# ENGAGING COMPLEXITY AND CONTRADICTION: UNDERSTANDING FORMULA SAE THROUGH CULTURAL-HISTORICAL ACTIVITY THEORY

**Michael L.W. Jones**

Program Coordinator, Communication, Culture, Information & Technology, Sheridan College
Ph.D. Candidate, Faculty of Information, University of Toronto

## ABSTRACT

This paper outlines continuing research in project-based learning in engineering education, with a specific look at Formula SAE engineering project teams. FSAE teams build a small open-wheeled racecar and compete against similar school teams in an international field of over 500 schools worldwide. FSAE is presented as a example of CDIO-based learning that raises specific challenges to the integration of CDIO standards in practice. This paper suggests cultural-historical activity theory (CHAT) as a relevant theoretical frame to highlight specific contradictions faced by such teams, and links these contradictions to items considered by the CDIO curriculum to assist schools in highlighting specific efforts that may help support such student-led integrated active learning activities.

## KEYWORDS

Formula SAE, cultural-historical activity theory, student design competitions, project-based learning, Standards: 6, 9, 11.

## INTRODUCTION

The development of practical and professional skills in engineering education has emerged as a key issue for industry partners and accrediting agencies (ABET, 2011). Engineering education has arguably shifted too far towards an engineering science model that neglected context of practice and the development of “soft” skills such as teamwork, effective communication and project management that are essential to professional practice (Crawley, Maimqvist, Lucas, & Brodeur, 2011).

Facing similar challenges, medical education moved towards integrating problem-based learning (PBL) from traditionally lecture-centered, information-transfer based pedagogy. Based in a constructivist, experiential and collaborative approach, PBL encourages student-led investigation of real-world problems, guided by faculty that play a primarily facilitative role (Savery, 2006). While there remains some debate about the overall effectiveness of PBL, even skeptics note that PBL increases student motivation, retention rates and develops key professional skills in teamwork, communication skills, critical information analysis, and project management (Albanese, 2000).

Such a model is also emerging in engineering education, with a particular distinction. Many engineering challenges are not problem but project-based, involving more complex integrated systems challenges that require a significant, sustained effort by a team of individuals to resolve (Bédard, Lison, Dalle, Côté, & Boutin, 2012; Kolmos, 1996). External agents are also frequently involved, including consortiums structuring intercollegiate design competitions. Intercollegiate project teams are formed and managed by highly motivated students who structure their work around determined rules and deadlines, supported at various levels by faculty, administration and curriculum support.

While there are a variety of student engineering project teams, one particular context will be examined here – Formula SAE (FSAE) racing teams, so named after the professional organization Society for Automotive Engineering who manage the original competition. This international engineering competition now has over 500 school teams participating in 10 worldwide competitions (Formula World, 2012), including 30 CDIO schools. FSAE teams design, manufacture, test and race a small one-seat open-wheeled racecar. FSAE team members primarily study mechanical and electrical engineering, but may also include students in other non-related disciplines. Students leverage their formal studies and other research to inform the design of their cars, and in doing hopefully create, apply and retain valuable team knowledge while negotiating the challenges posed by competition rules, financial constraints, administration and community concerns. Such work develops many of the core skills of the CDIO syllabus (Crawley et al., 2011) and is supported (at variable levels of depth) through CDIO standards (CDIO, 2014).

This paper proposes using cultural-historical activity theory (CHAT) as a theoretical frame to better understand how team members negotiate their challenges. CHAT is rooted in constructivist learning (Vygotsky, 1978) towards the resolution of specific outcomes, but situates that agency in social and historical forces that can uncover significant contradictions to resolve (Engestrom, 1987; Wilson, 2009). CHAT provides a multifaceted lens to examine the contradictions engineering project teams face, and will be used in this paper to analyze key contradictions in the FSAE context and highlight where CDIO-inspired curriculum design efforts can be of assistance to these student-led integrated active learning opportunities.

## FSAE AS A CDIO LEARNING CONTEXT

> "Graduating engineers should be able to: conceive-design-implement-operate complex value-added engineering systems in a modern team-based environment." (Crawley et al., 2011)

In the course of designing and building a competition-ready racecar, FSAE teams cover the majority of key considerations of the CDIO syllabus. While the larger research project underlying this paper is based on comparative analysis of multiple FSAE teams and their challenge, I will first ground FSAE in the CDIO syllabus through leveraging my personal involvement with the series. From 2001-2005, I worked at various levels, from student team member to management consultant, with Cornell University's team, where I experienced the intensity and breadth of this learning process first-hand.

With respect to *disciplinary knowledge and reasoning*, the competition rewards cars built on a strong engineering foundation. In preliminary technical inspection, teams that have not met baseline standards in car safety will be deemed unqualified to run until issues are resolved. At the same time, design judges question all teams in an intensive 30-minute question and answer session. The most accomplished teams enter a second, longer round of questioning to determine top designed cars. Success in the design event requires a deep and well-reasoned research program, significant theoretical and on-car testing, and a strong presentation of a data-driven defense of design decisions. While design is only 15% of the competition's overall point structure, well-designed cars usually find themselves at the front of the pack in the competitions' dynamic racing events.

Without attention to the skills listed under the second pillar of the CDIO syllabus, *building personal and professional skills and attributes*, a team likely would not survive the first round of design. In the case of Cornell's team, significant time and effort was spent in an iterative, cyclical design process based on systems engineering principles. Team leaders and faculty advisors supervised a three-stage design review for all core systems in the first four months of the academic year, during which core questions around feasibility, design for manufacturing, cost, weight, and systems integration were asked and answered. This approach created a bounded time for experimentation and innovation, transitioning to early manufacturing and testing which is essential to build a foundation of data and to detect and resolve unforeseen weak points in design. In the main event of the competition, an endurance event worth 35% of total points, well-designed cars with undetected weak links often do not finish the race and forfeit a large number of available points. A year's worth of work can be dashed with a simple mechanical or electrical oversight in a manner of seconds.

Attention to the third pillar of CDIO syllabus, *interpersonal skills: teamwork and communication*, can be essential in negotiating the many subtle challenges student team members face and to maintain team morale. My involvement with FSAE began in this domain – the team identified a number of organizational communication and teamwork issues and enlisted the assistance of a communication research lab for assistance. Over time, I specialized in this domain and identified new concerns, advising and assisting team leaders and advisors on such matters for four years.

Some elements of the fourth pillar, *CDIO in social and environmental context,* are addressed through other competition events, such as a business case presentation to product marketing judges and a cost report outlining the full cost of all components, with significant penalties for poor cost control. Fuel economy is also considered, with penalties for cars that run too rich in the endurance event. The balanced mix of static and dynamic events in competition stresses the importance of systems engineering. Balancing systems requirements of these events is a complex engineering and organizational endeavor.

Cornell's attention to systems engineering and team dynamics were identified as key factors by faculty advisors and competition judges in the team's sustained success. From 2001-2005, Cornell's team won the annual 120-school Michigan competition four times, a record of success only recently repeated by Global Formula Racing, a collaborative US/German effort between Oregon State and FHS Ravensburg who also demonstrates similar excellence in systems engineering and team collaboration.

## FSAE TEAMS IN THE CONTEXT OF CURRICULUM AND ADMINISTRATION

The CDIO 12 Standards (CDIO, 2014) provide a framework for curriculum design and development that can help schools looking to integrate CDIO activities such as FSAE in their overall educational mandate.

FSAE establishes a learning context (Standard 1), provides an introduction to engineering (Standard 4) and exposure to design-implement experiences (Standard 5) in an integrated active learning experience (Standards 7, 8). This happens even in schools that are not well supported by a CDIO-style curriculum.

While each competing team requires a sponsoring school and faculty advisor, the quality and depth of that commitment varies considerably. Preliminary interviews with FSAE teams at 2014 American competitions suggest a wide variety of experience with respect to three CDIO standards in particular: access to engineering workspaces (Standard 6), the quality of faculty advisement (Standard 9) and integrated learning assessment (Standard 11).

Access to engineering workspaces varies considerably among FSAE teams. The needs for an FSAE team can be quite expensive. Teams require secure workspaces for the car and associated parts/supplies. These spaces involve specialized manufacturing facilities that often require physical renovations and human resource support to run in a safe and reliable manner. Some teams are forced to make do with a bare minimum of budget, space and tooling, occasionally having to access off-site garages (often under less than safe conditions) or solicit industrial partners to assist with the construction of their cars. Teams at universities with well-supported sports programs note considerable frustration over unequal treatment – it is common for campuses to have expensive, specialized facilities for a single varsity sport team, while their engineering varsity teams scramble for resources. Few FSAE teams have reserved facilities, and often share space and technical support with other project engineering teams and research projects. This forces some FSAE teams to directly contend with the uncomfortable politics of space in academic institutions.

The support of a strong faculty advisor can help student teams navigate the byzantine bureaucracies of academe, but there is considerable variety on the level of faculty engagement and expertise. Many advisors are inactive in the day-to-day affairs of the team. This leaves student team leaders largely on their own to manage a complex balance of power with school administrators. Mishandling such relations can quickly end the schools' sponsorship of the team. Teams with weak faculty advisors can be competitive all the same, but they are forced to make do with less expert guidance than optimal. Less common but also evident are teams with the opposite problem – advisors that micromanage team activity. This is a strategy that can backfire – in one interview, a design judge noted that a normally competitive team was downgraded because students could not answer simple design questions. It became clear the advisor was wholly responsible for design, turning the CDIO experience into a simple IO one, and compromising the professional development of the young engineers in the process. Later interviews suggested that the students in quested resented the constant interference of their advisor.

With respect to the CDIO standard on learning assessment and evaluation, there is considerable variation in curriculum integration for student project teams. Increasingly, schools are providing independent study or capstone course credit opportunities to reward the significant amount of learning involved in project-based learning teams. There remain challenges on how to evaluate individual contributions to team success, however. Attaching evaluation to the outcome of competition is agreed to be an unfair metric – there are many factors influencing competition results that are far beyond individual or team control. Evaluation based on process and active contribution seems more common, and is progression towards a reasonable goal – e.g., a new team that manages to complete all events at competition should be proud of its accomplishments, whereas for an established team mere attendance would be seen as poor.

There are still quite a few schools that see FSAE team activity as a solely extracurricular activity however – more student clubs than academic efforts. This makes integration with curriculum tenuous at best, relegates teamwork to a lower priority than formal coursework, creates animosity among faculty suspicious of the time “wasted” on such work, and provides no easy basis for accounting for learning outcomes. Stronger integration of FSAE team activity into curriculum design as encouraged by the CDIO standards would provide guidance to faculty and students alike in acknowledging and evaluating the learning process involved.

## ENGAGING ENGINEERING DESIGN COMPLEXITY THROUGH CULTURAL HISTORICAL ACTIVITY THEORY (CHAT)

Another difficulty in analyzing the dynamics of the FSAE workcycle is finding a theoretical model that reflects and retains the complexity of the effort. Even within the tightly prescribed technical context of the FSAE competition, there are often no universally right design solutions, some design solutions that are right only in the context of given systems, some solutions that are only a few tweaks away from being the next competition standard, and plenty of solutions that are quite ill-considered indeed. Reducing this complexity to a simple rubric risks blackboxing what is a far more interesting process.

A potential solution to keep such a dynamic and complex context alive in analysis is to see engineering project-team work like FSAE through the frame of cultural-historical activity theory (CHAT). CHAT shares roots with constructivist learning and the work of Vygotsky, who argued that knowledge building is an active process, done by motivated individuals, using various mediating tools to interpret their environment towards the end of realizing their objectives (Vygotsky, 1978). This subject -> tools/instruments -> object relationship is seen as the core activity process in CHAT (Allen, Karanasios, & Slavova, 2011). This process is dialectic and iterative in nature, cycling between internalization of cultural knowledge and externalization through the creation of knowledge objects (Avis, 2007) in a manner similar to that described in Nonaka and Takeuchi’s SECI model of knowledge generation (Nonaka & Takeuchi, 1995).

The inclusion of sociocultural forces in CHAT is regarded to be the work of Vygotsky contemporary Leont’ev (Engestrom, 2008; Leont'ev, 1978) and the contemporary resurgence of CHAT is largely traced to Yrjö Engestrom, who interpreted Leont’ev’s work and raised its profile in contemporary Western scholarship (Engestrom, 1999; Roth & Lee, 2007). The resurgence of CHAT was aided by an iconic diagram, included below:

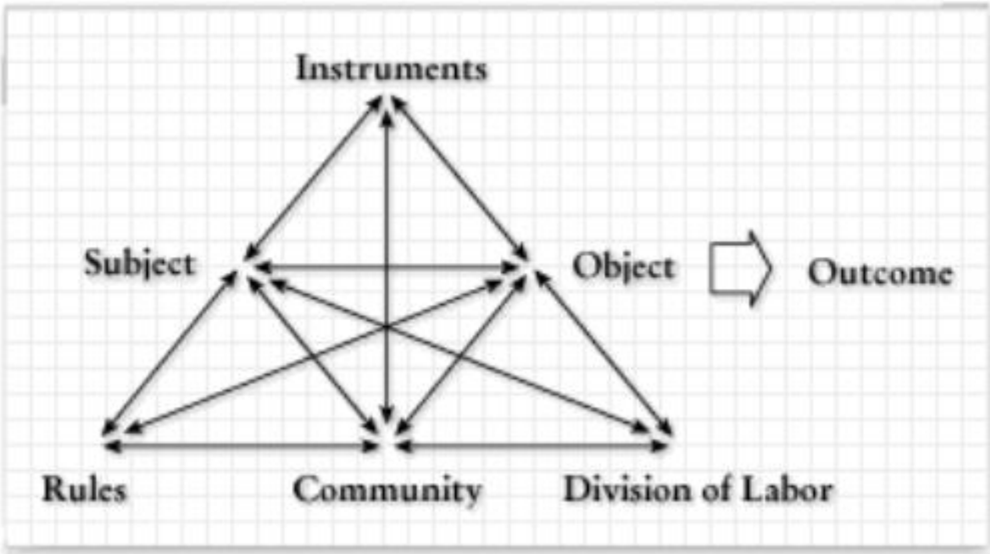


Figure 1: Engestrom's representation of cultural-historical activity theory, adapted from (Engestrom, 1987; 1999)

In the top triangle in Figure 1, we see the core construction of activity - a relationship between *subjects* and their intended *objects/outcomes*, mediated by *instruments* (also referred to as tools, instruments or artefacts, given translation issues) that facilitate knowledge generation.

Complicating matters are the components Leont'ev added to ground activity in social and historical foundations. *Community* includes all stakeholders that may be affected by the subject's desired outcome. *Rules* (also referred to as *praxis* or *norms* in some CHAT discussions) are both written rules and unwritten norms that govern social interaction. These are necessary to mediate order and regulate larger questions of justice, ethics, and morality. *Division of labor* acknowledges that subjects often require the assistance of others to realize their goals and that such relationships are often structured by inequalities in power.

The most compelling component of CHAT is what occurs when these forces act in contradiction to each other (Meyers, 2007). The concept of contradiction highlights particular points of contention that lead to transformative changes in activity patterns (Engestrom, 2008). Engestrom's notion of expansive learning through the identification and negotiation of contradiction (Engestrom, 1987) is similar in kind of the reflective, "double-loop" learning advocated in experiential learning (Argyris & Schon, 1992; Schon, 1983). Engestrom highlighted four levels of contradictions present in activity systems:

Table 1: Engestrom’s outline of contradictions, adapted from (Engestrom, 1987; 1999)

| Contradiction | Description |
|---|---|
| **Primary** | Conflict within a given node (e.g., competing ambitions of subjects) |
| **Secondary** | Conflict between given nodes in an activity system (e.g., conflict between subjects, instruments and outcome; conflicts among core activity and division of labor/rules/community) |
| **Tertiary** | Changes in activities over time (e.g., evolution of an activity such that later versions conflict with previous iterations) |
| **Quarternary** | Conflicts between two competing activity models |

## APPLICATION OF CHAT MODEL AND THE POTENTIAL ROLE OF CDIO SYLLABUS COMPONENTS

Identification of these contradictions yield robust and theoretically grounded research questions that can shape future investigation and analysis. Given the language of CHAT is often dense however, these contradictions make more sense when grounded in context. Of particular interest here are FSAE contradictions that can be addressed through CDIO-based curriculum redesign to support a better learning environment for such teams.

Preliminary interviews at competition suggest significant *secondary-level contradictions between team activity and university administrators*, who as stakeholders in the community and arbiters of rules often have competing priorities. Even established teams can run afoul of university administration and risk suspension if the team’s actions cross what can often be shifting governing priorities. Comprehensive and balanced implementation of CDIO standards regarding faculty development and curriculum integration can help normalize some of these relations, as well as developing team leadership skills as noted in CDIO Syllabus Section 4.7. However, there will always be a creative tension between the creativity and enthusiasm of young engineers and administrations’ mandate to govern an institution with some semblance of order.

An interesting *quarternary contradiction* is evident at competition. One might expect the FSAE competition to be a hostile space, with multiple teams aiming to achieve the same goal, but it is a surprisingly cooperative one. A sense of fair play governs the competitive environment. Teams will support a competitor with emergency tool/part loans, even if that team can now go on to beat them on the track. Team members also often divulge significant information with competing teams about their design work, mostly out of pride of their accomplishments. Yet, there is a certain ethics in this manner of industrial espionage. There is such thing as a stupid question – intelligent questions lead to reciprocal exchange of information, but attempts to unilaterally steal information are dismissed. Attempts to take hundreds of close-up pictures are resisted, often by having team members block access and camera angles. The dynamics of cooperative competition are still being unpacked in this research but are quite compelling, and could eventually be influenced by CDIO curriculum, such as incorporating appropriate practices in information sharing and publication and balancing the ethics of good citizenship with the necessity of protecting intellectual property in an entrepreneurial and competitive environment.

Another core interest of continuing research is the sustainability of team knowledge– *a tertiary contradiction between what was done in the past, what is done now, and what might be done in the future*. Ideally, a team can retain lessons learned from previous years to inform future design decisions, and this process can be more systemically structured through documenting progress through conceiving, designing, implementing and operating phases.

This is more difficult that it sounds in practice, however. One core challenge of my initial involvement with Cornell FSAE involved building a database of team reports. These reports only existed because of a required learning outcome in the associated course – extracurricular teams may not have such data to leverage. But the database itself was problematic - partially due to technical limitations easily overcome today, but more serious issues were report quality and the role of reports in the organic path of information discovery.

Through deeper participation with the team's activities, I learned that reports were not a particularly strong source of information, as they were plagued by sloppy writing, unstructured data presentation, and incomplete analysis. This was due to many reports being written as an afterthought after competition. This didn't matter a great deal in many cases, since past research and development work was passed down through personal connections with experienced team members and alumni and by trial and error experimentation with past systems and cars. Tacit and kinesthetic information sharing compensated for weaknesses in the written documentation.

In recent interviews, other information sources are commonly noted - YouTube videos on manufacturing techniques are seen as increasingly valuable, if perhaps decidedly less than scientific, sources, and online forums such as FSAE.com remain popular places to discover relevant design information. *The core activity contradiction of subjects using various tools of ranging levels of quality to achieve their goals* remains ripe grounds for continuing research, especially as the number of such pathways increase through easy access to computer networks. This path of information discovery and validation can be better supported by stressing the CDIO syllabus requirements of professional skills development (Section 2) to encourage critical information literacy, stressing the relevance of appropriate engineering research methods, and the importance of integrating guidance from faculty advisors, subject matter experts and academic research.

## CONCLUSION

The approach to engineering education advocated in the CDIO standards and syllabus are reflected well in the lived experience of FSAE engineering project teams, even at schools not formally part of the CDIO consortium or even where such teams operate as extracurricular clubs. Preliminary research has identified a series of CHAT-based contradictions that could feasibly be supported through the strategic implementation of CDIO standards and components of the core CDIO syllabus. More formal curriculum integration and developing a better understanding of the facilitative role faculty and administration can play may enhance the professional development of FSAE student team members and leaders as they engage their chosen CDIO project.

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## BIOGRAPHICAL INFORMATION

***Michael L.W. Jones*** is Program Coordinator for the Communication, Culture, Information and Technology program at Sheridan College and a PhD Candidate at the Faculty of Information at University of Toronto. Michael's dissertation research advances the pragmatic use of cultural-historical activity theory to better understand information challenges in project-based learning engineering student teams, with particular focus on Formula SAE (FSAE). Michael was a team member and advisor to Cornell University's FSAE team from 2001-2005, and also worked within the College of Engineering to support other project-based learning teams and experiential learning opportunities.

***Corresponding author***

Michael L.W. Jones
Sheridan College
1430 Trafalgar Road
Oakville, ON L6H 2L1 Canada
1-905-845-9430
michael.jones5@sheridancollege.ca