

February 2019

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Hite, Rebecca and Thompson, Christopher J. (2019) "Activity Theory as Theoretical Framework for Analyzing and Designing Global K-12 Collaborations in Engineering: A Case Study of a Thai-U.S. Elementary Engineering Project," *Journal of International Engineering Education*: Vol. 1: Iss. 1, Article 5.

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PRACTICE

Activity Theory as Theoretical Framework for Analyzing and Designing Global K-12 Collaborations in Engineering: A Case Study of a Thai-U.S. Elementary Engineering Project

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Introduction

Global competency is essential for U.S. engineers who now compete in an international market for engineering know-how. No longer is cultural sensitivity needed only for product design destined for diverse markets. Increasingly, successful entry into the engineering profession requires significant intercultural skills in order to join efficient and *productive collaborations with diverse engineering colleagues* [emphasis added]. (Allert, Atkinson, Groll, & Hirleman, 2007, p. 1)

With the recent boom in economical telecommunication technologies, K-12 classrooms have new avenues of access to students not only across the country, but also across the globe. This time-space compression has ushered in a new era of globalization, connecting people, cultures, and commerce (Harvey, 1989). The American education system has viewed this as both a crisis and opportunity, addressing fears of diminished economic competitiveness and potential threats to national security through a renewed effort to build global competencies for a diverse society. The United States Department of Education has called for students to “increase global competencies, learn from other countries, and engage in education diplomacy” (2012, p. 4).

The impetus for improved global competencies is particularly strong in the realm of Science, Technology, Engineering and Mathematics (STEM) and STEM education (Bybee, 2010), especially in engineering (Allert et al., 2007). Engineering is a fruitful STEM field, with higher earnings than comparable workers, lower unemployment, and experiencing steady growth both domestically and worldwide (NSF, 2016). American experts and leaders in engineering call for a future engineering workforce that encapsulate creativity and collaboration, two of many skills categorized as 21st century skills (National Academy of Engineering and National Research Council, [NAE/NRC], 2009). According to Plonka, Ahmed, and Carnahan (2001), in engineering, “collaboration and interactions do not happen by accident. They require a common vocabulary and language along with explicit planning and management” (p.173). Therefore, the most prized skills for future engineers are in collaboration (NAE/NRC, 2009), and more specifically in global collaboration (Blumenthal & Grothus, 2008; Chubin, May, & Babco, 2005; Gerhardt, Blumenthal, & Spodek, 2002). Development of

global competencies and collaboration may help broaden participation in engineering to a larger and more diverse audience. Therefore, cultivating globally competent citizens is not only about economic benefits, but also an ethical and moral mission to enhance avenues for much needed equity within engineering fields (Franzway, Sharp, Mills, & Gill, 2009).

To address this growing need from the field, school districts and K-12 classroom teachers are asked to embark on collaboration projects in engineering with a global focus (NAE/NRC, 2009, p. 161). A great many of these collaborations focus on 21st century skill development (P21, 2019; Griffin, McGaw, & Care, 2012), that include a variety of skills including, critical thinking, problem solving, creativity, communication, and collaboration (Dede 2010; Saavedra, & Opfer, 2012). Yet studies exploring the efficacy of global projects in K-12 STEM education, have reported mixed results (Gibson, Watters, Alagic, Rogers, & Haack, 2003; Lock & Redmond, 2006; Neal, Mullins, Reynolds, & Angle, 2013). Nascent practitioner-focused articles have been published to describe the type of interaction that occurs among students in global STEM collaborations (Nugent, Smith, Cook, & Bell, 2015). Coupling this early work with established theory may help to define these experiences by identifying key areas that aid in the success of and pitfalls within these unique collaborations. Activity theory (AT), pioneered by Lev Vygotsky and Alexei Leontyev (1981), is a theoretical model that describes the complexity of human activity (in this case, student learning within a global K-12 engineering collaboration) replete with inbuilt rhetoric regarding the complex schooling (social) environment including actors, culture, rules, products, artifacts, etc., such to report and analyze the activity or phenomenon (Engeström, Miettinen, & Punamäki, 1999).

This paper illuminates how activity theory may be used as a framework for identifying the many factors that comprise global K-12 engineering collaborations. The impetus for this work is to construct a coherent picture of this complex activity such to improve the facilitation of similar collaborative STEM-based activities. Elementary students are of particular interest; previous research by Tank, Moore, Babajide, and Rynearson (2015) found when examining elementary students engaging in engineering activity that:

The professional skills of engineering such as the engineering habits of mind, teamwork, and communication are also important aspects of integrated STEM learning environments. Here we saw students using iterative thinking, making decisions based on evidence, learning from failure, learning to work in teams, and communicating in drawings and oral presentations. These aspects of engineering need to be highlighted at the elementary level. (p. 18)

Furthermore, Brophy, Klein, Portsmore, and Rogers (2008) have stated “that children are natural engineers/technologists who can pursue a goal that meets constraints defined by others and their own personal interests” (p. 374). These “judgements and opinions” play well into the nature of “ill-structured workplace [engineering] problems,” (Jonassen, 1997; Jonassen, Strobel, & Lee, 2006, p. 139). With no linear path to a single solution, (engineering) design principles and collaborative techniques may facilitate

student understanding and skill growth. Specifically, global collaboration may permit students from different backgrounds offer different perspectives which may be undervalued in a Western or non-American context. These selected articles indicate that a closer examination of 21st century skill development is warranted at this age/grade level.

The activity theory synthesis presented in this paper is based upon a single case of a global K-12 engineering collaboration called Edible Lunar Vehicles (ELV) by Davey, Smith, and Merrill (2009) as it was implemented in a Thai elementary school science/engineering classroom in 2016. This case was included to help bolster and contextualize activity to a specific, activity-driven context, with a focus specifically on engineering content and practices, allows for a comprehensive understanding of activity theory in a contemporary, global classroom setting.

By categorizing a global K-12 collaboration in engineering to learning activity situated within their larger sociocultural context, we may begin to conceptualize how these collaborations take form and how participants in the classroom activity met challenges and persevered to a collaborative solution. This is particularly important to education researchers and practitioners alike to determine how global collaborations provide K-12 students opportunities to build non-cognitive (21st century) skills and core STEM (engineering) competencies. Since the learning activity in a global K-12 engineering collaboration is situated within a complex sociocultural context, activity theory will be used to analyze participant interactions in a specific social activity (the US/Thai ELV project collaboration). This information should continue the conversation on how to study, create, and implement future global K-12 engineering collaborations in classrooms worldwide; to ensure the students' success in the products of their international collaborative activity: namely garnering non-cognitive 21st century skills and learning engineering content and design.

Theoretical and Conceptual Background

21st Century Skills

Efforts to identify and describe so-called “21st century skills” have been ongoing and have produced nearly as many definitions as there are participants in the conversation (e.g., see Dede, 2010). One of most authoritative descriptions of 21st century skills has been produced by the *Partnership for 21st Century Learning* (P21, 2019) formerly known as the *Partnership for 21st Century Skills*. Established in 2002 between education leaders, the business community, and policymakers, a major outcome of this collaboration was the creation of a *Framework for 21st Century Skills* (Greenhill, 2010); that is also related to the *Assessment of Teaching of 21st Century Skills* (ATC21S, 2012), a consortium that includes both Australia and the United States. The Framework for 21st Century Skills put forward by ATC21S is similar to *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* put forward by the National Research Council (2012). It includes skills such as the 4Cs critical thinking, creativity, communication, and collaboration (NEA, n.d.), as well as cultural awareness (P21, 2015). More specifically, the Framework for 21st Century Skills (hereby referred to as the *P21 Framework*) divides 21st century skills into four main categories, Core

Subjects and 21st Century Themes, Learning and Innovation Skills, Information, Media and Technology Skills, and Life and Career Skills.

P21 Framework and Global K-12 Collaboration

An engineering project, like the ELV project by Davey et al. (2009), includes elements of global collaboration uniquely suited to students' development of many 21st century skills delineated in the P21 Framework (2015). Figure 1 summarizes the P21 skills aligned specifically to a K-12 global collaboration engineering project, and each theme will be discussed as it relates to global K-12 engineering projects.

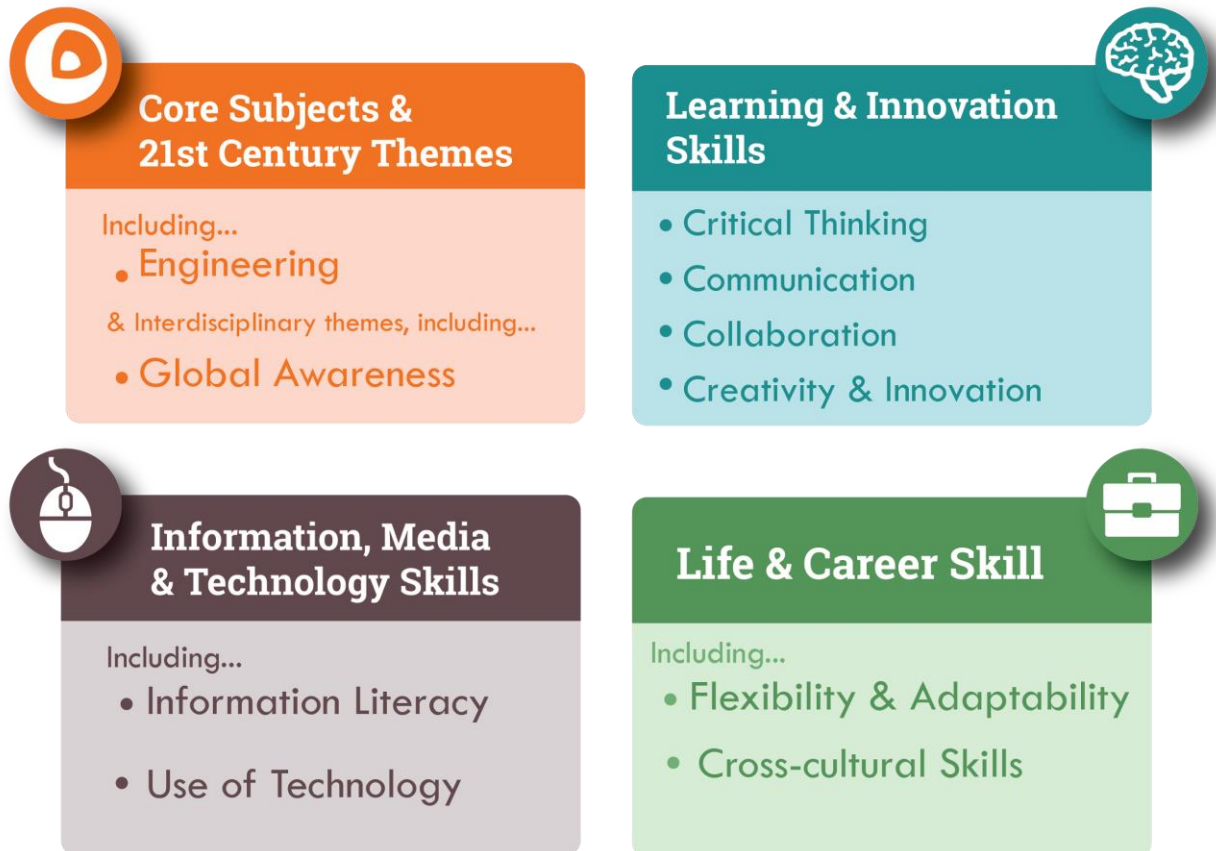


Figure 1. The 21st century skills in a global K-12 collaboration in engineering (Thompson, 2018a, adapted from P21, 2015).

Core Subjects and 21st Century Themes. Most teachers who develop classroom projects begin with an attempt to cover the core subject; this is a common dilemma for K-12 teachers who feel pressured to cover content first for high stakes testing (Au, 2007; Olson, 1981). Yet, Bowles and Gintis (1976) argue that school activities that never venture beyond the scope of core subject matter, and fail to provide critical non-cognitive skill growth, have detrimental effects on students' future school and career outcomes. Global K-12 collaboration projects, such as the ELV project, have the distinct advantage of not only covering core subject matter in a hands-on manner that is engaging for students learning engineering (Douglas, Iversen, & Kalyandurg, 2004), but also incorporating interdisciplinary aspects including critical thinking and problem-

solving skills (Bell, 2010). For example, students involved in the ELV project study explored aspects of lunar conditions and space travel and are challenged to solve a myriad of engineering problems, used mathematics in real-world applications, and also worked on language arts skills necessary to communicate effectively with their peers across the world.

Learning and Innovation Skills. Of the four categories of 21st century skills (see Figure 1), global K-12 engineering projects may be most effective in addressing four learning and innovation skills. These “4Cs” are defined by the National Education Association (NEA, n.d., p. 7) as critical thinking, communication, collaboration, creativity and innovation. First, critical thinking is an essential element of any engineering process, starting with a clear understanding of the problem to be solved as well as the constraints imposed by the materials and the task. This skill is important for engineering students to examine their initial and inevitable failures, and to determine possible improvements and workarounds (Woods, Felder, Rugarcia, & Stice, 2000). Next, students often work in teams in engineering design projects, hence collaboration skills are necessary throughout (Smith, 1995). Hoegl and Parboteeah (2007) found in their study that collaboration (teamwork) had a positive impact on engineering knowledge and team efficiency. Because students participating in global collaborations must cross cultural and linguistic boundaries, and are often forced to work asynchronously, communication skills are vital (Riemer, 2002). More important, though, is the fact that these communication skills are not practiced in isolation, but rather are applied to achieve a tangible and motivating goal. Lastly, although students’ products often must meet certain criteria or standards to reflect the constraints on engineering design (Chan, Scott, & Lam, 2002), engineering problems have a near infinite number of possible solutions promoting creativity (Cropley, 2016; Richard, 1989). Studies have shown creativity to be a unitary trait among professional engineers (Datta, 1964; McDermid, 1965) and a critical skill to cultivate in engineering education (Cropley & Cropley, 2000; Felder, 1988; Liu & Schonwetter, 2004; Stouffer, Russell, & Oliva, 2004; Zhou, Kolmos, & Nielsen, 2012). Collaborative engineering projects may be crucial in developing students’ creativity (Badran, 2007; Blicblau, & Steiner, 1998).

Information, Media and Technology (ICT) Skills. Per Ring and Van de Ven’s (1994) *Framework for Collaboration*, there are three required elements for collaboration to take place, mutual negotiation of communication norms; careful execution (implementation) of communication; and a continuous commitment among groups to continue their interaction. Managing this critical and ongoing communication across the globe necessitates the use of a variety of modern telecommunication technologies (Binder, 2016). Students collaborating with partners in other countries often have to handle multiple streams of information through multiple channels, dealing with email, online bulletin boards, teleconferencing applications, and media servers. Comprehensively, these tools can be categorized as information and communication technologies or ICT (P21, 2015). According to the International ICT literacy panel, information or ICT literacy can be ascribed as “the mastery of technical [technology-based] skills...includ[ing] both critical cognitive skills as well as the application of technical skills and knowledge. These cognitive skills include general literacy, such as reading and numeracy, as well as critical thinking and problem solving” (ETS, 2002, p.

1). Professional organizations including the International Society for Technology in Education (ISTE, 2007), Partnership for 21st Century Learning, (P21, 2019), and the Organisation for Economic Co-Operation and Development (OECD, 2006), have agreed that ICT skills are a part of the vital 21st century skills students need for academic, college, career, and global readiness. A study by Shachaf (2008) of global companies found ICT-based interventions mitigated negative impacts on intercultural communication while supporting positive decision making. Students who participated in global K-12 collaborations, like the case studied by Neal et al. (2013), perceived the project to be worthwhile and gained confidence in ICT skills. This research suggests that not only can global K-12 collaborations improve intercultural communication skills of students, but also that those collaborations (that rely on ICT) provide the additional benefit of developing technological proficiency.

Life and Career Skills. According to the P21 Framework, Life and Career skills include flexibility, adaptability, initiative, self-direction, productivity, and accountability, as well as social and cross-cultural skills (P21, 2015). Global K-12 collaborations can build many of these skills by virtue of its nature. First, these projects are uniquely challenging because they bring together different cultures, classrooms, and school systems, coupled with the unreliable nature of school-based technology, often creating unanticipated problems; flexibility and adaptability are necessary to continue the three metrics of collaboration (Ring & Van de Ven, 1994). With a collaborative focus towards a unitary, group-sourced product, self-direction, accountability and productivity are vital to seeing the project to a successful fruition. Lastly, social and cross-cultural skills are an integral part of any collaboration between students in a peer to peer global collaboration. Without respect for social and group norms, especially acknowledgement of cultural differences, K-12 communication and collaboration is not likely to be successful (Kim & Bonk, 2002). However, some research suggests that technology can mitigate cultural clashes as “these differences are less pronounced online than they are in face-to-face interactions” (Ardichvili, Maurer, Li, Wentling, & Stuedemann, 2006, p.104).

Activity Theory

Activity theory is a well-established and studied theoretical framework (Engeström, Miettinen, & Punamäki, 1999), grounded in a century of work by both German philosophers and Russian psychologists including Vygotsky (1978) and Leontyev (1981). Often represented graphically as interconnected triangles (Engeström, 1987), as seen in Figure 3 below, each vertex represents an element of human activity. It was originally comprised only of the first central triangle, representing the stimulus and response reactions between a subject (individual), object (goal of the activity), and the tools or mediating artifacts the subject uses to achieve the object (Vygotsky, 1978). Leontyev (1981) expounded on this model by differentiating individuals’ actions from a larger, situated collective activity, extolling the importance of social influences on individual activity. Refined and represented graphically as interconnected triangles demonstrating the influences of both social and community influences (Engeström, 1987), this model can account for a collection of interconnected human interactions, known as the activity system (Cole & Engeström, 1993).

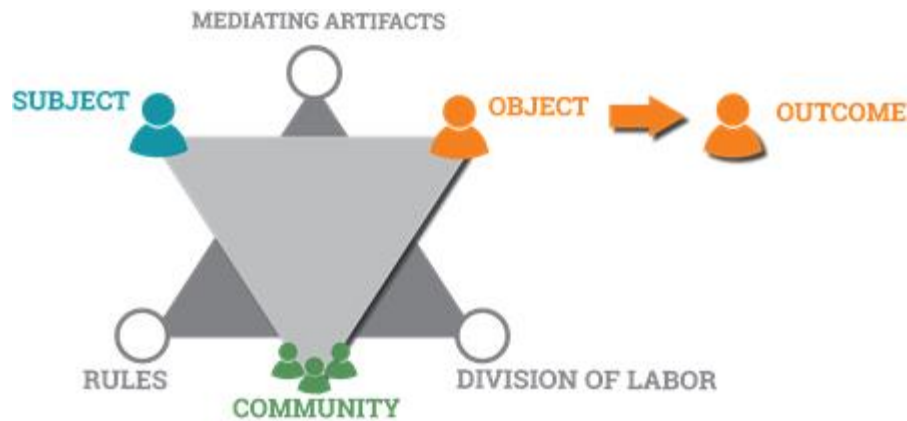


Figure 2. The activity system model
(Thompson, 2018b, adapted from Engeström, 1987).

According to Engeström et al. (1999), “today activity theory is transcending its own origins: It is becoming truly international and multidisciplinary” (p. 20). Activity theory provides the structure and language to discuss group collaboration (Bryant et al., 2002), concurrent with constructivist thinking of how individuals co-construct learning in a social context through active processes (Vygotsky, 1978). Activity theory has been used to describe human activity in a variety of contexts including human-computer interactions (Kuutti, 1996), design (Fjeld et al., 2002), health care (Engeström, 2000; 2001), and education (Jonassen & Rohrer-Murphy, 1999; Lim & Hang, 2003; Roth, 2004). De Graaff and Ravesteijn (2001) have identified communication and social skills as one of the four core competencies of engineers, therefore activity theory can capture how social experiences build these critical interpersonal skills.

Activity Theory and Global K-12 Collaboration

At present, the published cases of global K-12 collaborations have reported mixed results. Examining the literature through the lens of activity theory, certain areas of the activity system (subject, object and instruments) have received greater focus, whereas community and outcomes remain unclear in the efficacy of global K-12 collaborations in engineering. The following paragraphs outline the relationships between the research literature on global K-12 collaborations in engineering and activity theory, identifying areas of success and challenges, where activity theory may help to illuminate the differential effectiveness of these collaborations.

Of the reviewed literature, they suggest the *subject*, or teachers within the activity system as the most significant feature (activity) of global K-12 collaborations. First, studies found that global collaborations required a great deal of scaffolding for teachers (Lock & Redmond, 2006), as working on real-world problems in engineering can be complex and unpredictable (Daniels, 2010). This can be confounded by different interpretations of the subject’s role. For example, a study by Cifuentes and Shih (2001) found asymmetry in the beliefs on the role of the teacher in a U.S. and Taiwan global collaboration. In Eastern cultures, the teacher is considered as imparter of knowledge, so when the teacher behaves differently, say as a facilitator of knowledge seen in Western problem-based teaching (Hmelo-Silver & Barrows, 2006) common in

engineering education (De Graaff, & Kolmos, 2007; Lehmann et al., 2008), Eastern participants become frustrated and discouraged (Shih & Cifuentes, 2003).

In the *object* vertex, which reflects the nature of students in the activity system, one study of global collaborations in engineering by Daniels, Cajander, Pears, and Clear (2010) reported that undergraduate students needed an appreciation of the project purpose and to understand the added value of a global collaboration. Otherwise, “a common complaint... [was] that the students seldom saw their own role in problematic issues and especially in cases where they viewed the international collaboration as a burden” (p. 6).

Instruments and mediating artifacts play a role in the global K-12 collaboration activity system as technology is instrumental for global communication across time and space. Although ICT is necessary for global K-12 collaboration, a meta-analysis by Buabeng-Andoh in 2012 found American teachers lack not only confidence, skills and training in ICT but also access, suitable software, and the academic freedom to use ICT in their teaching practices. Other studies have had similar findings regarding ICT implementation in Australia (Jamieson-Proctor, Burnett, Finger, & Watson, 2006), Asia (Heo & Kang, 2009), and Europe (Pelgrum, 2009). Without proper access, understanding, and use of ICT in either of K-12 classrooms, the ability to provide a proper collaboration space (Ring & Van de Ven, 1994) significantly abates the efficacy of these efforts.

Yet, there is a dearth of understanding regarding the *rules* in global collaborations. Successful collaborations have often been between countries that share a common language and (western) culture, like the United States and Australia (Gibson et al., 2003; Neal et al., 2013) or Canada and Australia (Lock & Redmond, 2006). Even when English is used as a *lingua franca*, a study by Neeley, Hinds, and Cramton (2009) found that organizational policies governing communication between non-native and native English speakers caused the disruption in global collaboration. A study by Shih and Cifuentes (2003) found that cultural asymmetries in not only written expression (in English) but also in thinking patterns facilitated miscommunication between students in the U.S. and the (non-western) Taiwanese context. They suggest that language is not the sole barrier in rules within global collaborations, but also the diverse expectations of schooling (e.g. between teachers and students) and cultural norms (e.g. directness of feedback, excessive thanking by Eastern students) of dissimilar cultures.

There are possible issues within the *community* and *division of labor* vertices in the activity system for K-12 global collaborations. Ethnocentrism, due to cultural isolation or separation, may play a role in the differential success or lack of global collaborations (Mortensen & Neeley, 2012). Ethnocentrism is defined as an epistemological view that one’s own culture is central to all reality (Bennett, 1993). Studies have found educators who speak a second language or have studied abroad tend to hold less ethnocentric views (Olson & Kroeger, 2001). Studying abroad also helps engineering students (Groll, & Hirleman, 2007); in particular, a study by Jesiek, Haller, and Thompson (2014) found that the greatest gain in global competency occurs when students have multiple, in-depth exposures to different engineering cultures. Studying abroad is infeasible for K-12

students, yet electronic correspondence has been found to be fruitful in broadening multicultural awareness and developing content-based skills for K-12 students (Schoorman & Camarillo, 2000; Taras et al., 2013). Daniels et al. (2010) reported in their study that the undergraduate students felt there were not equally delineated and distributed responsibilities for the global engineering project, which produced negative effects including consternation and mistrust among participants. Furthermore, the everyday lives and experiences of elementary and secondary students from different cultural, racial, or ethnic backgrounds should be valued; K-12 Engineering education could learn a lot from the successes of global collaborations in engineering at the college level (see Gerhardt et al., 2002; Groll, & Hirleman, 2007; Jesiek et al., 2014).

Lastly, *outcomes* should be called into question within an activity system for K-12 global collaboration. The engineering community values global collaboration because of its ability to develop the interpersonal skills engineers need to be globally competitive (Abanteriba, 2006; Crawley et al., 2007), yet, research suggests there is little focus on the soft skill development derived from global collaborations in engineering (Daniels, 2010). Other additional positive externalities, including cultivating global awareness, learning adaptive skills, and building trust with foreign peers from global collaborative experiences, have not been fully explored (Mortensen & Beyene, 2009).

For education research, Jonassen and Rohrer-Murphy (1999) stated that activity theory “is a useful framework because the assumptions of activity theory are very consonant with those of constructivism, situated learning, distributed cognitions, case-based reasoning, social cognition, and everyday cognition that underlie [Constructivist Learning Environments] CLEs” (p. 62). In this same paper, the authors make a call to action to explore activity theory in context, with further exploration of the tools, rules, and symbolic systems that mediate group activity. Global collaborations in K-12 can provide a specific context to arrange human interactions among the vertices in Activity Theory to describe an activity system. Prior studies reported many limitations, contributing to the success or failure of global K-12 collaborations. Activity theory can help to explain how social artifacts (instruments, rules, division of labor) and social organizations (subjects, objects, communities) mediate actions (outcomes) (Bryant, Forte, & Bruckman, 2005; Kutti, 1996). This approach may provide a model to study and implement complex collaborative activities like global K-12 collaborations in engineering.

Methods

By exploring the utility of Activity Theory in various contexts, including education, the next step is to contextualize this model with an experience from a real world situation. By using a descriptive case study approach, the activity system is populated with a specific context, in order to explore its efficacy in describing the complex nature of global K-12 engineering collaborations. Data from multiple cases is more compelling than data collected from a single case (Herriott & Firestone, 1983), yet the intent was not for generalizability, rather the impetus for using a single instrumental case study approach was to be used for theoretical inference (Hesse-Biber, 2016). In this case, we wish to explore to what extent activity theory is compatible or models

(empirical) reality. This is defined by Walther, Sochacka, and Kellam (2013) as *pragmatic validation*, “fostering a deeper understanding of the social system under investigation rather than on the general application of theory to other contexts” (p.647). Leveraging concurrent validity by the methods utilized by Issroff and Scanlon (2002) in using a case study approach to explore activity theory in an educational setting, the authors present an elementary U.S. and Thai engineering collaboration case, a project of designing a lunar vehicle, diagrammed and analyzed using the lens of activity theory.

Intervention using Engineering Design Principles

“Engineering is a field that is critical to undertaking the world’s challenges” (National Research Council, 2013, p. 438). Engineering education endorses content-specific practices, like the Engineering Design Process (EDP), for students to use in engineering-based endeavors. The Next Generation Science Standards (NGSS) addresses this need, in the K-12 education sector, through intentional incorporation of engineering knowledge and skills standards to be taught throughout elementary, middle grades, and high school curricula. Nineteen US states and the District of Columbia have adopted the NGSS, begging the question of how K-12 teachers should plan and execute rich global collaborations in engineering among the remaining 31 US states (Bybee 2014; Hesse, Care, Buder, Sassenberg, & Griffin, 2015). For US states with or without adoption of NGSS, engineering knowledge and skills were found in 41 out of 50 US states either in their respective engineering, science, technology or vocational standards (Carr, Bennett & Strobel, 2012). Because of this shift, these authors suggested that “now is the time to move forward in the formation of a national pre-college engineering education agenda and a [movement for engineering] standards debate” (p. 561).

According to the National Academy of Engineering on Engineering in K-12 Education, teaching engineering to K-12 students improved their STEM content knowledge and information/technological literacy skills, helped them garner a better understanding of what engineers do, and encouraged them to pursue engineering careers (Katehi, Pearson, & Feder, 2009; NAE/NRC, 2009). K-12 opportunities to learn engineering have also been cited as instrumental in bolstering and diversifying the American engineering pipeline (Douglas, Iversen, & Kalyandurg, 2004; National Science Board, 2016; Schunn, 2009).

There are, of course, a number of engineering design processes that can be used in STEM education (see Hynes et al., 2011). In this case the EDP, used in the Engineering is Elementary (EiE) program, developed by the Museum of Science, Boston (2018), was chosen for its simplicity and appropriateness for the elementary classroom. To scaffold this iterative methodology for younger learners, Engineering is Elementary (EiE, 2018) has reduced the EDP to a 5-step process. The aspects of the EDP are found in Figure 2.

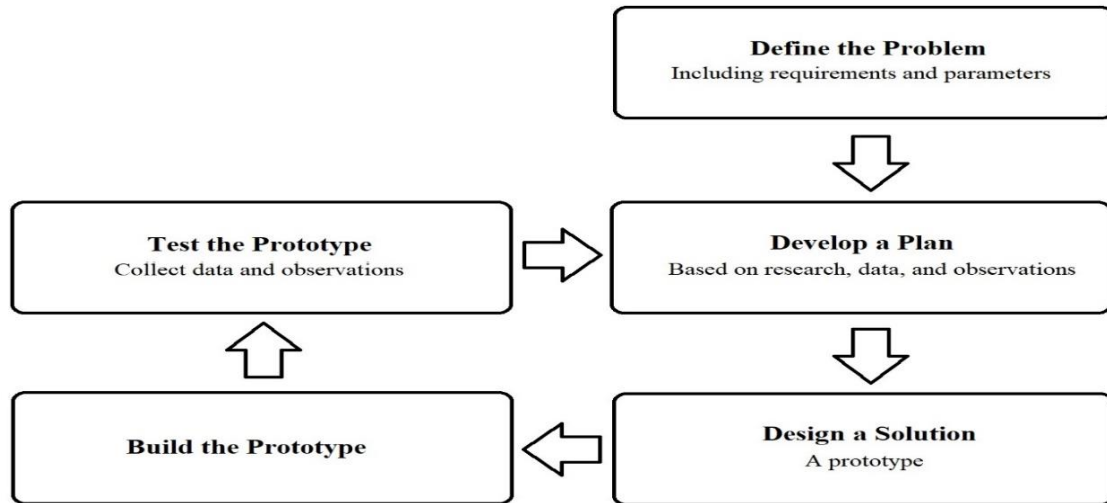


Figure 3. The engineering design process or EDP
(Thompson, 2018c, adapted from *Engineering is Elementary (EiE)*, 2018).

Engineering Education and Global K-12 Collaboration

Since the introduction of engineering education, the research literature has discouraged the use of direct instruction and advocated for more hands-on strategies, as it does not produce the creative and critical thinkers needed for engineering futures (Johnson, 1999). One particular pedagogical strategy that has been empirically proven to lead to success in students' mastering of engineering concepts has been project-based learning. Project-based learning engages students in working towards learning-appropriate goals while providing scaffolding, student agency or choice, and frequent opportunities for self-assessment (Barron et al., 1998). This pedagogy lends itself well to the design-based principles found in engineering practices and has been widely advocated for its specific use in engineering education (Dym, Agogino, Eris, Frey, & Leifer, 2005; Hadim & Esche 2002; Mills & Treagust, 2003).

Problem-based learning (in engineering education), refers to the introduction of abstract, core engineering concepts via problematized situations that relate to tangible, every day, or familiar circumstances and to the students' worldview (Smith, Sheppard, Johnson, & Johnson, 2005). Although project-based learning and problem-based learning are different pedagogies (Savery, 2015), elements and hybrids of these methods have been found to be successful in engineering education (De Graaff, & Kolmos, 2007; Lehmann, Christensen, Du, & Thrane, 2008). This modality of instruction can aid in the integration of STEM subjects and critical 21st century skill development (Roehrig, Moore, Wang & Park, 2012). More specifically, project-based pedagogies in global K-12 collaborations have been found successful in developing students' competencies in 21st century skills such as working collaboratively, using technology, effective communication, and problem solving (Bell, 2010).

The global aspect of engineering education is also important as future engineers not only need technical knowledge, but also global awareness regarding different work ethics and cultural environments (Abanteriba, 2006). Many scholars have advocated for

teaching the importance of global diversity (Burnouf, 2004), in STEM content areas (Clarke & Drudy, 2006). This is because global awareness is important for how the future global engineers communicate with one another (Riemer, 2002) and with clients and stakeholders (Damian, 2007). Therefore, “Today’s engineering graduates not only have to be work-ready, they have to be world-ready, that is, ready to work and ready to address global engineering issues of diverse peoples and environments” (Crawley, Malmqvist, Ostlund, & Brodeur, 2007, p. 29). The engineering education community has called for more international experiences for engineering students (Buisson & Jensen, 2008); Global K-12 collaborations can provide such experiences for students to develop both engineering and global competencies. Research suggests that teachers need professional development in engineering concepts (Custer & Daugherty, 2009), effective online collaboration (Neal et al., 2013), as well as in identifying and honoring cultural diversity (Lock & Redmond, 2006). Despite the need for increased training in these areas, research has shown that teachers who participated in global collaborations strengthened their self-efficacy in teaching science (Gibson et al., 2003).

The Global Collaboration Project

The global K-12 collaboration project in engineering utilized was the Edible Lunar Vehicle (ELV) project (Davey et al., 2009); a project appropriate to K-12 audiences that emphasizes engineering practices and P21 skill development in collaborative problem solving situations (Hesse et al., 2015). In its original inception, this project paired pre-service teachers in the United States with sixth grade students in Australia through online collaboration to design and build a vehicle that could navigate on the moon. However, this project allows itself to be implemented using a variety of formats for collaborative work as well as several different configurations of partners (students, teachers, experts, etc.) along a continuum of increasing interaction through communication (see Nugent et al., 2015). This project can be classified as one of the highest levels of global science education (*engaged collaboration*) where real time interaction occurred between the international partners (Nugent et al., 2015, p. 36).

The parameters of the project included three stipulations: the vehicle must roll down a 100 centimeter long ramp; travel at a minimum of 50 centimeters across the floor; and be constructed solely from edible materials. The last provision introduces several salient features to this engineering design project. First, it ensures that the materials needed are relatively inexpensive, familiar to students, and easy to obtain and manipulate. Most food elements can be readily broken by hand or even be cut with a plastic knife. Second, by limiting the materials to those that are edible, a unique design parameter is introduced, replicating restrictions or realistic constraints common to EDP (Haik et al., 2010). Other considerations for the design of the ELV, similar to lunar conditions, is that the materials must be strong, heat resistant, and lightweight. A positive potential outcome for using edible materials is a venue for students to learn about other cultures through a common, translatable, and important medium, food. Figure 4 is a drawing of a sample ELV project.

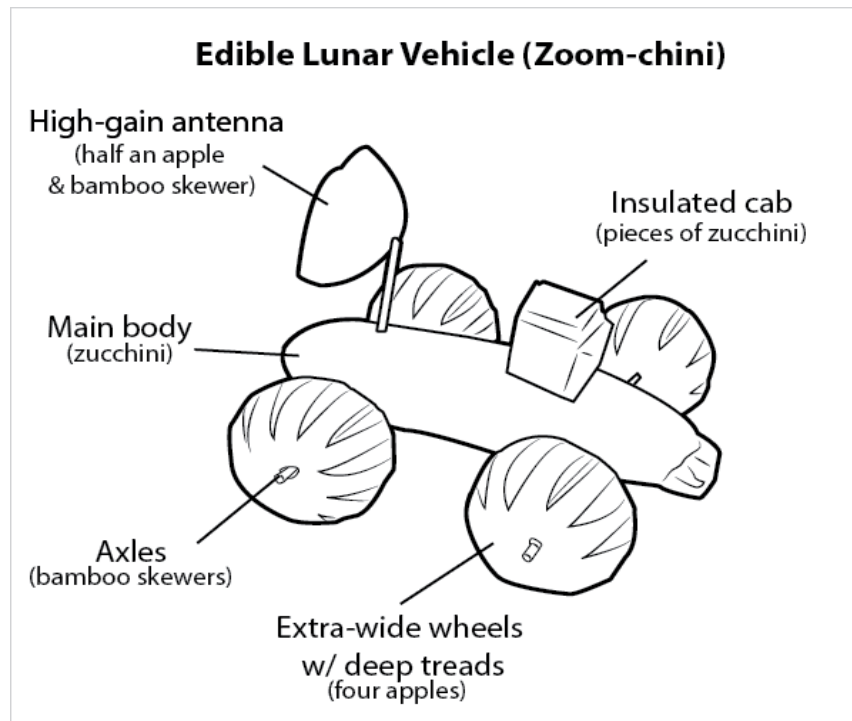


Figure 4. An example of an ELV
(Thompson, 2018d, based upon the design of the U.S. original lunar rover)

Site Selection and Participants

The site selected was an elementary school in Thailand. The global collaboration project was conducted in three 4th grade classrooms; each classroom consisted of approximately a dozen, for a total of nearly forty students, roughly half male and half female and approximately nine years of age. The school included instruction in English and exhibited other characteristics typical of schools throughout Europe and the United States. However, cultural rules and norms of this school exhibited more eastern aspects of education, like the hierarchical relationship between teacher and learners and open discouragement of collaborative, group learning (Hallinger & Bridges, 2007; Shaw, 1999). Hence, teachers were viewed as experts and mainly utilized a Confucian-based direct instruction or teacher-led modality to deliver knowledge to students (Cortazzi & Jin, 1996; Nguyen, Terlouw, & Pilot, 2006).

The teacher of the observed classroom, however, was an American, who was trained and certified in the United States although her decade long teaching experiences have only been in Thai schools. She was provided the ELV lesson plan by the researchers along with pedagogical supports for engineering expertise; yet she implemented each aspect of the activity on her own, at her school location in Thailand. Her pedagogical approach in this project was more student-driven, exhibiting a greater understanding of constructivist theory and thus placing more emphasis on inquiry. Her approach lied in stark contrast to her colleagues' pedagogies and the type of instruction to which students were generally accustomed. Additionally, the engineering expert consulted during the project was also American, another certified educator from the United States, trained and experienced in more Western teaching philosophies.

The Global Collaboration and Data Collection

The global collaboration took place over a total period of 8 weeks. Upon initial email exchanges between the engineering expert (researcher) and the teacher, the project (ELV) was selected as well as a sustained time frame (6 weeks) for collaboration and observation. The teacher prepared a slide show for students to discuss the design challenge of the ELV, the engineering design process, and desired outcomes for the global collaboration project. It was during this initial phase (lasting 1 week) that students were assigned to groups of 5 to 6 each (16 total groups among 3 classrooms) to begin drawing their initial designs for their ELVs. One student from each group was assigned as project leader to coordinate the efforts of the group and directly interface with the remote experts. Students were instructed to discuss the project criteria and identify appropriate materials that could be globally sourced for their build (model).

Students were aware that they would engage with an engineering expert in the next phase (week 2) for iterative feedback as they designed (Artifact 1), and (week 4) revised (Artifact 2), their ELV designs. The global partnership was conducted using *Skype* (2018), a software-based telecommunications application for synchronous video chat between computers. In total, there were two Skype sessions, 5 minutes per student group for 80 minutes with the engineering expert. In the first Skype session, student groups presented their initial designs and were provided feedback through guiding questions by the engineering expert (Artifact 3) regarding design flaws and avenues for revision. For two weeks, students tested and made adjustments to their designs followed with a second skype session (Artifact 4). In this second session, a NASA scientist provided additional support to the engineering expert. After two weeks (week 6), the 16 student groups, using their revised designs after two rounds of expert feedback, constructed and tested their respective ELV builds on a test ramp to determine the success of meeting the design challenge. The researcher was provided a video (Artifact 5) of all test runs by each student group to determine if their ELV structures succeeded or failed in the design challenge. Lastly, the researcher and the teacher debriefed over email with the researcher (Artifact 6) regarding the successes and challenges of the 6-week ELV global collaboration project. All data sources are summarized in Table 1.

Table 1. Data Sources (Artifacts 1-6) Collected and Analyzed for ELV Project

Data Source	Data Source Description
Artifact 1	Student ELV Designs (Drawings and Written Documents)
Artifact 2	Student ELV Redesigns (Drawings and Written Documents)
Artifact 3	First Round Design Feedback (Researcher Field Notes)
Artifact 4	Second Round Design Feedback (Researcher Field Notes)
Artifact 5	Student ELV Final Design, Build, and Execution (Videos)
Artifact 6	Participating Teacher Reflections (Email Documents)

Data Analysis

Student artifacts (1, 2, and 5) were coded based upon evidence of outcomes within the activity theory, namely 21st Century Skill growth in a Global K-12 Collaboration in Engineering (Figure 1). Student artifacts (1, 2, and 5) were used to assess three of the

four constructs (e.g. Core Subjects & 21st Century Themes; Learning and Innovation Skills; Life & Career Skills) and expert and teacher artifacts (3, 4, and 6) were used to assess the last sub-construct of Information, Media, and Technology Skills and Cross-Cultural Skills 1 for the category of Life & Career Skill. A code book was established from P21 (2015) explanations of how students can provide evidence for mastery in each of the 21st century skill categories. For example, per P21 (2015), an aspect of Core Subjects & 21st Century Themes (a 21st Century Skill Category) may be evidenced by the engineering outcome (which is termed as construct). In this activity, that engineering outcome was the ability of the ELV rolling down a ramp for 50 centimeters. Therefore, this is the relevant description of this construct, specific to the ELV activity. Then, data (artifact/s) from the collaboration was sourced to assess each description for analysis. To create the coding schema, all constructs from the four 21st century skill categories were provided a relevant description to the activity, such that they could be measurable (for mastery) using data (artifacts). The 21st Century Skill categories, including their P21 (2015) constructs, appropriate activity descriptions, and related artifacts, are shown in Table 2.

Each student group ($N=16$) was provided a pseudonym based upon the name of their project and ELV ingredients were catalogued (See Appendix A). Each group ELV was individually coded using relevant artifacts (1, 2, and 5) to the coding schema (see Table 2). Teacher and expert artifacts (3, 4, and 6) were open coded for evidence of *success and challenges* of the global project for the last construct of 21st century skills in information, media, and technology skills (see Table 2). To evaluate students' understandings of outcomes, group responses on the purpose of the ELV project were coded using the stated outcomes separately from artifact 5.

Trustworthiness

Similar to the standards of qualitative research, credibility (confidence in interpretation), confirmability (minimization of bias), transferability (translation to other similar settings), and dependability (consistency of findings) of Lincoln and Guba (1985), this study utilized the Walther et al. (2013) typology for research validation: theoretical (appropriate theory to model the social reality); procedural (suitability of research design and methods); communicative (data collected can address the research inquiry); and pragmatic (adequately modeling reality in findings). To address validation, the theoretical framework of AT was appropriate to apply to the situation of a K-12 global collaboration in engineering. The intention of AT is to understand and describe a phenomenon, which was the purpose of this study. The purposeful sampling of the Thai classroom, within a descriptive case study, provides procedural validation to document activity systems (using AT) in K-12 global collaboration phenomena, related to engineering. To that end, several different sources of data were collected ($N=6$) and analyzed using a deductive reasoning framework (i.e. 21st century skill growth in global engineering, see figure 1) as an extant and coherent domain of knowledge from which to interpret the data set (Hickey & Kipping, 1996). Regarding objectivity or communicative validation, both the data collection rationale, protocol, and coding schema are provided to the reader (see Tables 2 and 3). Furthermore, both authors reviewed and coded data together, to ensure the fidelity during the application of the deductive framework to the data set. Walther et al. states that “the ultimate integration of knowledge claims into the

Table 2. Code Book for Analyzing Outcomes of ELV Project

Skill Categories and Constructs	Description	Data Source (Artifacts)
Core Subjects & 21st Century Themes		
Engineering Outcome	Did groups successfully roll down the ramp For 50 cm? (How far did it go in cm?)	5
Engineering Design Process 1	Did groups follow parameters of project: Correct ramp length and height (100 cm x 35 cm)?	5
Engineering Design Process 2	Did groups follow parameters of project: Correct ELV length and width (20 cm x 10 cm)?	5
Engineering Design Process 3	Did groups follow the parameters of the project: ELV with 4 rotating wheels?	5
Engineering Design Process 4	Did groups follow the parameters of the project: Were ELV completely edible (except for toothpicks)?	5
Global Awareness	Did groups use global foods to assemble the edible ELVs?	1
Learning and Innovation Skills		
Creativity and Innovation 1	Were ELV names creative?	1
Creativity and Innovation 2	Were ELV designs novel from the provided sample/example? (See Figure 4).	1
Creativity and Innovation 3	Were ELVs composed from a diversity of ingredients (foods)?	1
Critical Thinking 1	Judgments & Decisions: Were the 2 structural features relevant for a moon rover? (for an astronaut and space travel)	2
Critical Thinking 2	Reasoning: were final designs functional for a moon rover? (circular wheels and solid chassis).	2
Critical Thinking 3	Solve Problems: Was anything clever regarding a particular design feature for the ELV?	2
Critical Thinking 4	Ask questions: Did they identify issues or ask questions to lead to better solutions?	2
Communication	Were groups able to communicate orally (to expert, teacher) and written (designs?)	5
Collaboration	Did students work collaboratively together in groups?	1 and 2
Life & Career Skills		
Flexibility and Adaptability 1	Were there evidence of structural ^a refinement(s) between Design 1 and 2?	2
Flexibility and Adaptability 2	Were there evidence of functional ^b refinement(s) between Design 1 and 2?	2
Cross-Cultural Skills 1	Was there evidence of groups writing in English?	1 and 2
Cross-Cultural Skills 1	Was there evidence of groups speaking in English?	3, 4, and 6
Information, Media, and Technology Skills		
Information Literacy A	Were groups able to incorporate information from the interaction with expert on ELV design?	3, 4, and 6
Information Literacy B	Were student groups able to effectively interpret the learning goals of the project?	3 and 6
Technology Literacy	Were groups able to effectively interact with the Expert using Skype	3 and 4

^a Structural refinements included attributes for a vehicle in motion (going down a hill).

^b Functional refinements included attributes for astronauts to survive outside of Earth's atmosphere (related to its purpose as a space craft).

cumulative body of knowledge is dependent on the debate about their trustworthiness (communicative validation) and usefulness (pragmatic validation)” (2013, p. 654). Hence, the utility of this study is warranted by the application of AT, from the information provided from the data analyses, to providing insight into how a K-12 global collaboration in engineering activity systems (vertices) can be used for educational outcomes.

Table 3. Code Book for Students’ Perceptions of Outcomes of ELV Project using Purpose Descriptions from Artifact 5

Assigned Value	Relationship to Value	Coding Description of Purpose of ELV feature
3 point value	strongly related to purpose and outcome	describes some benefit to astronaut and/or space travel
2 point value	related to purpose and outcome	describes some element of science and/or engineering design
1 point value	poorly related to purpose and outcome	describes an application to the food, but not to the ELV
0 point value	not related to purpose and outcome	describes some other relationship to food, students or decoration

Note: Coding descriptions are sourced from ELV project parameters and student learning outcomes.

Results

To analyze outcomes as a whole, totals for all 16 ELVs were combined into an aggregate table to elucidate how the success of outcomes categories aligned to the activity. Outcomes of the first three categories of 21st century learning (coded using schema in Figure 1 and Table 2 are reported from student artifacts (in aggregate) in Table 4.

Students were moderately successful in the category of Core Subjects & 21st Century Themes with six (40%) of groups achieving the engineering outcome of creating an ELV that rolled past 50 cm on the test ramp. Largely students were able to follow the project parameters (60% 53% 93% and 81%, respectively), whereas students struggled with understanding the use of globally sourced foods where only 56% of groups were successful. For the second category, Learning and Innovation Skills, student groups were not very successful in creating novel names (31%) and designs (50%), employing a basic variety of foods (6 +/- -2.83) to create their ELVs. In critical thinking constructs, half of groups made relevant structural design decisions whereas all groups were successful in functional design decisions. Only 31% of groups were successful in solving problems and half identified issues to lead to better designs. Slightly over half demonstrated evidence of successful communication (54%) whereas all groups showed evidence of collaboration. In the third category, regarding Life & Career Skills, 44% of student groups incorporated structural changes and 25% of groups integrated functional refinements in their ELV designs. Although there was evidence of all groups writing and speaking in English, the group spokesperson solely communicated with experts (in English) and remarked that by and large they were not comfortable using English (Artifact 3).

Table 4. Analysis of Outcomes of ELV Project: Core Subjects & 21st Century Themes, Learning and Innovation Skills, Life & Career Skills

21 st Century Skill Categories and Constructs	Frequency (Total & % successful)	Successful in Task and Unsuccessful in Task
Core Subjects & 21st Century Themes	64% overall success, 72% in EDP (1-4) construct	
Engineering Outcome	6/15 ^a (40%)	Yes (229), Yes (72), Yes (93), No (5), No (25), Yes (147), No (0), No (0), Yes (76), No (30), NO DATA, No (23), No (32), No (10), Yes (214)
Engineering Design Process 1	9/15 ^a (60%)	Yes, Yes, No, No, Yes, Yes, Yes, Yes, Yes, Yes, Yes, NO DATA, No, No, No, No
Engineering Design Process 2	8/15 ^a (53%)	Yes, Yes, Yes, No, Yes, No, No, Yes, No, Yes, No, NO DATA, No, Yes, No, Yes
Engineering Design Process 3	14/15 ^a (93%)	Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, NO DATA, Yes, Yes, No, Yes
Engineering Design Process 4	13/16 (81%)	Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, No, No, Yes, Yes, Yes, Yes, No
Global Awareness	9/16 (56%)	Yes, No, No, Yes, No, No, No, No, Yes, No, Yes, Yes, Yes, Yes, Yes, Yes
Learning and Innovation Skills	58% overall success, 41% in Creativity & Innovation construct; 58% in Critical. Thinking Construct	
Creativity & Innovation 1	5/16 (31%) successful	Yes, No, No, No, No, No, No, Yes, No, No, Yes, Yes, No, No, Yes, No
Creativity & Innovation 2	8/16 (50%) successful	No, Yes, Yes, No, Yes, Yes, Yes, Yes, Yes, No, No, No, No, No, Yes, No
Creativity & Innovation 3	6 average	SD = 2.83; See Appendix A
Critical Thinking 1	50% ^b average	Out of 2 (0, 50, 100): 50, 0, 50, 50, 100, 50, 50, 50, 0, 50, 50, 50, 50, 100, 50, 50; SD = 25
Critical Thinking 2	16/16 (100%)	All 16 coded as yes
Critical Thinking 3	5/16 (31%)	No, No, No, No, Yes, Yes, No, Yes, Yes, No, No, No, No, No, No, Yes
Critical Thinking 4	8/16 (50%)	No, No, No, No, Yes, No, Yes, Yes, No, No, No, Yes, Yes, Yes, Yes, Yes
Communication	7/13 ^c (54%)	Yes, Yes, No, No, Yes, NO DATA, Yes, Yes, No, NO DATA, NO DATA, No, No, Yes, No, Yes
Collaboration	16/16 (100%)	All coded as Yes
Life & Career Skills	67% overall, 35% in Flexibility & Adaptability Construct	
Flexibility & Adaptability 1	7/16 (44%)	No, No, No, Yes, Yes, No, No, Yes, No, No, Yes, Yes, No, No, Yes, Yes
Flexibility & Adaptability 2	4/16 (25%)	Yes, No, No, No, No, No, Yes, No, No, No, No, No, Yes, Yes, No, No
Cross-Cultural Skills 1	16/16 (100%)	All coded as Yes
Cross-Cultural Skills 1	16/16 (100%)	All group spokespersons communicated in English. Students were shy, not comfortable speaking in English (3) ^d

Note. Each response is in order of ELV design (ELV 1, 2, 3... 16); see Appendix A for descriptions.

^aOne group (ELV-12-YS) did not have data for this category.

^bSuccessful examples in this category included: energy, parachute, space for astronaut, window/door, antenna, nose cone and unsuccessful examples included: no response, storage for food

^cThree groups (ELVs 6, 10, and 11) did not have data for this category.

^dDescriptive information is from Expert Artifact 3.

Outcomes of the last category of 21st century learning (coded using schema in Figure 1 and Table 2) are reported expert and teacher artifacts (in aggregate) in Table 5. The expert identified that for Information Literacy (A), some student groups were able to identify and solve problems, and internalized feedback to improve their design. However, some groups were not able to accomplish that, and the teacher indicated students struggled with the concept of inquiry and group learning, hindering their ability to be successful. In terms of students' understanding of the activity, students engaged with the expert in content conversations and the teacher noted they were using scientific skills while constructing the ELVs. However, it was challenging for students to abandon a Thai-based cultural emphasis for aesthetic beauty (compared to functionality) and lacked some fundamental skills of experimental controls and measurement. Last, although students appeared to be comfortable with the telecommunication platform, time differences and student attention spans were challenging for all actors in the system.

*Table 5. Analysis of Outcomes of ELV Project:
Information, Media, and Technology Skills*

21 st Century Skill Category	Constructs	Successful	Not Successful
Information, Media, and Technology Skills			
Information Literacy A	Information Literacy A	Opportunity to identify potential problems and made improvements (3)	Some Groups did not use feedback to improve designs (4)
		Students internalized information to revisit designs (3)	Students struggled with inquiry and collaborative (group) learning (6)
		Some groups used feedback to improve designs (4)	
Information Literacy B	Information Literacy B	Discussions of the moon environment (3)	Extra parts on ELV that had no clear use (3)
		Discussions of vehicles operable on the moon (3)	Repurposing ELV parts that had a purely aesthetic role likely due to Thai cultural ideals (3 & 6)
		Students were building their engineering skills in practice (6)	No use of experimental controls or measurement (6)
Technology Literacy	Technology Literacy	Students used camera to present designs (3)	Time differences (3) Attention span (3 & 4)

Note: The number in parentheses represents the data source or artifact.

To understand the students' perceptions of purpose and design of the ELV project, each group provided two written reasons or justification of the two design choices within the ELV design. The 32 group responses (Table 6) were sourced from artifact 5 and coded using the schema within Table 3 and further analyzed in Table 7. Interrater agreement (between two coders) was 100 percent.

Table 6. Coding of Students' Perceptions of ELV Project Purpose and Design

ELV Project	Purpose 1	Purpose 2	Codes
ELV-1-BR004	To help astronaut that don't have enough food	To make a time beneficial	1, 2
ELV-2-BF	To help astronauts with their foods.	To learn the basic of making Vehicle	1, 2
ELV-3-SSC	To make astronauts don't die because hunger.	To help astronauts	1, 2
ELV-4-DEV	we can help astronaut when they want some food.	We can eat when we finished.	1, 0
ELV-5-SS	To use the design for the future when it has a problem that we can use it.	To send food from the earth to the moon (quickly)	2, 1
ELV-6-BGSFC	To help astronaut	To design the ELV	2, 2
ELV-7-OO	to can eat vegetable in the space	to help NASA think for us will go to the Moon.	1, 3
ELV-8-AP	To test how strong it be	How to know some fruit	2, 0
ELV-9-YT	can eat	to make experiment	0, 2
ELV-9-YT	snack for kids	can cut the part of the carrot and can grow again	0, 0
ELV-11-BAC	Use to catch and Alien in the Moon.	It will protect an astronaut	3, 3
ELV-12-YS	use this as concept to make it real in the future	when the nasa made this so can eat if the food not enough	2, 1
ELV-13-TBOSC	To know idea for the thing to bring to space	to decorate the house or anything	3, 0
ELV-14-CC	Race	learn about if we run out of the food we can eat the vehicle	2, 0
ELV-15-CoS	Think idea how make a space-ship	to have idea how can go to space	3, 3
ELV-16-SCC	can eat it in the space	can use in the space when we go there	1, 3

Note. Spelling and grammatical mistakes are intentional.

Purpose 1 and 2 are written verbatim from students group responses from Artifact 5.

Coding was performed using the Codebook from Table 3.

Table 7 shows an analysis of student groups' responses by alignment to task purpose and project outcome. Seven of the responses (22%) did not provide any understanding of the purpose of the project, 8 (25%) of responses were somewhat related to the purpose and outcome, 10 (31%), described some element of science and engineering goals, and 7 (22%) described how their choices benefitted the astronaut or space travel (being the actual purpose and design of an ELV). Only one group (ELV-11-BAC) had both choices directly related to the purpose and design.

Table 7. Analysis of Students' Perceptions of ELV Project Purpose and Design (from Table 6)

Point Values Assigned	Frequency Totals (N=32)	Percentage of Total Responses	Scaled values (Point total x value)
0 value responses	7	22%	0
1 value responses	8	25%	8
2 value responses	10	31%	20
3 value responses	7	22%	21

Note. There were 16 student groups with 2 justifications each for a total of 32 group responses.

Applying Activity Theory to a U.S./Thai ELV Global Collaboration in Engineering

A case of a U.S.-Thai collaboration in elementary engineering, designing and building of ELVs through the student, teacher, and expert was documented. It illustrates how activity theory may inform global K-12 collaborations in engineering education. Each element of human activity observed in the case was mapped onto the corresponding aspect of activity theory. When mapped to activity theory, the following relationships emerged in Figure 5. The subject was the student groups and the object the ELV product. The community consisted of the engineering community (curriculum, engineering expert); the Thai or Eastern education system (school culture, faculty); and the US or Western education (instruction, teacher) system with competing behavioral expectations. The Western communities favor cooperative group learning and inquiry-based learning while the Eastern favors individual learning and rote memorization. The rules included ELV parameters (engineering constraints); engineering design process (design, revise w/feedback, then build, test); cooperative groups; P21 skills (collaboration, creativity, critical thinking, communication); and writing and speaking in English. The division of labor was divided among the group leader and group members in each student group. Last, mediating artifacts were the initial presentation and parameters of ELV project (by teacher & expert); ELV designs themselves; tools (including globally sourced food, toothpicks, paper designs, pencils, and test ramp) and the experts (teacher and engineers).

The components of the Thai-US global collaboration case using activity theory posited by Engeström (1987) are demonstrated in the labeled vertices of activity within this collaboration to the activity system paradigm (as shown in Figure 5). The *subject* for the U.S./Thai ELV collaboration was, for the most part, the American teachers in Thailand as they were the most influential actors in terms of the direction and logistics of the project. As the engineering consultant one of the authors had a smaller role, he still exerted influence over the experience of the students. The fourth-grade students in Thailand were the *objects* in this project, both as owners of the activity product or as outcome. The *outcome* sought was not only an improvement in their 21st century skills, but also English-based communication skills and, to a smaller extent, a familiarity with the EDP. The *community* for the project consisted of not only one of the authors, as the engineering consultant, but all other entities that informed, influenced, or provided the context for the project, including the Thai educational system, the school administration, the other teachers in the school, as well as the educational system of the United States with which the American teacher identified.

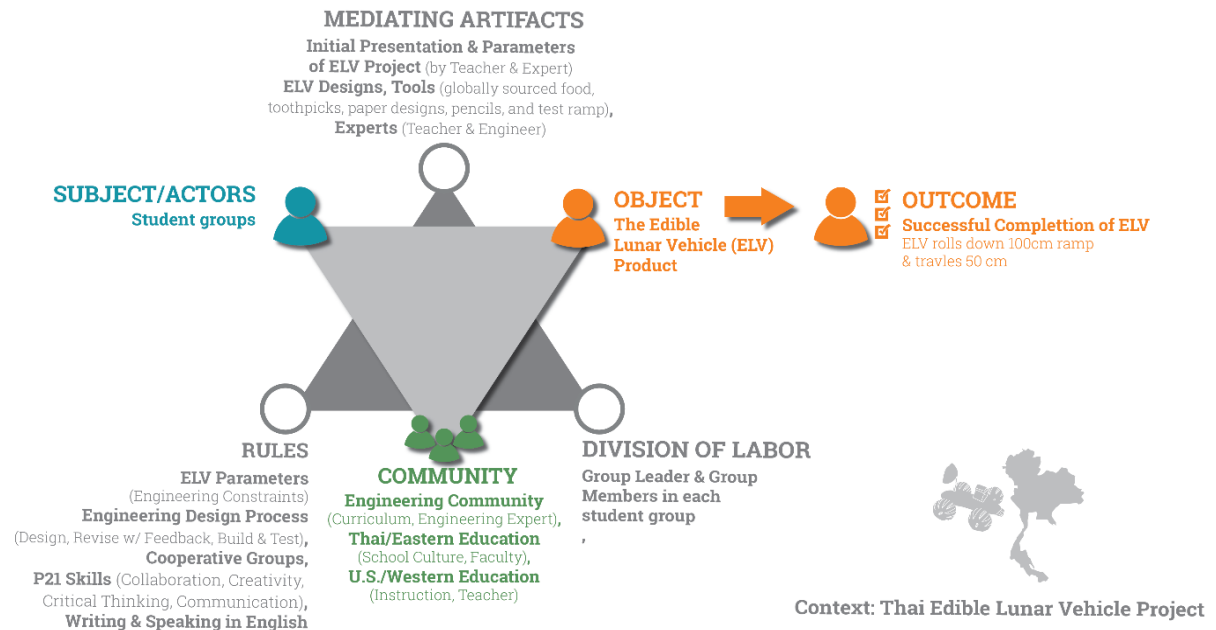


Figure 5. Engeström's (1987) activity theory applied to a global K-12 collaboration in engineering (U.S./Thai ELV) (adapted by Thompson, 2018e)

The *division of labor* in the project followed a model used in many American classrooms in which students are divided into small, three or four student strong teams to work together collaboratively on a specific learning outcome. The Thai fourth graders were put into similar groups where they collaborated on the design and construction of their ELV. When it was time to receive feedback on the original design, a *team captain* interacted with the engineering expert to discuss strengths and weaknesses of the design as well as explore and evaluate possible modifications. Throughout the process the classroom teacher acted as a coach, guiding students through the design process, and moderating their interactions with the engineering expert. The *mediating artifacts* of the ELV project included both the manipulation of physical objects and materials, as well as the use of appropriate language, Vygotsky's (1978) *signs and tools*.

Students used simple kitchen tools or their hands to manipulate and shape a variety of edible materials. During this time, students learned about the physical properties of these edible materials. All the while, students were communicating with each other, mostly in their native Thai language, as well as in English with their American teacher and the engineering expert. Through the ELV context, they were provided opportunities to acquire new English words, especially technical terms specific to engineering. For this project, the *rules* were essentially synonymous with the learning outcomes. These learning outcomes were never explicitly expressed to the students and it was difficult, when observing the classroom activities, to determine which outcomes were the primary focus. The outcomes included not only a number of 21st century skills, as outlined by the

P21 Framework, but also English language communication skills and a familiarity with EDP.

Discussion

To explore the power of activity theory to evaluate global K-12 collaborations in engineering, activity vertices were explored in depth and elucidated by the data analysis to reveal contradictions and discrepancies between the expected activity relationships compared to what was actually being observed (Engeström, 1987). The following discussion outlines areas where activity theory has elucidated contradictions, which we ascribe as challenges in developing, sustaining, and assessing successful global K-12 collaborations in engineering, especially in non-Western contexts based upon the analysis of artifacts collected from the case study. One of the unique affordances of activity theory is that it may be “used as a framework for understanding how the different components of the activity impacted each other and to develop modifications to alleviate tensions between activity goals and observed factors” (Doubleday & Wille, 2014, p. 367). Therefore, through identification of these challenges we may devise recommendations, based upon data and information from the case and model respectively, to help advise the design of future K-12 classroom experiences using global collaboration in K-12 engineering education.

The Importance of Rules to Facilitate or Obfuscate Outcomes

The most important element regarding the success or failure of the U.S./Thai ELV project was what activity theory defines as the *rules*. In designing any global collaboration project, or indeed any multifaceted classroom experience, it is important to be thoughtful about the number and size of the learning outcomes to be negotiated by the objects. Here, by *size* we mean the level and number of challenges achievable by the objects or students; namely their ability to balance the expectations set forth by the rules and division of labor. This gap existed between the current skill level of the students and the skill level required by the activity. Of course, in any learning experience, there will be some gap between the students’ current skill level and the skill level required to attain the activity outcome. This gap is what Vygotsky (1978) coined the Zone of Proximal Development (ZPD); the area between what an individual can learn on their own and with peer intervention. It posits the importance of social experiences and building knowledge incrementally (scaffolding) to facilitate learning. Careful attention should be paid to these cognitive gaps, as too large of a gap, poor or no peer interaction, or a lack of adequate and appropriate scaffolds, will not lead to learning (Dixon-Krauss, 1996).

Similarly, if the outcome requires students to bridge sizeable, yet appropriate, gaps in multiple areas, this may lead to mixed activity outcomes. For example, the Thai students involved in the ELV project were required to try to bridge several considerable skill and knowledge gaps evidenced in the analysis. First, students had little prior knowledge to the conditions of the lunar surface (Table 5) and fifteen responses to the purpose of design elements of the lunar vehicle were not germane to aiding an astronaut for this purpose or task (Table 7). Second, this EDP activity required students to develop their own creative solutions to problems as well as openly identify and analyze failure with their design for modifications. This was a challenge in which only 40% (6 out of 15

groups) were successful in achieving the stated outcome of the design challenge (see Table 2). Students struggled to develop skills in each category of 21st century skill growth. Only 41% of the groups were successful in creativity and innovation tasks; 58% in critical thinking tasks; and 35% successful in flexibility and adaptability indicators (see Table 4). This was also reported by both the teacher (artifact 6) and expert (artifact 4) in Table 5 (see not successful, Information and Literacy A). This low success rate may be understood by reflecting on the fact that the Thai students may be culturally accustomed to a direct or lecture-based instruction model of teaching and learning that devalues individualism (Hofstede, 2001) and students are passive recipients of knowledge (Pagram & Pagram, 2006). Cultural factors may also explain the students' reluctance, noted by the expert (artifact 3) and teacher (artifact 6), to revise aesthetic elements of the ELV without purpose (see Table 5, not successful, Information and Literacy B). Third, when it came to written communication and speaking with the Americans involved in the project, students were required to use English, a language very different from Thai in terms of grammar, syntax, and phonemes. Although all groups were successful in writing and speaking English (see Table 4), students were shy and reluctant to speak (see artifact 3, Table 4).

Any of these challenges individually would be difficult for these students, but the combination of all of them simultaneously was quite overwhelming. Although the intent was for students to develop 21st century skills, these skills, like the Engineering Design Process, were too far outside their usual classroom experience. Challenges such as these often arise when the learning expectations are poorly defined (Daniels et al., 2010), when teachers must take on a new role as facilitator (Cifuentes & Shih, 2001), or when linguistic issues cause confusion and miscommunication among actors (Neeley et al., 2009; Shih & Cifuentes, 2003). However, it is important to note that six groups (i.e. ELV-1-BR004, ELV-2-BF, ELV-3-SSC, ELV-7-OO, ELV-10-SCC, and ELV-16-SCC) were able to understand the rules, as the expert noted in Artifact 4, "Many of the groups had grasped some of the issues we previously discussed and had integrated their new understanding into a revised design." This is further evidenced by success in 72% of the engineering design constructs (1-4, see Table 4) and the 17 responses that aligned to the outcome of the ELV activity (see Table 7). This suggests that elementary students, even diverse (non-Western) primary students, can garner important engineering and 21st skills envisioned by Tank et al. (2015) and Brophy et al. (2008).

Leveraging the Community for Successful Global K-12 Collaborations in Engineering

Nearly as important to the rules for the success or failure of U.S./Thai ELV collaboration was the community. For an endeavor as ambitious as this global engineering collaboration, the support, or, at the very least, tacit acceptance of the community is essential. A critical component of the community that may not be obvious is asymmetry between Western and Eastern educational systems. Even though this teacher was working in Thailand, she made it clear that her teaching philosophy and approach to pedagogy were informed by Western, American ideals. Her practice emphasized constructivist pedagogies and hands-on exploration in which students co-construct understanding through interactions with phenomena and with their peers, rather than passively assimilating content dispensed by the teacher. She wanted students to develop

skills in creativity and innovation over mere memorization. In artifact 6, she remarked on the mixed learning outcomes of the global collaboration, “*this wasn't just a class management issue. In my opinion, it's 90% cultural. They just don't have the school experience of how to work in these types of environments.*” Herein lay one of the struggles faced by the American teacher. Crucial to the success of the project was the promotion of modalities, skills, and pedagogies that were not part of the traditional education system in Thailand. Collaboration required students to work together in groups rather than individually. The activity also sought to promote critical thinking skills and creativity, reflecting the “current reforms in science education worldwide...the shift from the dominant traditional teaching for algorithmic, lower-order cognitive skills, to higher-order cognitive/thinking skills” (Miri, David, & Uri, 2007, p. 354).

Any K-12 teacher who embarks on a global collaboration project should consider specific learning outcomes, the rules in AT, and keep in mind the importance of communicating with the community in which the objects operate, namely the other teachers and the school administration. It is important to ensure that the community understands and, hopefully, supports these goals. This is particularly important in a context such as this and any K-12 global engineering collaboration, where the project leaders is/are (a) foreigner/s. The American teacher is much more likely to elicit the support of the community if they can effectively communicate the desired learning outcomes in a way that makes them seem less alien, by drawing connections to the goals that are important to the Thai faculty and administration. School culture and administrative support are important when teachers engage in novel pedagogies; numerous studies suggest that the administration and their colleagues influence the success or failure of new constructivist initiatives (Anderman, 1991; Baylor & Richie, 2002; Windschitl, 1997, 1999)

Case-based Informed Recommendations and Interventions from Activity Theory

The successful achievement of the educational goals of a project such as this requires that the *subjects*, the project leaders, carefully consider and thoughtfully design all elements of the project. The very first consideration should be the *outcomes*. Are the learning outcomes too numerous or too far beyond the capabilities of the students? One way to improve success is to reduce the challenges facing students by either providing scaffolding, to help students bridge the gap, or to decrease the size of the gaps themselves. Let us consider the *rules* of the project, in particular the new science knowledge we want students to acquire. To begin with, the students might have been provided with some grade-level appropriate text, perhaps even in Thai, that would have supplied them with the background knowledge they needed about the lunar environment. Alternatively, the students might have been asked to design a vehicle for transporting students to school, making the context of the engineering challenge more familiar. To help students deal with the novel experience of EDP the teacher might have provided scaffolding by walking students, perhaps even in a whole group, through each step of the process until they became more familiar with it. When it came to communication, if insisting that the students operate in English was an essential component, scaffolding could have been provided in the form of sentence frames (Carrier, 2005). One consideration that plays an especially important role in the development of communication skills is *division of labor*. Having the students work in

groups ensures that they will have to communicate, and when this communication is in a second language, group work is particularly effective. (Pica & Doughty, 1985) These are only a few suggestions for how some of the skills and knowledge gaps faced by the students involved in the Thai ELV project could have been reduced or scaffolded. Further reflection would, no doubt, produce many more.

It should be pointed out that all of the considerations described above are dependent on the current knowledge and skill level of the students. In other words, we must consider the *rules* in terms of the *objects*, showing once again how all elements of AT are interdependent. As a further indication of this interdependence, it should be pointed out that, in particular for this project, the *community* was an important consideration. From this case emerged an understanding that different cultures included appreciating their respective, albeit often different, pedagogical strategies. Not forcing a Western approach and leveraging aspects of both cultural expectations around class pedagogies may foster learning environments where students from both cultures can readily participate and thus, learn (Doherty & Singh, 2005). A study by Tolley, Johnson, and Koszalka (2012) found in their research that Thai students who were given explicit instruction in active learning activities showed significant improvements in student engagement. It may be incumbent on educators to consider embedding culture-specific, research-based interventions in pedagogical strategies before students begin the content-based activity. A lack of common communication may influence asymmetrical expectations among subjects. If the two educators in the activity system each desire different learning outcomes, activity theory predicts that the objects (students) will be in conflict. Figure 7 summarizes the recommendations using the Activity Theory framework for planning future K-12 global collaborations in engineering.

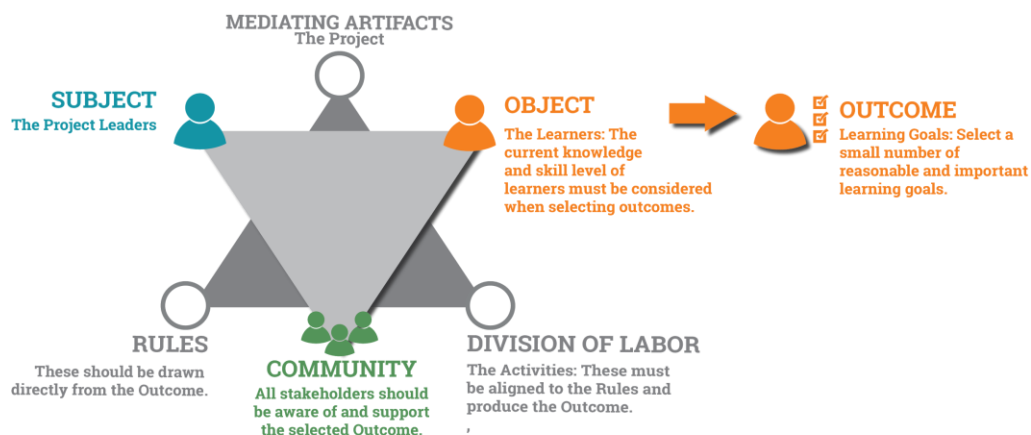


Figure 7. Summary of recommendations in using activity theory in the design and execution of global K-12 collaboration in engineering (adapted by Thompson, 2018f)

Conclusion

Activity theory provided a framework for understanding, discussing and designing complex and comprehensive school-based activity, such as K-12 global collaboration in engineering. Global K-12 collaborations provide a unique opportunity for students to develop important 21st century skills, including the four C's of critical thinking,

communication, collaboration, and creativity, as well as cross-cultural skills and the use of technology. Frequently, these projects have many more participants, and last much longer than the typical classroom activity, making them very deep and rich learning experiences, necessary for the development of globally-minded engineers. While providing students with more rigorous and meaningful learning experiences is a laudable goal, those designing these collaborations must be conscious of not overwhelming learners with too many ZPD (zone of proximal development) based gaps derived from the rules, division of labor, and community within the activity system. Based upon the relationships established within Activity Theory, outcomes directly inform the rules of the activity which supports these findings that the rules were key to the success or failure of the collaboration. If the rules demand more than what the learners are capable of, the objects will more likely become frustrated, diminishing the outcome or the development of new skills. Similarly, learners can just as easily be defeated if the goals are individually reasonable, but too numerous. For this reason, it behooves practitioners designing global K-12 classroom collaborations in engineering to carefully consider which outcomes are essential and which can be deemphasized or even eliminated. In aligning the rules for objects directly to outcomes increases the likelihood that learners will be successful in obtaining the learning goals.

Furthermore, one should consider the division of labor in the design of a global classroom collaboration to ensure that the activities engaged in by the learners are likely to produce the desired outcome. Finally, it is essential that all members of the community understand and support the outcome. If not, there is always the possibility that stakeholders will have asymmetrical goals, each emphasizing and evaluating success based on their personal, unshared outcomes. Future considerations of these collaborations should have a clear idea of the desired outcomes in order to ensure that they are both reasonable and essential. Acknowledgement of the differential communities' mindsets of schooling cultures have led to the adaptation of instruments to evaluate Western-based global-mindedness (Hett, 1993) into Eastern contexts (Lawthong, 2003). Similar work in exploring hybrid pedagogies and soliciting administrative support should be elicited when implementing pedagogies and communication into non-Western contexts. Carefully considering the current knowledge and skills of learners, selecting a small number of learning goals for the outcome, developing clear and concise rules and activities aligned to these rules, and communicating all of this to the whole community, will help to ensure the success of a global K-12 collaboration in engineering.

Limitations

This proposed model of Activity Theory in global K-12 collaborations in engineering is inherently situated to this specific case and the unique activity of engineering practices, and such should not be used to generalize to other content domains. The ideas discussed in this article, while reflecting years of working in the educational field, were inspired by a single global classroom collaboration with elementary students in Thailand. The authors invite others to expand on the ideas presented here to evaluate their efficacy in other diverse contexts, including students in other grade levels as well as other linguistic and cultural settings. It should be noted that there are several factors that impact how

students and teachers engage in engineering including personal experiences (i.e. these students had not participated in this type of inquiry based activity before) and prior knowledge (i.e. of the EDP and the preserving life on the moon using a ELV). Also, this case included an American expert, and non-American students, which brings further nuanced issues and challenges to a global K-12 collaboration in engineering not deeply explored in this paper. Further empirical exploration of the model is warranted to ensure an adequate portrayal of the *segment* of the activity theory design. According to Bryant et al., (2005) “It is useful to imagine that the dimensions of AT provide a silhouette that needs to be filled in, rather than a detailed map of human activity” (p.3). In addition, other activity systems within schooling environments may influence this particular activity system, causing unintended effects (Engeström, 2009). It is entirely possible there may be two or more interacting activity systems creating a novel joint outcome (Engeström, 2001), similar to third spaces (Gutiérrez, 2008), where there is hybridization of outcomes between interacting objects among classrooms. Empirical research studies which may strengthen, refine, or even refute this model, are greatly needed.

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Appendix A

Student Names of Projects, Corresponding Pseudonyms, and ELV edible ingredients type and total (number minus toothpicks, rope, and chopsticks). Please note that brand name items were converted to generic food terms.

Items not permitted by ELV guidelines:

1. Items in *Italics* were food items categorized as local, not globally available ingredients
2. Items in **Bold** were items not categorized as authorized (toothpicks) non-food items
3. Names Underlined were not deemed creative (did not incorporate the space aspect of the project)

Banana Rocket 004 – ELV-1-BR004: bananas, cookie, toothpicks, marshmallows, apple, chocolate (5)

Beauty Fruity – ELV-2-BF: bread, French toast, orange/lemon, marshmallow, crackers, whipped cream, *Asian candy*, candy topping (8)

Super Salad Car – ELV-3-SSC: carrots, baby corn, apple, stick, egg, *Asian candy*, little sausage, *French bread*, cheese, bacon, ham, potato (12)

Delicious Edible Vehicle – ELV-4-DEV: carrots, lime, toothpicks, apple, small tomatoes (4)

Sandwich Sweety – ELV-5-SS: apple, toothpicks, cookie, French bread, dark chocolate, banana, cheese stick, *microwaved sauce*, *hot dog*, *currant*, ham, sliced cheese (12)

Bear Grill Super Food Car – ELV-6-BGSFC: potato, sausage, corn, *spaghetti*, cucumber, chocolate bar, banana (7)

Oree Oree! – ELV-7-OO: banana, *Asian candy*, *hot dog*, cookie, carrot slices, toothpicks (5)

Angry Podracer – ELV-8-AP: *Asian candy*, oranges, *pizza*, pineapple, grape, *seaweed* (6)

Yummy Toast – ELV-9-YT: bread, cookie, chocolate, cherry, strawberry, banana, apple (7)

Sweet Candy Car – ELV-10-SCC: cookie, chocolate, lime, bread, cherry, tomato, **chopsticks**, toothpicks, chocolate ball, apple, *Thai food* (9)

Banana Alien Catcher – ELV-11-BAC: cookie, banana, stick, chocolate, apple, nut/bean, **rope**, carrot (7)

Yummy Spaceshing [sic] – ELV-12-YS: carrot, orange, bread, toothpicks, cucumber (4)

The Bread Oreo Super Car – ELV-13-TBOSC: cookie, orange, bread, toothpicks (3)

Carrot Car – ELV-14-CC: carrot, candy, jelly (3)

Carrot of Space – ELV-15-CoS: carrot, sausage, tomato, ham (4)

Sausage Cucumber Car – ELV-16-SCC: sausage, lemon, chocolate, toothpicks, **rope** (3)