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Of Green Monkeys and Failed Affordances: A Case Study of a Mechanical Engineering Design Course

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Abstract. *This article reports on an ethnographic study of a mechanical engineering design class. The findings are based on participant observation of one student design team of three students as they designed, tested and built an engineered solution to a problem over a period of ten weeks. The paper describes the curricular efforts to provide social and material affordances both for learning and doing design, and the failure of students on the observed team to take up those affordances. It offers explanations for failure within a framework of conflicting classroom views and pedagogic issues. It discusses the implications of the observed student behavior for design education in general, and mechanical engineering design, in particular.*

Keywords. Design education; Design learning; Distributed cognition; Inscriptional systems

1. Introduction

There was once a green monkey who lived along the banks of a river. Reviled by the other monkeys for the odd color of his fur, he spent the days solitarily lolling on branches suspended over the river. Now the other monkeys feared the river and would not venture near it because of an ancient tale of humans swallowed by its fierce waters. One day asking himself what was so terrible about this peaceful looking river, the green monkey ventured into the murky water. Immediately he discovered the wonders of bathing in its cool currents. Thereafter he swam daily and came to love the river as much as his high perch. When a baby monkey fell in, the green monkey, to the astonishment of his peers, dove in and saved her. No longer an outcast but a hero, he was welcomed into the fold, for he had been able to help them see the value of this thing that they had ignored and feared.

This story assailing *status quo* thinking is one of many green monkey fables told by an innovative professor of mechanical engineering. Such stories are intended to illustrate the special qualities of reflective practitioners—the kinds of engineers he wants his students to become. As he likes to point out, the genius of the green monkey lay in his ability to see beyond the entrenched river taboos, and to forge a new understanding about something long taken for granted. Admonishing his students to 'think outside the box', to become 'green monkeys', he tries in a short ten weeks to make them into lifelong learners of the science of engineering design. In the process, he shakes them off their branches and into the river through a variety of in-class learning activities and out of class learning essays developed to introduce students to design as a 'cognitive, intellectual activity'. Some students take to the water appreciating the plunge as an important learning experience. These are the ones who come to see the affordances of the activities.* Yet, many students rush back toward the shore never appreciating the brisk invigorating waters.

I report here on an ethnographic study of this course, ME3110 Creative Decisions and Design. While recent design education studies have investigated design learning under controlled classroom or laboratory-like conditions [1,2], this study is based on participant observation of day-to-day classroom practices and contingently developed design practices of one student team observed over the course of ten

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*Following Gibson, James J. 1979 *An ecological approach to vision perception.* Houghan Mifflin, Boston MA. I call support for specific activities created by the relevant properties of the things and materials in the situation *affordances*. Materials in the setting only become affordances when they are perceived as such by the participants in activity.

weeks. It focuses on the mismatch between instructor intentions and student interpretations of the affordances provided to scaffold design learning. Representational tools ranging from TQM matrixes for problem dissection, and understanding to linear graphs instructive in arriving at design trade-offs were not readily appropriated by members of the team as useful design tools. Rather, they were constructed as yet another set of school tasks to be completed. Intentions that students learn from others on their design teams and from off-loading cognitive tasks onto 'technological' artifacts were often unrealized. These failed affordances illustrate the ways in which design and design learning are social processes, socially shaped and, in turn, shaping the context in which they occur. While well-intentioned, innovative teaching practices and authentic design experience may be offered to apprentice students to sound design practices, student appropriation of those practices is not ensured.

I begin by presenting a framework for the study grounded in ethnographic studies of engineering design teams in industry and activity theory developed by Russian psychologists. I then briefly sketch out current issues in engineering education in the United States as a backdrop to the development of this course. I next describe the context of the study and the features of the course that embody ideas from newer models of education. I then present a summary of the findings followed by more in-depth analysis of those findings. I offer an explanation of students' responses to the class within a framework of conflicting interpretations of class events/activities and failed affordances. I conclude with implications the study has for design learning and education.

2. Tools and Inscriptional Systems in Design Learning

Engineering design practice is dependent on a broad spectrum of tools. Their function is to mediate [13] between the designer and the object being designed. Some tools such as ammeters can be physically handled, while others like energy conversion equations are manipulated mentally. Drawings or partial sketches are tools; binary decision charts and charts for scheduling parts output in the product realization cycle are tools. Computer generated models and simulations are tools. People are also tools for they bring expertise of various kinds to the enterprise of design. Taken together, they afford the opportunity to 'see' the object-in-design in specialized ways. They allow for and reflexively create a particularized 'object world' [6] or 'domain of thought, action, and artifact within which participants in engineering design . . . move'. Like generic tools that mediate action in practice, their 'affordance' or functional property is not immediately obvious or transparent to the outsider. It must be realized in the context of engineering practice. Take a computer model generated to simulate how a photo voltaic array under design will potentially transform energy flow. To the uninitiated, this model is nothing more than a collection of numbers and mathematical equations – useless and without meaning. What the electrical engineer 'sees', however, is a model of how the photo voltaic design module will behave. It has meaning and can be said to 'talk to' the designer, and she in turn can carry on a dialogue with her design using this tool. Tools of various kinds afford interaction with the evolving design solution.

Tools are useful to designers because they carry intelligence in them. As social artifacts, they inscribe 'patterns of previous reasoning' by stabilizing and reifying activity in a semi-permanent form [11,16]. Designer's tools, therefore, are not neutral objects but carry the sociohistorical legacy of a community's practice. It can be said, then, that learning to use such tools is learning to reason, 'see' and dialogue like an expert designer. For this to happen, the novice has to (1) perceive the tool's affordance in achieving a design-related goal, and (2) understand the intelligence inscripted in the artifact so that expert vision and dialogue can ensue. But achieving these two steps can be difficult as will be illustrated in this study.

3. ME 3110: Creative Decisions and Design

3.1. Context for the Study

Required of all junior level mechanical engineers, Creative Decisions and Design, ME3110 is the first design course in the mechanical engineering curriculum of a large technological institute located in the southeastern part of the United States. Students typically take it early in their junior year, followed by a mechanical component design course and a capstone design course in the senior year. Over a ten week term, student teams grapple with an ambiguously represented engineering problem trying to design, build, test and evaluate the best possible solution given the constraints identified within the problem and in real terms. In many respects, this course mimics conditions that inhere in real world engineering design: (1) the stated problem is ambiguously represented and must be constrained to be solved; (2) deadlines and deliverables are determined by a client/customer; (3) teams of four to six students tackle the design problem, (4) multiple tools and representational systems are available to manage the problem parts; and (5) engineering knowledge and skills are required to design and build a working prototype. Overall, its intent is for students to undertake a design project that spans the entire product realization cycle from problem formulation to marketing a product.†

Each quarter, the 75–100 students in three sections are introduced to their design problem via a written scenario set in an imaginary world, *Planet Vayu*. The inhabitants of that world, the Vayuns, invariably find themselves in predicaments requiring engineered solutions which students design and build. One quarter they may need to build an evacuation device for Vayuns trapped underground, another quarter a device that will transport and drop sleeping potion in enemy territory, and another a device that can scale a wall and retrieve trapped explorers from an overhanging cliff.

While the problem varies from term to term, the intent and movement forward does not. Over ten weeks, the team transforms the design specification from an imperfectly written description of an outcome into a working mechanism that has to perform in a demonstration/competition. Students experience this movement from ideas to mechanism as a team. The professor strives to support the following activities:

- identifying team members that compliment each other
- planning the activities to complete the full process
- understanding the problem
- identifying constraints the solution must meet
- generating alternative concepts
- using informed decisions as key engineering constructs
- meeting design requirements subject to resource constraints
- applying engineering analysis
- selected most-likely-to-succeed alternatives
- resolving trade-offs
- arriving at the best possible compromise given the constraints
- building, testing and refining the design
- developing teams mechanisms for governing

†For a detailed syllabus, description of projects, case libraries of student work, etc. visit http://srl.marc.gatech.edu/education/ME3110/me3110-Web.html

Over the term, students write six reports, each with a specific purpose, about their efforts and about their learning. They participate in classroom activities orchestrated to help them 'think outside the box'; they make presentations on their solutions and build for competition. Computers are used as tools to support parts of this multi-phased process and to support asynchronous communication.

3.2. Learning to Learn: The Course Philosophy

The major course goal is to help students 'learn how to learn'. The professor believes that engineering education trains students to 'plug and chug' or run algorithms in response to class assignments. They must therefore undergo a 'paradigm shift', which turns them into green monkeys and helps them develop a habit for life-long learning. His philosophy becomes clear in his answer to the question 'Why is the building phase of design played down?'

> Hard-prototyping is not important because it's skills-oriented . . . it's production, not knowledge oriented . . . I want them to deal with mental skills, not physical skills. If the focus were on physical skills that would be a different class. . . . A tranformative process must occur. . . . A shift in perspective is required from traditional notions of design as hard prototyping to design as intellectual activity.

To achieve this paradigm shift, he has configured his class so as to draw on newer models for learning. Some of these models have been motivated by the perceived mismatch between the kinds of cognitive activities found in and out of school [12,17]. Others by research on models of cognitive activity [4,5], and still others by the recognition that students bring robust misconceptions to many learning contexts [7,9], and so instruction must address these misconceptions head-on. A prominent feature of these models is *collaborative learning*. Student teams work on a design problem that requires them to become interdependent in a reciprocal fashion [8]. Students are therefore encouraged to assemble teams with complimentary sets of skills, e.g. a builder/tinkerer, a math whiz, a writer, an artist, an organizer. Such groups are intended to learn from each other by exchanging information and relying on their diverse resources during design planning and execution.

Design involves interative problem-solving at various levels of abstraction and problem decomposition. The more complex the design and the more members on a team, the harder the maintenance of such activity becomes. It therefore becomes necessary to distribute cognitive activity across artifacts of various kinds [16]. Recognizing this need, the course designers provide the student teams with a variety of paper and electronic tools which are meant to facilitate the management process. The intent is for cognition to be 'stretched over' tools, people, settings and activities [12]. Learning design is therefore conceived not as an activity isolated in the head, but one which is socially mediated across people, events and contexts [19]. Students use computer software in decision-making, tools from Total Quality Management (TQM) for carving up the problem space, paper schedules and flow-charts for planning and the computer network for communicating and developing soft prototypes. In each case, the idea is for them to off-load the cognitive effort from the head to an external artifact so that they can externalize and better understand an important step in the process of design.

In Winter 1995, I was invited to conduct an ethnographic investigation of one section of ME3110. The class comprised 30 students and maintained the normal demographic features of this institute, two white females, one African-American male and the rest white males. That term the predicament faced by the Vayuns was called *PROJECT SCALE*. Students designed an escape vehicle for some Vayuns who had become underground captives of the Tolzarian government. The mechanism had to be a self contained device that would climb vertically inside a pipe approximately 15 cm in diameter and 170 cm tall. The device had to travel the distance in the shortest time possible carrying the maximum payload. At the top of the tube, it had to burst six balloons attached symmetrically to the periphery of a collar. The device could be no longer than 25 cm. In this class section, there were six student teams varying from four to six students on each team. I participated as a team member on the four person team, consisting of three males and myself. The three males were all in their junior year of the mechancial engineering curriculum.

4. Research Objectives and Ethnographic Methodology

In joining a design team, my research objective was two-fold. The product realization process involves multiple steps and cognitive phases. Engineering students who have previously solved only well-constrained and structured problems with one solution can flounder and thrash about seeking firm ground. In this light, the first research question was: (1) How do students understand and participate in this first design experience? What and where are the difficulties and why do these arise? The second addressed the uptake of the varied affordances provided by this learning environment. Given that his class afforded so many of the features found in new models for education, and so many tools for learning design the question was: (2) How do the students understand and what uses do they make of these affordances for learning?

Because these questions targeted the lived experiences and the derived meanings/understandings of design learners, an ethnographic approach was required. The goal of ethnography, which is the research methodology used by anthropologists, is to discover a community's world view. A world view determines how participants in that community understand and interpret happenings in their lives [18]. World views control what can be counted as significant or silly, valuable or valueless, knowledge or stupidity. As members of communities, we all bring our world views to our understanding of any event. Ethnographers seek to uncover this world view through the process of participant observation. The ethnographer first seeks entree into a community and then assumes a role, often assigned by the group. By participating marginally in all activities, the ethnographer observe the rituals and happenings within the group, describes those in extensive field notes, continually analyzes these notes developing coding schemes and looks for emergent themes that unlock the enigma of that community's interpretive system. A process of analytic induction is used whereby all new data are analyzed against the emergent themes and the themes are refined so as to account for as much of the data as possible. The outcome of an ethnographic study is a thick description of a community's practices, interpretation/translation of those practices to the outside world and a grounded theory that supports the interpretation.

In ME3110, my participant observer's activities included the following. During the ten week term, I attended all classes, took extensive field notes on these classes that included general descriptions of the activities, professor talk and student dialogue taken verbatim, artifacts from the board and hand-outs. I participated in and took extensive field notes on all team meetings. I completed a portion of all assignments, designed and built a subsystem and helped build the team entry for the end of term competition. Altogether I put in 10–15 hours/week collecting data on tasks related to the design class. In addition, I interviewed both my own team and other team members during and at the completion of the course, as well as the professor. Throughout and at the conclusion of the data collection phase, I worked to triangulate the emerging themes and issues across the varied data types using analytic induction. The findings present an account of the team's world view (summary of findings) and the interpretive procedures used in learning design (analysis). It should be noted that prior to this research I had no education in mechanical engineering or engineering of any sort.

5. Learning to Design: A Tale of Two Views

5.1. A Summary of the Findings

Co-existing in ME3110 are contrasting conceptions of classroom occurrences. These conceptions are informed by differing world views. What I refer to as the *learning view* is held by the professor teaching the course and the two other professors who have aided its development. This view, made explicit through direct classroom articulation and instantiation in activities, analyzes the goal of the course as 'learning how to learn'. The professor orchestrates this through a variety of in-class and out-of-class activities: (1) asking students to stop in the middle of class and reflect on what they have taken from the activities so far; (2) writing these reflections on the board for others to ponder; (3) drawing graphic representations of 'mental models' that target the metacognitive skills of analysis and synthesis, articulation and reflection; (4) assigning learning essays that focus on moving students from an analytic or 'bits and pieces' understanding of the design process to a synthetic or conceptual understanding of the phases of informed decision-making; and (5) describing design as an 'intellectual, cognitive activity'.

The 'cookie activity' is an in-class activity which embodies the principles of learning to which the professor subscribes. He orchestrates this activity by giving every student three different kinds of cookie. He then asks them to choose one to buy based solely on experience. On the board he tabulates the answers. Next, he asks them to observe and experience the cookies very carefully using all the senses and to choose a second time. Again he tabulates the answers so as to note changes. Finally he asks each person to 'talk to the cookie' to get inside it, to experience it from a different angle. Again, he tabulates the answers noting changes. For third year engineering students well-enculturated into learning via lectures and white boards blackened with strings of algorithms, such an activity is unsettling and discomforting. Its intent, though, is to move them away from decision-making based on experience alone toward informed decision-making based on observation and innovative angles of analysis.

A suite of tools is provided to scaffold the analysis of the design problem, planning for the term, selection of the best concept, and the choice among trade-off issues. The professor regularly reminds the teams to make the best use of each others' resources and to aid one other on this learning journey. 'Adding value' is a recurring theme. It means starting with existing resources – ideas, experience, knowledge and members – and building on them, making them better. In short, the professor operates with a conception of the class as being an environment designed to foster learning (see Table 1).

In contrast, the student view of the course is based on a different set of assumptions, ones informed by years of participating in the institution of schooling. For that reason, I refer to this as the *institutional view*. Because they have been trained from kindergarten on to complete teacher-initiated tasks, their gloss or interpretation of the classroom looks much more like a work-flow approach found in business organizations. Opportunities for learning about the design process are represented as tasks to be completed and turned in. The know-how that is supposed to come out of activity-based learning is understood as getting straight the set of tasks and operations required to get a good grade. Conceptual understanding is glossed as just another set of methods and procedures to be mastered or cleverly faked to pass the course. Moreover, the numerous cognitive tools such as TQM affinity diagrams, House of Quality decision-making charts, phase/event/information charts to manage planning and software packages are not tools but impediments to speedy task completion. Further, student groups are understood not as hubs for

Table 1.

	Learning View Explicit	Institutional View Tacit
Goal of course	Conceptual understanding	Procedures/methods
Meaning of activities	Vehicles for learning	Tasks to complete
Function of assignments	Development of know-how	Create busy work
Function of tools	Distribute cognition	Impede task completion
Role of collaboration	Promote learning	Divide and conquer

collaborative learning but as a collection of individuals ready for parallel processing of an action plan that will lead to task completion.

This mismatch between the espoused course objectives and the enacted interpretations of classroom activities and tools impedes student appropriation of the tools of the trade. An institutional context driven by bell curve assessment and exams designed to weed out the less talented have constructed task completers motivated not so much to learn as to get an acceptable grade. Historically, this institution took pride in the fact that a third of the entering students failed to complete the four years. Course loads that are too heavy, timetables that are so tight that meeting with team members is problematic, family and job responsibilities and core courses designed to fail a certain percentage of students have each helped to construct the task-focused model with which students operate. There is no simple cause and effect here, but a web of experiences, activities, memories and models derived from years of being students. The fallout from these differing interpretations is discussed in more detail below. I have titled this section *pedagogic issues* because the findings impact on both the learning and the teaching of design.

6. Pedagogic Issues

6.1. Initiation into Inscriptional Systems

Design in this course calls for a great deal of soft proto-typing (ideation, paper work and model building) leading in the end to a hard prototype or artifact built by the students. This transformation is facilitated through a series of six reports designed to move students from the conceptual phase to the embodiment phase and finally on to the building, testing and execution phases. In these reports, student knowledge is represented or *mediated* differently. At times, students use spoken words to articulate ideas, at others, paper documents, graphic representations, or math models. As the team moves from an intuitive understanding of the design problem (conceptualization) to engineering analysis as the basis for selecting the best concepts and on to final selection of the best concept, knowledge assumes a variety of forms. Essentially, there are five categories of assignment types:

(1) *Text-mediated assignments*: knowledge is represented linguistically in written documents. These include contracts, abstracts, technical briefs, executive summaries, justifications.
(2) *Graphics-mediated assignments*: knowledge takes the form of bubble diagrams, time/event diagrams, flow charts, bar charts, pictures, TQM tools such as affinity diagrams and house of quality matrix and drawings of the device.
(3) *Symbol-mediated assignments*: knowledge is represented in algebraic equations and linear graphs.
(4) *Computer-mediated assignments*: knowledge is represented in computer generated charts using course specific software for solving decision support problems.
(5) *Speech-mediated assignments*: knowledge is represented in individual speeches and group presentations.
(6) *Artifact-mediated assignments*: knowledge is represented in a hard prototype built by team.

Managing the product realization process is hard, and by giving students these assignments, the instructor's intent is to guide the teams through the turbulent waters. The explicit function of these assignments is to scaffold both the process of doing design and the process of learning to do design. The reports have been designed to facilitate the decision-making process and to have student/designers pay attention to the stages through which a decision-based designer passes. Transforming one form of knowledge into another is crucial to the design process. Students turn concepts and fledgling ideas into articulated statements. Such statements can be represented graphically as models. The manufacture of an idea is then broken down and represented in a planning tool. Engineering analysis in the form of math notations becomes the basis for final selection, compromise and building.

The intent is well-motivated. The differently mediated assignments are offered as learning affordances for understanding the complexities of design. Scaffolding student passage through an ill-structured, complex problem-solving domain can both help them reach the set goal (support performance) and model a process for future activity (promote learning). But how well does it work? What were the difficulties in making the transitions between different representations of knowledge?

There were times in the term when students on the observed team maneuvered easily between these differing representations of knowledge and understood their role in the whole design process. However, there were four times when students missed the affordance of a representation. These occurred in

- transforming conceptual problem understanding to graphic representation of problem space using the seven management and planning tools from TQM;
- transforming the preliminary design concept to computer mediated decision support problems;
- transforming the design concept into mathematical notations;
- transforming linear equations, representing feasible design space, to hard proto-typing.

To illustrate, I discuss the first instance above. To carve up the design problem space, the author's team used seven graphical management and planning tools from TQM. These included the Affinity Diagram, Interrelationship Digraph, Tree Diagram, Prioritization Matrices, Matrix Diagram, Process Decision Program Chart, and Activity Network Diagram [3]. This suite of tools can help students understand the relationships between the varied parts, requirements and features of the problem. They can serve as a representation of the current understanding of a problem space against which new information can be compared and contrasted. The observed team dutifully plotted out the problem space using these graphic tools as required by the assignment, but it was clear from discussions that the team members never appreciated the affordances of these tools for exploring a problem domain. For them, the exercise was just about filling boxes, drawing lines and filling in charts on the way to completing a required assignment. As evidence for this assertion, the team never returned to these representations as greater knowledge about the design needs develop. Once turned in as part of an assignment, the tools were forgotten. A different source of evidence for this assertion surfaced in a very different context. While collecting data on a senior level design team in another course, students who had previously completed ME3110 failed to use any of these tools in the problem-structuring phase. When I asked about the tools, the response from one of the students was, 'They are a waste of time'. Since these tools were not perceived and understood as alternate ways of representing current information and knowledge about a problem, it is doubtful they will be used again by the members of my team. The affordance of the TQM graphics was not taken up.

One explanation for this failed uptake is the tacit task-oriented view presented in Table 1. For the team members, the diagrams, diagraphs, matrices and flow charts were just another set of tasks to be overcome, not useful tools to be learned and used in other problem-solving contexts. This explanation may in itself suffice, however, research on learning shows this failure to recognize an affordance to be a common phenomena even among motivated learning-oriented students. In particular, external representational systems, or what Pea refers to as 'inscriptional systems', often pose difficult problems for learners.

> Inscriptions rarely reveal their affordances for activity. It is too rarely recognized that inscriptional systems, while allowing for efficient achievement of certain goal-directed activities, also make those very activities opaque to persons not privy to the conventions for their interpretation and use, an unfortunate circumstance for learning mathematics and science. [16]

Graphic representations from TQM, linear equations, and written documents are all examples of inscripted intelligence. Mature users of such systems know what the systems are good for, what tasks they afford, the questions and inferences they can tackle with their use, and the limitations. To the novice, such things are unclear because these functions do not lie in the inscriptions themselves but in the roles they play as people do things in specialized contexts. As Pea observes [16], to fully appreciate the affordances provided by such systems, notices must be introduced to and participate in activities that give meaning to the inscriptions. Although the students on the team participated in activities meant to reveal the affordances of these tools, that participation in itself was not enough.

Several features of the ME 3110 learning experience may account for this. First, TQM tools were used only once to carve up the design space, but never used again. Just one experience with this system was not enough for the students on my team to grasp its affordance. It may have been beneficial to introduce fewer inscriptional systems and allow for repetition of each in several instances. Moreover, the long distance between the example used to teach the TQM tools and the students' engineering design problem made understanding difficult for some students. The illustrating example targeted a student planning for the day ahead. Clearly, the attempt to map onto student experience and knowledge was well motivated, but the example was so far removed from mechanical engineering design that the observed team had difficulty making the connection and mapping between the engineering design problem and the example. Finally, in the class materials, TQM's evolution as a management tool was foregrounded not its use in engineering problem-solving. As a result, students had difficulty making the connection between TQM tools and design. The findings suggest that when tools are introduced, their usefulness to the immediate problem context needs to be foregrounded even though they may have been designed for another situation.

6.2. Distributing Intelligence: Social and Material Dimensions

Very much related to this question of how best to initiate students into the uses and limitations of inscriptional systems, is how to apprentice students to the distribution of intelligence that underlies the use of technological tools and collaboration. Pea explains that there are two parts to distributed intelligence:

> There are both social and material dimensions of this distribution. The social distribution of intelligence comes from its construction in activities such as the guided participation in joint action common in parent–child interaction or apprenticeship, or through collaborative efforts to achieve shared aims. The material distribution of intelligence originates in the situated invention of uses for aspects of the environment or the exploitation of the affordances of designed artifacts, either of which may contribute to supporting the achievement of an activity's purpose. [16, p. 50]

Both forms of distribution are important in the ME3110 design course. The social distribution comes as students tackle the design problem together as a team and build for the competition. Students have differing forms of expertise which others can potentially learn and, in this sense, students can take turns guiding each other. A student with extensive shop knowledge, for example, can distribute this intelligence so that others develop this knowledge too. There were times when this kind of social distribution of expertise occurred on the observed team. Three members came away from the experience with knowledge of three computer applications, Excel, Word and MacDraw, that they did not have at the start. This was due in part to the on-line tutoring of one team member. Two members also developed skills in using shop tools from working with a team member who had tinkered both with his father and alone at home in a garage workshop.

Nonetheless, on the whole, different forms of expertise failed to get passed around. Apprenticeship opportunities were ignored or avoided in favor of a 'divide and conquer' strategy. Tasks were processed in parallel so as to reach completion as soon as possible. Two events illustrate this. Mindy was the writer, so she handled many of the documents.[‡] For one assignment, each student had to turn in an abstract of their subsystem. Two members of the team had no idea what an abstract was while Mindy did. The two struggled alone turning in what they thought it might be and, as might be expected, were wrong. The opportunity for them to learn how to write an abstract, an important skill, was lost. The second missed opportunity occurred when the student responsible for the power system was developing gearing for the drive train, an often difficult topic in mechanical engineering. Bill was deemed the builder, so he went off, figured out the gearing alone and presented the concept for the power subsystem when he had figured out the essential engineering analysis. The others on the team saw the system 'black-boxed' when it was completed, but did not learn about the specifics of the gearing that went into the construction of this subsystem. Given that these students were learning to be engineers, a valuable learning opportunity was lost.

Individual student knowledge and skills were harnessed only to get the job at hand done. More often than not, the 'student-expert' would take over and complete the job with the other team members abdicating any learning responsibility for that portion. The result being that they failed to pick up those skills. One reason for this 'divide and conquer' strategy is that students saw themselves (tacit view) as completers of assignments (tasks) rather than as accumulators of know-how. In another paper, it was suggested that this might be thought of as the 'engineering model' of collaboration [15]. In this model, we conjectured that engineers, in contrast to scientists, work together more for achieving a desired effect (a design) than for achieving understanding or learning. Likewise, the observed team members valued efficiency in building a solution more than distributing expertise or understanding among the group members. As a result, they did not intentionally mine the group for resources or expertise in an effort to learn. Rather, each member staked out his own subsystem, learned that area and little more.

An obvious impetus for this situation was the fact that most student assessment focussed on subsystems for which individual students were responsible. Only in the group presentation in week seven and in the final stages of building and testing did the team have to focus on the whole mechanism. More specifically, the major assignments required each team member to

[‡]All student names are pseudonyms to protect the anonymity of the respondents.

take responsibility for developing concepts, doing preliminary selection, final selection and compromise on their own piece (subsystem). This arrangement washed back into the group process so as to minimize the need for intersubjective understanding of the total project. In other words, although the project was touted as a team endeavour and total project performance was evaluated, on the whole, the assessment tools targeted individual students, thereby minimizing the need to distribute skills, knowledge and understanding among members of the team.

The material distribution of intelligence should occur in this design project as students exploit the affordances of a variety of tools, computerized and otherwise. These include TQM graphics, planning diagrams and flow-charts, MacDraw, Word and Excel. Professionals who use these tools know how to exploit the intelligence carried in them or, put another way, understand why it is useful to off-load certain tasks in achieving a goal. Novices often resist off-loading cognitive tasks preferring instead to manage tasks in the head. I witnessed this on my team.

In concurrent engineering, planning is crucial because all design phases from conception to analysis to manufacture need to be anticipated and undertaken. Two planning tools useful for developing an overview of the whole process and for helping students budget time throughout the quarter were provided. One, the PEI Diagram, assists students in planning for the Phases (P) in the design cycle, the Events(E) and the Product Specification Information (I) needed for them to accomplish tasks. Phases include such things as designing for concept, designing for manufacture, designing for improvement. Events, on the other hand, include stages such as group bid, initial conceptual designs, preliminary design, selection, competition, etc. Information entails what the team would need to know at a particular time. This would include problem specifications, problem understanding, basic concepts, subsystem specification, or interface requirements, to name a few.

The other tool, the DSPT (Decision Support Problem Technique) Palette, instantiates the flow of activity from start to finish and how the Phases, Events and Information-creating tasks fit into that flow. Both tools serve as a public record for view and review. They are designed to help the team keep on track as they move from problem statement to built artifact. The problem was that for the observed team, task allotments and schedules were not in some graphic representation but in the head. The team filled out the charts to complete the assignment but resisted off-loading this individual in-the-head activity onto a tool that could be useful as a group document. As a result, there was no time to test the device before the competition and on-the-fly adjustments had to be made to broken parts minutes before the competition.

This failure to grasp the power of the planning tools stems partially from the demands placed on students in the number and breadth of the assignments required in ME 3110. Students had little time to reflect on and develop an appreciation for the tools being introduced even though the professor continually reminded the students how important both initial and revised planning were to eventual success. Moreover, for novices to turn what they perceive to be in-the-head tasks over to out-of-the-head cognitive tools, they must be convinced that such a route is more effective. The problem is that this often becomes clear only with repeated use. Students in this class used the tools on one large, extended project only, so they never perceived the ways in which they could support complex cognitive activity. The data suggests that for the affordance of a material tool to be understood, reflection and repeated use of that tool in a variety of domains will be required.

7. Implications

The lessons to be learned from this case study of engineering students learning to become designers are varied. Lesson one is that old ontologies die hard. As has been observed by others [10], doing design does not insure the learning of design, for tacit student understanding and constructions of classroom activities and affordances can run afoul of intended outcomes. Even if the teacher sets up an environment that values and promotes knowledge building and learning to learn, students will not necessarily assume the concomitant roles of knowledge builders and learners. Student interpretations will not necessarily map easily and unproblematically onto those of the teacher. This study suggests that, at least with post-secondary students, the tacit view is so resilient and resistant that it overrides and confounds the explicit view. The result is that even in a classroom where a great deal of reflection and attention to learning is present, activities specifically developed to promote reflective practice, life-long learning and knowledge building are, for many students, nothing more than tasks to be completed. It would seem that changing successful engineering students from grade-getters and task completers to green monkeys at this late stage in their educational careers required more than just teacher talk and student reflection. The student meanings ascribed to activities, tools, and work configurations need to be transformed from a task-oriented *verteshen* to one that is learning-oriented.

Interestingly, I believe members of my team began the quarter with a learning view, but after getting back the first assignment with a disappointing evaluation, shifted back into a task-oriented mode. I believe this happened for two reasons. In a previous ethnographic study of freshman composition [14], I identified a recurring cycle of interaction, the PTE structure – Prompt/Text/Evaluation, in which a teacher-assigned topic is answered by a student essay and responded to with a teacher-assigned grade. I noted that students almost without fail turn directly to the grade rather than the comments, suggesting that they interpreted the event as grade-driven. I concluded that the PTE sequence promotes a task orientation rather than a learning or communication orientation to pedagogic activities because the grade focuses attention on performance not understanding. This same situation was witnessed with the design team. The return of the first graded assignment revoked the sense that this class might be different (i.e. not punitative). The team in response abandoned the early orientation to learning in favour of a task orientation.

This shift to task orientation was further encouraged by the assessment system which entailed quantitative comparison. The assessment tools for each of the six reports consisted of a list of desirable assignment features that were graded on a scale of 1–10. The quantitative nature of this tool very specifically focused the students on achieving 10's on the second assignment rather than understanding the tasks that would go into the product. Ethnographic data suggests that a way to refocus students on learning might be to develop assessment techniques that more closely resemble the kinds of evaluation found in apprenticeship relationships. A successful apprenticeship is a dialogic relationship between an expert and a novice. Through observed and shared activities, the expert models behavior. Feedback to the novice is qualitative, instantiated in dialogues that ask the student for explanation, justification and articulation of the tasks being undertaken. Although the professor in this course did use the learning essays as alternative assessment, the numerical nature of the report feedback led students back to a task-driven, performance driven mode and few students really took the learning essays as a serious form of assessment.

Lesson two is that less is more. As described earlier in the paper, this is the first course in the mechanical engineering sequence that calls for real application/integration of skills and knowledge in service to complex problem-solving. It is also the first experience these students have working on teams for the whole quarter. Additionally, others have few or no computer skills. In other words, the scaling up that is required in a number of areas from doing individual back of the book analysis problems alone on paper to building a complex engineered mechanism with several subsystems on a team with four or five other people using a suite of tools is too great. To become competent in each one of these areas – application and integration, team work and tool use – students need time, repeated experiences, and a lot of reflection on the learning. Although reflection played a big role in ME3110, it was insufficient to help students make sense of parts of the experience. Thus, students often missed the affordances of certain tools, the team expeience and the reflection itself. Scaling down seems to be an obvious solution. This could be accomplished in either of the following ways:

- Fewer tools, a less complex design problem and team coaching on communication and collaboration would provide a better venue in which to learn and practice design and the complimentary skills of collaboration and tools use.
- Alternatively, certain central pieces of product realization such as problem analysis and understanding, using TQM tools, team work or use of computerized tools could be introduced earlier in the curriculum so that when students tackle the complex design problems in ME3110 less would be on the table for them to learn.

Lesson three is that teacher-orchestrated reflection on learning is necessary, but not sufficient. The professor in this course strove to help students develop into reflective practitioners. Thus, he asked students daily either during or at the end of the period to reflect back on what they had taken from class. Each student had a chance to articulate what had been significant in some way for her. Additionally, learning essays were turned in with every assignment that asked students to observe and describe what was going on with the project and extract from that higher principles or abstractions. Finally, a part of the final grade depended on an end of term essay on ME3110 as a learning experience. Even with all of these teacher scaffolded forms of reflection, many of the students failed to develop the ability to look at or back at experience in order to extract important principles so as to build a rich scenario or case. In fact, many never grasped the importance of reflective practice, rejecting such teacher-orchestrated activities as 'a waste of time'. The question that both the professor and his collaborators continue to grapple with is how to help students reflect on experiences so as to extract the important learning issues. Current efforts in this class are directed toward understanding the prompts/tools that will help students build 'learning vignettes' or mini-cases for group learning and later retrieval and transfer to new problems.

8. Summary

Collaborative design is an activity that all engineering graduates must be educated for if they are to succeed in industry. New models of education offer resources for teaching this complex activity; however, existing educational practices make it very difficult to transition third year engineering students from back-of-the-book problem-solvers to knowledge-makers. This study offers avenues for helping students with this transition process. Nevertheless, to really move students towards practices of life-long learning and attentive knowledge-making, design-based activities should be experienced in all four years of the curriculum. Currently, there are movements afoot in certain technological institutions to reconceive engineering education and to infuse design into fundamentals courses. For students to truly develop the capacity for solving the complex problems regularly encountered in product realization, this is the best solution. For this to happen, on a large scale, however, major changes throughout most institutions of engineering would need to occur. Whether industry and recent alumna can exert enough pressure on these institutions to make that happen remains to be seen.

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