communication, and collaboration – the skills students need most for success in the workplace – are not even covered by the tests they spend so much time preparing to take. Therefore, when teachers teach to the test, or when they employ teacher-centered methods in order to teach a curriculum that will allow students to be successful on statewide assessments, students may be missing opportunities to develop their creativity, critical thinking, problem solving, communication, and collaboration skills. While students may seem successful based on their tests, they may be lacking the abilities to succeed in the working world. As a result, today's students may be able to pass standardized reading, writing, and math assessments, but these test do not show if a student is adequately equipped with all the skills necessary for success in the rapidly changing world.

Even though standardized testing does not adequately measure students' skills, testing has greatly influenced the learning environment. Accommodating standardized testing has led to teaching practices that limit the development of 21st century skills. Because of high stakes testing, "teaching to the tests has led to the adoption of teacher-centered pedagogical strategies to meet the time and content demands of the tests" (Dole, Bloom, & Kowalske, 2016, p. 45). Teacher centered instruction (e.g. lectures and teacher demonstrations) is prevalent in many classrooms because it allows teachers to have more control of the pacing of the curriculum (Dole et al., 2016). However, these teacher-centered strategies do not often allow for the development of 21st century skills like creativity, critical thinking, or problem solving, which are essential for success in the modern world. One of the best ways to promote the development of 21st century skills, properly prepare our students for the future, and combat ineffective teacher-centered instruction is through problem-based learning (PBL). Advocates of 21st century skills stress the importance of student-centered methods like PBL or project-based learning. PBL and other student-centered teaching methods are widely acknowledged as being effective, even if they pose classroom management challenges to teachers (Rotherham & Willingham, 2009).

The PBL Environment

The essence of teaching 21st century skills is for students to "learn to develop their own ideas," test and share those ideas, and take input from their teachers and peers to further develop their ideas (Prettyman et al., 2012, p. 11). This type of teaching and learning is best reflected in the PBL approach. PBL is an educational method that provides students with authentic learning opportunities with a focus on teaching through real-life situations and solving real world problems. In PBL environments, teachers introduce a situation that their student care about or can relate to. The students then identify problems within the given situation, brainstorm ideas to solve those problems, test their solutions, and communicate their results. Through the problem solving process in PBL, students not only gain content knowledge, but also develop their 21st century skills.

In addition, PBL is highly student-centered and involves students developing their own knowledge and discovering important information through teacher guidance, not teacher lecture. Therefore, PBL is fundamentally different from teacher-centered approaches that involve teachers simply giving students the information they need to know. Through PBL, students are no longer passive "consumers of knowledge," but are becoming active "creators of knowledge." In other words, students in a PBL environment are not just handed information so they can pass standardized assessments; students have to learn how to use information in new and unique ways and create their own knowledge by attempting to solve a problem that is relevant to their lives. In this way, students gain experience with finding answers to their own questions and rely less on their teachers for the right answers. In life there is not always going to be someone around to answer questions or solve problems; by incorporating a student-centered learning environment students become self-dependent and are better able to face the changing world with confidence (Prettyman et al., 2012, p 13).

History of PBL

PBL is not a new concept and the idea behind it has not changed much over the years. In the past, PBL was used much the same as it is today – as a teaching method to provide students with "authentic learning experiences" and to aid in the development of essential life and career skills like creativity, critical thinking, problem solving, communication, and collaboration (Vega & Brown, 2013, p. 8). PBL was originally designed to aid medical programs when instructors discovered that students were graduating with a "wealth of information but without the problem-solving skills to use the information wisely" (Vega & Brown, 2013, p. 8). By training medical students in a PBL environment, they were better prepared to think quickly, solve problems, and stay calm under pressure while interacting with patients. After success in the medical field, PBL began to be recognized as an effective teaching method in other areas of education.

PBL was such a powerful and innovative teaching method that multiple educational reformers in the 1800's believed PBL was essential to student learning. These reformers like Fredrich Froebel and Johann Heinrich Pestalozzi thought that students should be taught "in a full range of real-life activities...using a hands on approach" (Kelley, 2012, p. 34). It was an "attractive idea" if these activities could be the base to integrate multiple academic contents and incorporate issues that affected or interested students (Kelley, 2012, p. 26). In other words, Froebel and Pestalozzi believed that learning academic content through hands-on activities would make the information more relatable and pertinent to their students. Even John Dewey – one of the "fathers of modern education" – recognized the importance of students' "natural curiosity" concerning their learning (Crippen & Archambault, 2012, p. 158). This curiosity could be more easily tapped through hands-on PBL than through lecture-based instruction.

All three of these educational reformers were aware that "students need to be able to relate their own life experiences to the topics that they are learning" in order to engage in their education. These reformers were also aware that hands-on problem solving activities like those found in PBL are a great way to make educational topics relatable. The authenticity found in PBL provides a "clear application" of what the students learn to their own lives and makes content more relevant to them (Strimel, 2014a, p. 9,10). Through the efforts of educational reformers like Froebel, Pestalozzi, and Dewey, school systems continued to adjust in order to reflect the changes in society and provide for the needs of the students.

Learning to Think

While educational reformers focused on making classroom topics more relatable to the students through PBL, using PBL as a teaching and learning method also has the ability to "[emphasize] higher order skills" like critical thinking, creativity, and problem solving instead of "lower level skills...[like] memorizing facts and repeating procedures" (Morrison, et al., 2015, p. 245). Teaching content is important to develop the minds of students, but teaching students to think is even more important. Problem solving, like that done through PBL, is important to this process because "problem solving is one of the most valuable ways in which [people] think" (Gomez & Albrecht, 2014, p. 14). Through PBL, students are expected to "internalize" important themes and concepts instead of memorizing facts (Asunda & Mativo, 2016, p. 11). The most important idea in PBL is for student to learn "how to think, not necessarily the specific details" (Morrison et al., 2015, p. 249). This idea is a reflection of the student-centeredness of PBL – teachers do not give students all the answers, but provide them with enough of the main concept that students can solve their own problems and find their own answers. With the rapidly changing world, it is more important than ever that our students can think for themselves and solve their own problems. Being dependent on others for the right answers can slow down communication, prevent innovation, and create a lack of creativity. Students who depended on their teachers to give them the right answers may struggle in the workforce when they are expected to think critically and use problem-solving skills when issues arise (Vega & Brown, 2013).

This undesirable dependency on others for answers can be either encouraged through teacher-centered instructional methods, or lessened through student-centered practices like PBL. When teachers simply "spoon feed" all the answers to their students – as is common in teacher-centered approaches like lecturing – the students become unused to "thinking on their own" (Vega & Brown, 2013, p. 18). PBL helps to remedy this detrimental situation by providing opportunities for students to use critical thinking skills and other 21st century skills. When students are engaged in problem-based activities that teach 21st century skills, the students "are not learning what to think, but how to think" (Prettyman et al., 2012, p. 11). As a result, students begin to have confidence in their own ideas, rely less on their teachers for all the answers, and become independent thinkers.

Benefits of PBL

Students who become independent thinkers by partaking in authentic learning opportunities like those found in PBL are the students who are on the way to having a developed set of 21st century skills and are better prepared for the real world (Strimel, 2014a). In order to fully gain 21st century skills, students need to learn through "relevant, real world ... contexts" by participating in authentic and PBL opportunities (Partnership, 2015, p. 9). These types of PBL opportunities have been "shown to improve the understanding of basic concepts and to encourage deep and creative learning despite academic content area (Clark & Ernst, 2007, p. 24). This improvement and development of skills is apparent in all learners who have had exposure to a PBL environment. Studies have shown that when "low ability" students are "immersed in a PBL environment" they show 446% increased used of critical thinking and collaboration skills; "high ability" students show an increase of 76% of these same skills (Mosier et al., 2016, p. 3). Clearly, PBL is suited for all learners – high and low achievers alike – to improve their 21st century skills. As a result, PBL helps to prepare all students for the rapidly changing world regardless of their cognitive abilities.

PBL not only develops 21st century skills, but also improves student motivation, which is another important aspect to success in the modern world. PBL improves student motivation in two ways: (1) introducing meaningful activities and (2) developing positive student perceptions of the PBL strategy. Students who participate in activities which are meaningful to them become more interested and motivated to complete tasks, even if the tasks are difficult and challenging (Morrison et al., 2015). When students persist at difficult tasks, they increase the quality of time spent learning and developing their academic content knowledge and 21st century skills. In addition, the use of PBL is "strongly linked" to student perceptions of content relevancy and 21st century skills (Moiser et al., 2016, p. 8-9). Overall, these perceptions are positive. Students believe that by participating in solving real world problems – like those presented in PBL – they are learning 21st century skills as well as content. Students also feel that a PBL environment provides learning opportunities that are suited for different learning styles (Moiser et al., 2016). Most importantly, after being engaged in a PBL environment, students feel like they have "learned how to learn" (Morrison et al., 2015, p. 250). Students with positive attitudes and perceptions towards PBL, who believe that their learning needs are being met and that the content is relevant to them, are more likely to be cooperative, engaged, and motivated in the PBL environment. Likewise, students who are more engaged in their education learn more and develop more skills than those who are not engaged or motivated to participate. Therefore, by increasing student motivation, PBL is also providing students with more skills needed for success in the modern world.

Another benefit of PBL is increased scores on state assessments. Studies have shown that after two years of being immersed in a project based learning environment, high school students improved more and scored higher on state and year-end assessments as compared to their peers who were not immersed in a project based learning environment (Morrison et al., 2015). This suggests that learning through PBL can also help students retain and recall more information. While remembering information is not necessarily a 21st century skill, the more knowledge students have readily available to them, the more they will benefit as they enter the working world.

The reason PBL can lead to an increase in academic success is that a PBL environment creates a "culture that is interdisciplinary" and takes resources from all the content areas into account in order to solve a problem (Prettyman et al., 2012, p. 10). In other words, PBL integrates multiple content areas so students can learn in context. Problems in the real world are not based on a single subject matter, and neither are the problems proposed in a PBL environment. By partaking in PBL, students develop 21st century skills while gaining experience working in interdisciplinary situations. With this concept in mind, a new movement in education has been specifically designed to integrate the content areas of science, technology, engineering, and math through hands on PBL.

STEM Education

STEM is the "integration of science, technology, engineering, and mathematics content" and is the epitome of interdisciplinary education (Clark & Ernst, 2007, p. 26). In recent years, there has been a STEM Education Reform movement to increase the quality of STEM education in schools. This movement arose because of "national workforce issues" caused by the changing work environment (Strimel et al., 2017, p. 19). Like PBL, STEM education provides reasoning for learning academic content by introducing hands on and PBL experiences. Through real-world or career oriented problems and activities, integrative STEM demonstrates the rationale for learning academic content and provides a context in which concepts can be applied (Gomez & Albrecht, 2014). Through the PBL found in STEM education, students are able to become "actively engaged in learning" and "realize the meaning" of what they learn and importance of why they learn it in regards to specific content areas like science, technology, engineering, and math (Capraro & Han, 2014, p. xvi). Just like PBL, STEM helps to answer the question of 'why are we learning this?'

However, STEM takes providing rationale to a new level. Students need to be "explicitly shown the rational and application" of the content they learn and STEM does just that (Gomez & Albrecht, 2014, p. 8). Not only does STEM provide students with reasons for learning content, but STEM also links content in ways that allows students to see connections between various academic disciplines - through STEM, students are better able to perceive the relationships between the various fields of study. These connections make learning experiences even more meaningful because "direct continuity between content across subject areas serves as an agent that conveys relevance to students by allowing them to observe a sequential process in place of disconnected educational components" (Clark & Ernst, 2007, p. 26). In other words, a holistic education that connects different content areas provides more relevance than teaching content areas separately. This relevance can lead to more student engagement and higher levels of student motivation within the STEM classroom.

STEM also takes PBL to a new level by placing an emphasis on technology and engineering to solve problems. "STEM has been described as much more than math and science education, but a way of thinking that views technology and engineering as tools in solving problems and promoting innovation" (Talley & Scherer, 2013, p. 340). In STEM education the relationship between science, technology, engineering, and math in conjunction with a problem solving method work together to form a "whole solution" for a given problem. Science "proposes why" and provides the theory behind the problem. Technology "explains how" by describing the necessary processes needed to solve the problem. Engineering "determines what" and provides the design concepts. Math "reveals relationships" and helps to tie all the concepts together (Mitts, 2016, p. 31). By learning to incorporate various content areas to understand and explain concepts, students are no longer compartmentalizing the skills and knowledge they learn in specific content areas. When students are able to de-compartmentalize the skills and knowledge they learn in one subject area, they are able to bring those skills and knowledge with them into other content areas. This ability to use skills in all situations is critical if students are to be able to adapt in the changing world.

While STEM education focuses on science, technology, engineering, and math, STEM lessons are not limited to only these four content areas. Other academic disciplines like art, social studies, and reading should be incorporated as well when they "support student learning and provide elements to the learning experience" that enhance and enrich the STEM lesson (Froschauer, 2016, p. 5). By encouraging students to think in cross-disciplinary ways, STEM educations better prepares student for the type of thinking that is necessary for success in the modern world.

Although many administrators and teachers have seen the benefits of STEM education and strive to implement STEM programs in their schools and classrooms, it is important that they do not to force STEM integration into lessons that do not provide natural connections between academic disciplines. STEM "involves constructing valid experiences that highlight all disciplines" (Froschauer, 2016, p. 5). Therefore, to create these valid experiences, STEM education needs to be fostered in an environment that allows for the smooth integration of content areas. When STEM is implemented through "disconnected projects," students may fail to see the connections between content areas (Asunda & Mativo, 2016, p. 8). Instead, STEM lessons should focus around a theme that allows for the integration of content areas (Asunda & Mativo, 2016). In this way, students are able to get the most out of STEM integration and develop abilities to think across disciplines.

In addition, it has been proposed that "students cannot fully comprehend STEM-related concepts without engaging in problem-based learning experiences" (Asunda & Mativo, 2016, p. 9). Therefore, the environment in which STEM will be most effective is in a PBL classroom. Since the teaching of STEM is "rooted in interdisciplinary applied application of knowledge designed around a cooperative effort to provide students with a comprehensive, meaningful, real-world learning experience," PBL and STEM education go hand in hand (Gomez & Albrecht, 2014, p. 8). PBL is a great student-centered method that can integrate STEM concepts. At the same time, STEM content is a great way to introduce meaningful hands-on, PBL activities. Working together, PBL and STEM can help students learn the content and skills they need in order to thrive in the modern world.

Technology and Engineering Education (TEE)

Another program that supports both STEM and PBL is technology and engineering education (TEE). TEE is a field that strongly supports STEM education and even incorporates STEM principles through hands-on, problem-based activities. According to Loveland & Love "STEM should focus on active learning through engineering problem-based activities" (2017, p. 15-16). Through TEE, students are exposed to these types of engineering problems and engineering habits of mind (Strimel et al., 2017). In order for STEM to be effective, teachers in various content areas must work together to implement an integrated STEM education. Since TEE naturally incorporates components of STEM and utilize engineering design problems, TEE and its teachers can be a great starting point and model for implementing school wide STEM (Clark & Ernst, 2007).

Like STEM, TEE has a "longstanding history" of using PBL (Kelley, 2012, p. 34). "Activity-based learning is the signature characteristic of technology and engineering education" (Mitts, 2016, p. 30). As a result, TEE will also be looked to as an environment in which both STEM and PBL can thrive. Since technology and engineering activities provide "doing-based" or hands-on activities to solve problems, technology and engineering are the "logical subject matter to deliver STEM education (Moye, Dugger, & Stark-Weather, 2014, p. 25). As a result, TEE is also the logical subject matter in which to teach 21st century skills.

In addition, TEE is a great foundation for STEM because TEE has a history of integrating various academic content areas into the TEE curriculum seamlessly (Kelley, 2012). Since TEE is cross-curricular by nature, TEE can implement STEM without forcing content integration; STEM education is already naturally found in many standard TEE activities. For example, building and testing bridges – a common TEE activity –teaches science and math principles in addition to technology and engineering content. Through bridge activities, students have the opportunity to learn concepts based in trigonometry and use those concepts to study and calculate forces on structures while they build and test their bridges (Gathing, 2011). The central theme of bridge constructions allows for connections between science, technology, engineering, and math to develop naturally and in ways that are unified and natural to students.

Other themes are often found as a focus of instruction in the TEE classroom. These themes like bridges, rocketry, simple machines, robotics, and drafting serve to successfully combine STEM subjects in meaningful ways. Due to the focus on central themes in which science, technology, engineering, and math are logically connected instead of introduced through several unrelated project or activities, TEE is especially suited for the integration of STEM through the use of PBL. Therefore, like PBL and STEM, TEE is also suited for preparing students for the future.

In addition to teaching STEM principles, TEE is a source for engineering education and 21st century skills. Since "current educational initiatives ... are placing increased emphasis on the importance of engineering education for providing the skills necessary for the 21st century," TEE will be looked to as the provider of 21st century skills through engineering concepts (Strimel, 2014b, p. 16). TEE will become a provider of these essential skills because TEE can be used to "provide a context for learning math and science" through technology and engineering (Kelley, 2012, p. 37). TEE lessons can tie together multiple subjects and provide context to learning because TEE activities often incorporate the application of science, technology, engineering, and math in a single lesson. By providing these necessary contexts and applications of academic content through PBL and STEM, TEE can increase student motivation, pique student interest in other academic disciplines, and develop students' 21st century skill sets through engineering activities.

Technological Literacy

One 21st century skill that is unique to TEE is the development of technological literacy. Technological literacy is the "ability to use, manage, assess, and understand technology" (Ward, 2015, p. 18). Since our world is full of technology, students need to be able to understand and use technology in their everyday lives. As a result, technological literacy is one of the most important 21st century skills that TEE can provide.

However, technological literacy goes beyond being able to operate a computer. The International Technology and Engineering Educator's Association (ITEEA) describes a technologically literate person as one who understands "what technology is, how it is created, how it shapes society," and how society shapes technology. According to Loveland and Love, "technological literacy is not a characteristic of an individual, but a characteristic of how one experiences and acts in relation to situations and technological processes" (2017, p. 14). A technologically literate person must be able to consider the "nature, behavior, power, and consequences of technology" and use his or her knowledge to make decisions about technology

(Ward, 2015, p. 18). When it comes to technology, “there are very few other things that influence our everyday existence more and about which citizens know less” (Bybee, 2010, p. 30). In other words, technology is a major part of modern society, but citizens rarely understand all of the consequences and implications the use of technology involves.

Without the essential understanding of the technology they use every day, students will never be able to comprehend how much technology affects their lives and the lives of those around them. As a result, it is important to educate students about the use and effects of technology so they can make “informed and responsible decisions” regarding the technology available to society (Strimel, 2014b, p. 16). Technological literacy is such an important set of skills that the ITEEA created an educational framework for developing these skills called *Standards for Technological Literacy* (Loveland & Love, 2017). Since technology is a prominent factor in the modern world, it is of the utmost importance that students are able to use and understand the technology available to them. Without these skills and understandings, students will quickly fall behind in the rapidly changing world.

A Closer Look at TEE and STEM

The ITEEA defines integrative STEM as “the application of technological/engineering design based pedagogical approaches to intentionally teach content and practices of science and mathematics education through the content and practices of technology/engineering education” (ITEEA). This definition indicates that STEM and TEE are inter-dependent on each other. With such a close relationship, it is not a surprise that TEE and STEM are very similar. Both utilize hands on, problem-based activities to facilitate learning. This student-centered strategy is unique because many teachers continue to use teacher-centered approaches to meet the demands of high stakes testing. In addition, both TEE and STEM offer avenues for content integration. Like STEM, TEE often integrates technological concepts with other content areas like science, math, engineering, reading, and writing into a single cohesive lesson. This is why TEE is often looked to as an example of STEM implementation.

However, when considering TEE and STEM, it is important to realize that they are not identical. The purpose of TEE is to increase technological literacy so students are able to make informed decisions in a technology driven world (Loveland & Love, 2017). The purpose of STEM education, however, is to create connections between various content areas. TEE is an established content area, while STEM functions as a teaching method. TEE has its own content, follows standards and curriculum, and uses teaching methods like STEM integration to increase technological literacy. STEM education, on the other hand, is a “comprehensive and interdisciplinary teaching and learning approach” (Capraro & Han, 2014, p. xv). There is not a set curriculum or standards that STEM follows because it is a pedagogical practice, not a content area. However, classroom teachers of any content area can implement STEM to meet their content’s standards and create an enriched learning environment.

Although there are slight differences between STEM and TEE, both are excellent programs that cultivate 21st century skills. By participating in TEE or STEM activities, students have the opportunities to develop and grow their critical thinking, problem solving, creativity, collaboration, and communication skills. As a result, student who participate in PBL through TEE or STEM programs are better prepared for success in the future.

How TEE, STEM, and PBL Promote 21st Century Skills

Although STEM and TEE both use PBL (which has been proven to increase 21st century skills), it is not always easy to discern how TEE and STEM influence student development in these areas. Participating in engineering activities – like those often seen in STEM and TEE classrooms – allows students to develop 21st century skills in a meaningful way through PBL. STEM education often focuses on combining science, technology, engineering, and math to solve real world problems. These authentic and problem-based STEM activities provide students with opportunities to think critically and creatively, collaborate with others, and communicate their results verbally or in writing (Partnership, 2015). In addition, engineering habits of mind are often incorporated in the TEE classroom through design projects. These habits of mind have "direct links" to 21st century skills like creativity, collaboration, and communication that engineers use on a daily basis (Loveland & Dunn, 2014, p. 13). As a result, when students take part in well-developed TEE or STEM activities, they are able to work not only on their technological literacy and science, technology, engineering, and math abilities, but also on their 21st century skill sets. These skill sets are important for success in the changing world.

However, since TEE is not a core academic subject, it "has been overlooked as a tool for improving student achievement" (Kelley, 2012, p. 38). However, STEM and TEE are great resources to instill numerous 21st century skills in students. This is because STEM and TEE incorporate PBL and promote critical thinking and problem solving through hands-on, problem-based activities that allow students to use high order thinking skills (Partnership, 2015). These high order thinking skills include 21st century skills like creative and critical thinking, collaboration, communication, and problem solving.

Critical Thinking and Problem Solving

Critical thinking and problem solving are skills that involve analyzing and critiquing situations in order to make educated decisions. Both critical thinking and problem solving involve various habits of mind like persisting when tasks are difficult, managing impulsivity, thinking flexibly, applying past knowledge to new situations, taking responsible risks, and learning continuously (Costa & Kallick, 2007). These habits of mind can be developed and promoted by using the engineering design process, which is a common problem solving method used in many STEM and TEE classrooms. This process requires students to define a problem; brainstorm solutions; and build, test, and evaluate their solutions all while considering criteria and constraints of the problem. Through the engineering design process, students must analyze a problem, consider any criteria or constraints, and make decisions based on their observations and prior knowledge to come up with a suitable solution. These actions activate critical thinking and problem solving skills in addition to design thinking skills. Closely related to critical thinking and problem solving, Dym describes design thinking as a "broad spectrum of talents" that includes "various kinds of judgment, reflection, and experience[s]" (2006, p. 423). Once students become familiar with the engineering design process and develop their design thinking, critical thinking, and problem solving skills, they may begin to apply these skills to solve problems in their personal and professional lives (Rigler, 2017; Strimel, Grubbs, & Wells, 2017).

In addition, TEE uses PBL to increase technological literacy. This same approach is also crucial to developing critical thinking skills (Kelley, 2014). Therefore, while developing technological literacy, students are also learning to think critically about technology and solve problems that pertain to technology or technological processes. Through both STEM and TEE, students have multiple opportunities to gain critical thinking and problem solving skills that they can apply to any problem they encounter, not just the problems that are assigned during the school day.

Creativity

Not only does PBL require higher levels of critical thinking, but it also requires higher levels of creativity to solve the problem. Creativity, which involves creating new and unique ideas and products, is another skill that can be cultivated through exposure to PBL provided by TEE and STEM. Creativity is "developed, not taught" (Kelley, 2014, p. 19). Therefore, it is important for students to be given opportunities to work creatively so that they can develop their creative skills. Problem-based engineering design activities and lessons like those found in TEE and STEM are "ideal contexts" in which to foster creativity (Loveland & Dunn, 2014, p. 14). TEE and STEM provide creative opportunities when they "employ ill-defined design problems" (Kelley, 2014, p. 19). This is because these activities do not have a single best answer or one correct solution. When students are exposed to activities that do not have strict right or wrong answers, they are able to think of creative answers instead of searching for the single right answer.

In addition, STEAM – Science, Technology, Engineering, Art, and Math – is a new twist that places emphasis on creativity by including the arts. This focus on the arts (which are creative in nature to begin with) further encourages creative thinking by combining the creativity of art and music with the somewhat structured nature of science, technology, engineering, and math. Once students begin to think creatively, they will be able to carry that creativity to other aspects of their lives.

Collaboration and Communication

While STEM and TEE activities help to develop critical thinking, problem solving, and creativity, these activities also develop collaboration and communication skills. These skills are essential for working with others and effectively sharing ideas. Since STEM and TEE activities usually require or encourage group work, students encounter numerous situations in which they can develop collaboration and communication skills.

Although students often feel that working in groups is more challenging than working individually, it is important that students develop good team working skills that enable them to work efficiently and effectively with others (Morrison et al., 2015). A 21st century learner is one who is capable of learning independently, yet is also able to work well in groups (Prettyman et al., 2012). As a result, it is important for students to have opportunities to bring their individual skills and knowledge to a group setting and share those skills to accomplish a common group goal.

When technology teachers group students to work in teams, this gives students the opportunity to share their individual talents in addition to enabling students to develop "competencies in intrapersonal skills" (Loveland & Dunn, 2014, p. 15). These intrapersonal skills like communication and collaboration enable students to work not only with others similar to themselves, but also with others who differ in some way.

Working in groups can also promote collaboration that is effective and respectful. Through teamwork, students work together to combine their ideas into a final team solution. In doing so, they are also developing communication skills. When working in groups, students must clearly explain their thoughts to each other in order to complete the activity. In addition, problem-based activities like those common in STEM and TEE encourage students to present their findings to others during class presentations or class conferences. Since students collaborate and communicate so much through TEE and STEM activities, they are able to become comfortable working with others and presenting their ideas. These traits of comfortably collaborating and communicating will follow students throughout the rest of their personal and professional lives and benefit them in the global workplace.

Not only does participation in group work enhance communication and collaboration skills, but it also promotes better understanding of academic content. Sometimes the way a teacher phrases concepts can be confusing to students. Students who work in groups are able to ask their peers questions about the material and have it explained in another way that makes more sense. In addition, students who tutor or aid their groupmates reinforce the concepts they already know by teaching them to their peers. Through the peer tutoring and mentoring that occurs naturally in group work, students can develop a better understanding of the content and form better relationships teammates. As a result, students are better able to solve conflicts within the group and show more respect to each other, both of which are skills needed in the workplace (Loveland & Dunn, 2014).

Communication is recognized as such an important 21st century skill that educational curricula have been developed to make sure communication skills are taught in schools. As a result, communication – especially communication through text – is enhanced through literacy requirements of the Common Core State Standards (CCSS). These standards focus on improving "critical-thinking, reading, writing, speaking, and listening skills" (Loveland, 2014, p. 8). One of the focuses of the CCSS applicable to PBL is to improve comprehension of technical and informational texts (Loveland, 2014). These texts are often rich in information, but due to technical wording, students often have difficulties understanding the text. Since "reading is enhanced when there is a purpose of gaining information or verifying existing knowledge in order to complete in-class assignments," STEM and TEE activities are opportunities to enhance student reading skills like comprehension (Loveland, 2014, p. 10). Therefore, reading skills can be enhanced and developed through hands on activities found naturally in TEE and STEM education. Such activities are often accompanied by design briefs, which can include extensive, detailed, or technical directions (Loveland, 2014). By reading and breaking down the information and instructions found in design briefs, students are developing their comprehension and written communication skills.

Specialized Classrooms for PBL Environments

Since it can be agreed that 21st century skills are necessary for success in the modern world and PBL is especially suited for equipping students with a multitude of 21st century skills, it would be easy to assume that schools incorporate areas and classrooms appropriate for PBL. However, it is not always the case that teaching and learning environments are arranged in ways conducive for PBL even though TEE and STEM already employ PBL. The reason for this discrepancy between educational expectations and classroom design is a result of the history of education in America.

The educational framework many modern schools employ has been around since the late 1800's. This framework "reflected the factory model" so that schools would prepare students for the industries and economy of that period (Vega & Brown, 2013, p. 6).

> America had developed into an industrial and technological giant. Factories covered the landscape. … It was a manufacturing economy that was reflected in all parts of society. Even the process of education was modeled on the factory. Classes changed on the sound of a bell. Each student tended to his or her own studies. The teacher was the center of focus. (Childress, 2017)

As a result, classrooms were arranged with rows of desks and operated on a bell schedule to reflect a factory environment. What is more, by promoting the factory style framework, students were "not expected to learn at high levels," but play a role of "compliance and obedience". Although factories and industry have less influence on society today and other factors like creativity and ingenuity are valued instead of rote memorization, many schools still employ the factory framework of teaching and learning. However, the attitudes set by the factory model can "[hinder] the educational experience and development of students" (Vega & Brown, 2013, p. 6).

In addition, methods of instruction from the 19th and 20th centuries, such as chalkboard lectures, are now considered to be "insufficient for representing 21st century understandings and intellectual/psychosocial performances" (Prettyman et al., 2012, p. 7). Due to changes in TEE and with the new focus on STEM, many TEE facilities have become outdated and "ill-equipped to accommodate" new standards in TEE (Daugherty, Klenke, & Neden, 2008, p. 19). These outdated facilities can have negative impacts on the way teachers are able to deliver instruction and can even "influence student and public perceptions of the [TEE or STEM] program" (Daugherty et al., 2008, p. 20). If students are expected to master 21st century skills like critical thinking, problem solving, creativity, collaboration, and communication, they need classrooms that are adapted to teach those skills (Martin, 2015). Since there is such a strong connection between learning 21st century skills and PBL, modern classrooms should be equipped to provide a PBL environment. Therefore, in order for students to get the most out of their education and develop the skills they need, up to date facilities designed to accommodate PBL are of the utmost importance.

Several characteristics separate 21st century PBL classrooms from factory style classrooms of the past. Over the past decades, the K-12 environment has been changing to accommodate the new skills needed for the modern age. There has been a shift from "mastery of declarative subject knowledge" to a "focus on literacy" (Crippen & Archambault, 2012, p. 157). As a result, teachers act as facilitators in PBL environments, encouraging critical thinking in their students (Partnership, 2015). In other words, the role of teachers is not to lecture. Instead, teachers "[guide] the construction of knowledge" as students go through creative and problem solving processes (Schnittka, Brandt, & Evans, 2012, p. 10). As a result, students become less reliant on teachers as they explore new information and become more self-directed.

In addition to a shift in teacher roles, 21st century PBL classrooms also include computers and other technologies that are accessible for student research and technology skills development as well as to help teachers enrich and their lessons (Martin, 2015). Since today's society is dominated by computer technology, it is important that students have experience using computers and the Internet and they understand how to reap all the benefits these resources have to offer. If schools do not take advantage of available technologies in their classrooms they "cannot hope to meet the demands of a globalized, knowledge based society" (Crippen & Archambault, 2012, p. 158)

The final characteristic of a 21st century PBL classroom is active learning. Active learning is the process of having students that are engaged in their own learning – the students are active participants in their education and not just passive bystanders. If content is taught in a "contextual or applied manner," learning experiences become more "meaningful" to students (Gomez & Albrecht, 2014, p. 15). When educational experiences become more meaningful, students are more likely to become active participants in their own learning. Students who participate in active learning take interest in their education and become more likely to retain the knowledge and skills they gain through PBL (Morrison et al., 2015). All these classroom characteristics – teachers as facilitators instead of lecturers, access to computers, and active learning – have one goal in mind: create environments that foster 21st century skills and provide opportunities for PBL.

STEM and TEE classrooms take the 21st century PBL classroom a step further by creating environments designed exclusively to support PBL. These classrooms have the space and resources students need to think critically and creatively, collaborate with each other, and communicate their ideas and findings. Therefore, STEM and TEE classrooms should not look like the typical classrooms that consist of rows of desks. Instead, STEM and TEE classrooms are designed to "blur the boundaries between formal and informal, individual and group" (Daugherty et al., 2008, p. 24). As a result, well designed STEM and TEE classrooms should have separate areas for presentations, collaborative group work, research, fabrication, and testing (Daugherty et al., 2008). The goal is to create flexible learning spaces that will help to facilitate learning through student collaboration and innovation (Martin, 2015). Common trends found in up to date STEM and TEE classrooms include access to digital tools like computers, 3D printers, and laser engravers; mobile tables that can be moved to suit either individual or group work; and separate areas for lab and lecture (Martin, 2015; Daugherty et al., 2008). All these trends and characteristics help to create classrooms that have the space and resources necessary for hands on group work that will promote 21st century skills through PBL.

Many specialized STEM environments and TEE classrooms have already been created with these characteristics and trends in mind. One example of STEM education that utilizes a specialized space is Studio STEM. In this program the studio or classroom is used for "tinkering and experimenting" while learning engineering and science concepts in a "supportive environment" (Schnittka et al., 2012, p. 25). In an environment that provides "mental and physical spaces," students are able to develop "deeper understanding of content" and are overall more successful and motivated to complete engineering and science tasks (Schnittka et al. 2012, p. 3).

Other creative learning environments, such as STEM Labs, Makerspaces and Tinkering Studios, are also being integrated in schools. These educational areas provide the tools and space for people of all ages to build, tinker, explore ideas, fail and retry, and collaborate on projects of interest. In essence, STEM Labs, Makerspaces, and Tinkering Studios provide an environment where students can explore and experiment. These special learning and working environments are designed with hands on activities in mind, incorporating areas where students can work collaboratively on projects. However, the way these specialized classrooms are implemented can vary from school to school. Some STEM programs use their classrooms for afterschool clubs or extracurricular activities, while others integrate the use of the classroom into the curriculum as part of the school day (Martin, 2015).

No matter how dedicated classrooms like Studio STEM, STEM Labs, Tinkering Studios, or Makerspaces are used, they all have a common goal to provide students with an environment in which they can work on collaborative, hands-on, problem-based activities. These specialized learning environments provide the room, materials, and resources students need in order to work together effectively, solve problems creatively, and take ownership of their learning. By doing so, these classrooms provide students with authentic opportunities to develop 21st century skills like critical thinking, problem solving, creativity, collaboration, and communication. Therefore, as the drive for teaching 21st skills continues to increase, the need for specialized classrooms like STEM Labs, Tinkering Studios, and Makerspaces to house PBL is going to increase also. Not only are these environments essential in teaching STEM skills and technological literacy, but they are opening doors to the skills of the 21st century as well.

Conclusions

It is recognized that having a well-developed 21st century skills-set is the key to success in a technology driven, global society. However, due to teacher-centered methods, not all students have mastered these essential skills. With the help of PBL, STEM, and TEE, more students are being given opportunities to develop 21st century skills like technological literacy, critical thinking, problem solving, creativity, collaboration, and communication. By providing opportunities for authentic learning activities and content integration, PBL, STEM, and TEE are preparing students to survive and thrive in a technologically driven world. Although the benefits of PBL, STEM, and TEE are easily observed, classrooms that support these methods and programs can be hard to come by because of the prevalence of out dated facilities and teaching methods. If our students are expected to gain the skills they need through PBL, STEM, and TEE, classrooms need to be designed with hands on activities in mind. The only way students will be able to keep up with the changes in our technology driven world is if they are provided with the tools, materials, and environments (like those suited for PBL, STEM, and TEE) necessary to develop 21st century skills.

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