Using a Developmental Model to Facilitate Team-Based Design Experiences in a Pre-College Engineering Science Camp

W.C. Duncan-Hewitt[1], D. Mount[2], S.W. Beyerlein[3], D. Cordon[3], and J. Steciak[3]

Abstract

Design projects in engineering education should help students both develop and demonstrate integrated performance capabilities. Ideally, design experiences should produce growth in student's cognitive, social, and affective processes. The central question driving this work is how to purposefully design and facilitate classroom projects in order to generate all three types of growth. To this end, we applied a model of development, synthesized from the educational and developmental literatures, to investigate successful and unsuccessful design activities in the context of an Engineering Science Camp for teenagers. To assess the efficacy of the model of development, we gathered qualitative research data through observation, mentor notes, and interviews with campers. Our study supports the notion that beginning college students occupy a distinctly different cognitive and social level than that expected of graduating seniors. Furthermore, these differences stem more from 'how' they think and relate to other's points of view than from 'what' they know. Effective project learning needs to include a strong mentoring element that builds trust by engaging cognitive, affective, and social behaviors at the current developmental level and then promoting new, more complex behaviors through appropriate learning challenges.

Introduction

A central purpose of engineering education is to help students internalize systematic thinking processes such as the scientific method and the engineering design process (ABET, 2008). These processes tend to be more abstract and complex than the thinking patterns to which young engineers, many still in their teens, have previously been exposed (NAE, 2004). The literature of constructivism (Fosnot, 1996; Steffe, 1995) and the associated method of problem-based learning (Boud, 1985; Albanese, 1993) suggest that realistic, design experiences provide an efficient solution. However, introducing open-ended design problems without providing interventions that generate growth in self-concept, thought-structure, and design behavior can lead to dramatic failures in comprehension and performance (Woods, 2000). For this reason, a guided-design approach to problem solution better matches the skill level of undergraduates (Wales, 1987). This work begins by outlining the major features of a developmental model that spans the ages, demographics, and learning domains associated with engineering education. This work then illustrates how the model provides a rational basis for choosing appropriate teaching methods for design experiences associated with an engineering summer camp that occurred between 1998 and 2000. In as much as the teenage participants in the camp are at the beginning of the same developmental transition that undergraduates are completing, the results of this qualitative research can be generalized to the undergraduate experience (Bransford, 2000).

Developmental Model

The developmental model selected for this work is the Crux Developmental Model (CDM) (Duncan, 2001) which is a synthesis of work by developmental constructivists (Erikson, 1963; Csikszentmihalyi, 1993; Gruber, 1997) and the work of William Perry (1970), Mary Belenky (1986), Robert Kegan (1994), and Paulo Freire (1973). The model is neo-Piagetian, defining levels of developmental that connect adolescence to adulthood. Although the model suggests that the individual moves through a series of cognitive paradigms with a qualitatively distinct construction of both subjective and objective knowledge, the movement between these paradigms is not sudden. The CDM identifies six observable levels of cognitive complexity (L0 to L5) for which there are differences in self-concept, thought-structure, and behaviors. Each level poses, in effect, a "crux" that students must climb past.

Deeper, more complex levels incorporate the abilities of simpler, more superficial ones, but they also transcend them. It is significant to note that the individual capable of operating at a deeper level does not consistently operate there. One of the functions of deeper complexity is the ability to discriminate between tasks that require more intricate, systematic and time-consuming thought and those tasks for which more superficial approaches are acceptable. Table 1 describes characteristics of each level in the CDM, supplying additional detail about the middle three levels which are most relevant to teaching young adults in college classrooms.

[1]School of Pharmacy, Saint Louis University
[2]Educational Consultant
[3]Department of Mechanical Engineering, University of Idaho

It is generally accepted that in middle-class America, L2 is the level to which adolescents construct their general knowledge while L3 is the level to which knowledge is constructed in conventional adulthood. The learning outcomes for engineering undergraduates expected by the Accreditation Board for Engineering and Technology (ABET, 2008) are probably best characterized as L3 behavior. Similarly, a goal of graduate education is to help students build L4 behaviors. A large number of engineering professionals operate at L4, although some display L5 behaviors. The transition from L2 to L3 typically occurs in the late teens and early twenties. While faculty may ultimately want engineering graduates to display characteristics of L4, this is not possible without building a bridge from L2 to L3 in undergraduate courses and subsequently building a bridge from L3 to L4 in professional practice and/or graduate education. Successful negotiation of each bridge is made easier by the guidance of a mentor who balances supportive activities at the current level of development with more challenging ones from the next level of development.

L2 requires the teacher to be a decisive, discipline-oriented authority. An educator whose goal is to help learners grow from L2 to L3 starts with an authoritative style and moves toward being more of a reciprocal motivator/guide as additional responsibilities are accepted by the learner. While affirming self-sufficiency, competence, and role differentiation, the educator must demand reciprocity and expect trustworthiness. In the process, the educator must expect and plan to deal with the learners' conflicting emotions. Such internal conflicts typically arise when L2's alternately feel constrained and controlled when facing mutual responsibilities and expectations, and then out-of-self-control when they do not meet self-expectations to master their impulses. Teamwork builds commitment to interpersonal expectations, while continued individual assessment affirms identity and discourages exploitation of others.

Table 2 maps the Crux Development Model to intermediate levels in a rubric for self-growth suggested by the Process Education Literature (Myrvaagnes, 2007). Cognitive, social, and affective performance is described in terms of typical classroom behaviors. L2 individuals are comfortable with the status quo. They have some self-assessment and personal development skills that support low-quality feedback, but they tend to view these skills as a poor investment of time and energy. L3 individuals are responsive to others, seek assessment by others, and are eager to implement feedback that bolsters project-related performance. These individuals are enjoyable and productive team members. They are willing to accept responsibilities for tasks and accountable for timely, high-quality completion. L4 individuals are self-starters. They actively seek assessment from others, listen carefully to their ideas, and are attuned to personal strengths that they can effectively and efficiently use to implement change. The broad research question motivating this study is how to catalyze movement between L2, L3, and L4 in college-level coursework. Movement from L2 to L3 is assumed to be the developmental challenge associated with undergraduate education. On the other hand, movement from L3 to L4 is assumed to be the developmental challenge associated with the transition to graduate study.

Table 1 Crux Developmental Model

Developmental Level	Self-Concept	Thought Structure	Perception of Teacher
L5	Autonomous	Conceptualizes multiple large-scale, interacting systems	Co-evolver
L4	Conscientious Individualistic	Conceptualizes abstract systems Makes key decisions using fundamental principles	Serves as role model Challenges personal performance to grow proficiency in skills
L3	Conformist Self-aware	Links multiple abstractions at a time Makes key decisions based on consensus	Approves of efforts Manages conflict
L2	Opportunistic Self-protective	Relates one abstract concept to another Expects others to make key decisions	Gives information Protects from failure
L1	Egocentric	Linked concrete concepts	Someone to mimic
L0	Embedded in caretaker	Concrete concepts	Magician

Table 2 Relationship Between the Crux Development Model and Levels of Self-Grower Commonly Observed in Higher Education

Level	Cognitive	Social	Affective
L4 Self-Starters	Greatly exceed expectations for project work, discovering and sharing valuable knowledge with instructors and other teams	Initiate and mange social structures that get the most out of every hour of team activity, motivating contributions by other members at lower developmental levels	Secure and well-balanced but often feel frustrated when they are not being challenged to perform at higher levels
L3 Responsive Individuals	Use their problem-solving, learning, and thinking skills to improve their performance and get results that usually meet project expectations	Are positive people whom classmates enjoy and want to have on their teams, capable of successfully resolving team conflict with minimal external guidance	React to challenges with improved performance rather than complaints, feeling good about their individual and team outcomes
L2 Content Individuals	Are satisfied with modest levels of effort in learning, thinking, and problem solving that often do not meet project expectations	Interact freely with friends, but actively avoid more diverse contacts and are not able to resolve team conflict, even with extensive external intervention	Do little more than what is asked, feeling their contributions are not very significant or important

Camp Organization

Context: The Idaho Engineering Science Camp was designed to be an exciting adventure into the fields of science and engineering for students enrolled in the 8th to 10th grade. Selection criteria include a recommendation from teachers or counselors, an interest in, and ability to benefit from a pre-college engineering experience. The camp uses hands-on activities and projects involving self-discovery, cooperative learning, critical thinking, and problem solving. Most activities are team oriented and occur in a variety of settings, including computer labs, experimental labs, and design labs. During the camp, the students live on-campus in a college dormitory under the supervision of camp staff. The camp was also conceived as an opportunity to introduce graduate students in modern teaching methods and build community among faculty and graduate students around best practices in team-based design.

Objective: The goal of the one-week camp was to have teenage campers appreciate that anyone can have fun building and operating a model vehicle, but that if one wishes to optimize the performance of that vehicle in a timely manner, physics and engineering theory become essential tools. As such, the camp was conceived to generate interest in technical careers and to sustain commitment to math and science preparation in high school, keeping the door open for seamless articulation with pre-engineering programs in college. To support this goal, various engineering tools and pertinent physical principles were the focus of various hands-on laboratory sessions during the first half of the camp. A team-based, transportation-related design competition was the focus of the second half of the camp.

Instruction: All learning activities took place in a small-group, cooperative learning format in which critical thinking questions and large group feedback (to assess their answers) were used extensively to guide discovery. Computer technology was used for information processing and modeling. Camp activities taught theory, engineering design and fabrication, modeling (solid modeling and spreadsheet analysis), and presentation skills (posters, PowerPoint, and web-page design). All activities had the following components: Purpose, Plan, Assessment Criteria, Learning Resources (models, concrete examples, and materials), Critical Thinking Questions, and Reflector Reports. These activities were implemented in three stages:

- set-up—a brief lecture explaining the activity and orienting the students to the components of the activity and associated learning resources;
- group activity—guided by objectives and critical thinking questions, and usually involving the manipulation of concrete or abstract models; and
- closure—large group discussion, ensuring that the intended learning was actually achieved, and often provides time for self-reflection as a means of continual improvement.

There was a wide range of difficulty associated with the different learning activities because they often were designed and taught by instructors with very different experience and expectations (undergraduate students, graduate students, engineering professors).

Teams: Learning communities were initially comprised of eight members. Each community was paired with a mentor (an undergraduate or graduate student) who was there to ensure safety and to facilitate the design process. After a few days, the mentors subdivided their large group into two sub-teams of four members each according to their observations of interpersonal dynamics. The two sub-teams then worked independently in undertaking an open-ended design project, but ultimately, their scores were combined in the final design contest.

Design Project: Each camp session culminated with the design and fabrication of a vehicle (cars, boats, submarines, and rockets) according to explicit rules. At the beginning of the week, the building activities were highly structured and geared toward safety, introduction of building tools (e.g., table saws), and constraints (e.g., materials that could and could not be used). Later in the week the activities were less structured as the teams planned, built, and tested their own prototypes. The vehicles were entered in a competition on the last day. Scoring was not as simple as awarding the most points to the vehicle that was the fastest, or went the furthest. Instead, the scoring was based on reliability, reproducibility, optimization, and technical communication.

Research Methodology

Undergraduate students, graduate students, engineering professors, and educational researchers associated with the camp kept logs of their observations, both to discuss at daily mentor meetings and to serve as data for consideration in writing this paper. Up to two educational researchers observed while others facilitated learning activities involving 12-15 students. Notes relevant to the following questions were compiled, verified against instructor perceptions, and analyzed to produce the recommendations in this paper.

What behaviors were demonstrated that were at slightly higher levels of complexity?

What particular learning skills appeared to pose the greatest barrier to good performance?

How did the instructor support L2 behavior and/or challenge students to display L3 behavior?

What was the impact of common instructor-team interactions? Why?

The assessment of understanding in a camp environment is somewhat problematic. In a traditional classroom situation this would be achieved through testing. But since such testing is not fun, it was not deemed appropriate for a summer camp environment and we probed understanding by asking the campers to apply the knowledge or to explain it verbally, either during the activities or during large-group debriefing. In analyzing the observations collected by camp staff, special attention was given to observations about teamwork, comprehension of physical concepts, and problem solving. Thinking patterns of more than 100 campers were observed over a three-year period involving multiple camp sessions.

Results

A range of behaviors, abilities, and knowledge was observed among the campers. Below we report our most frequent observations—ones that were representative of the average camper. Among a few campers, usually the same ones each time, more mature and less mature behaviors were occasionally observed.

Teamwork

Communication and interpersonal negotiation were almost always unilateral (having one's way or appeasing). With one exception, those who attempted to take leadership roles did not communicate or explain their plans, but just told others what to do. So-called followers sometimes listened but mostly did their own thing without explaining why, or attempting to come to an agreement about the best approach. A concerted effort sometimes emerged, but it was based on non-verbal communication.

Often, but not always, it was the member who was louder or more willful whose wishes became the team's goals, even when scientific evidence said otherwise. In groups with more than one strong-willed member, we frequently observed that failure to resolve design disagreements led to splitting of teams into two sub-teams (consisting, in some cases, of only one individual). Each sub-team built and tested their design independently, participating with the remainder of the team in a superficial manner. Consensus was not reached easily afterwards either, because, short of catastrophic failure, they could not agree on decision criteria. The feeling was "Well, so what? My prototype might work better than yours NEXT time." It seemed that many campers held a world-view that prevented them from seeing order and predictability in prototype testing.

Social loafing was not uncommon, with broken commitments, playing while others worked, procrastination, and daydreaming in hopes that others would pick up the slack during particularly challenging sessions that required either hard thinking or difficult work. Given the age of the camp participants, the appearance of these L2 behaviors was not unexpected. The more mature behaviors that were observed at other times indicate that the transition to L3 is underway, which is also expected. Interventions that strengthened campers' social skills included asking them to rephrase each other's statements until they received affirmation that the message was correctly understood, making privileges contingent on cooperative behaviors, and modeling self-aware behavior.

Selection of a cooperative learning format was very appropriate for the transition to L3. As such, it is desirable at the start of a design project to assert control and set boundaries. This aspect of CDM was emphasized in a staff workshop we held prior to the camp. Yet, our mentors were often reluctant to exercise this authority, preferring to act as friends and sometimes tacitly supporting disruptive behaviors through laughter or conscious efforts not to notice. Especially in introductory activities, close observation and intervention is necessary to ensure that performance tasks are clear and concise. While a number of more open-ended activities appealed to advanced campers, most students struggled with task organization and benefited immensely from group processing of activity instructions and from various interventions intended to promote time management (i.e. gaming, role playing, and daily progress reports).

Comprehension

Understanding of the various concepts taught in the physical science and modeling activities ranged from near complete to minimal. Concepts that campers correctly assimilated included (a) distinguishing weight and mass, (b) acceleration, (c) the meaning of a bar chart, and (d) terminal velocity. Individuals at L2 are competent at abstractions to the extent that they have a concrete reference. Second order abstractions such as Reynolds number, drag coefficient, and assumptions appeared particularly difficult for this age group. Even terms that campers used in their day-to-day language, such as viscosity and power, were incorrectly constructed. When asked to hypothesize why glycerin is so viscous relative to water, a participant answered "because it is so dense." Campers, when asked to define "power," confused it with "work" and "strength."

Campers easily followed step by step instructions for creating web pages, operating experimental equipment, and graphing data. They had a more difficult time making decisions on web page content and layout, determining sources of experimental error, and explaining trends in simple graphs. One intervention that introduced L3 thinking when students were using trial and error to resolve word processing and spreadsheet difficulties, was to ask them to (a) explain their approach, (b) assess strengths and areas for improvement, and (c) help them revise their plans before allowing them to continue. Another intervention that introduced L3 thinking when students were analyzing experimental data was to ask students to hypothesize why different results occurred and how these might change under different experimental conditions. While students enjoyed instructor interaction, these interventions were never explicitly invited and the new insights created were held suspect if they contradicted common sense. Not surprisingly, only a few campers chose to use discretionary time in the lab for reflection.

Problem Solving

An open-ended design process requires that a multi-step methodology be applied to a self-determined goal, making it fundamentally an L4 problem. L4 problems are characterized by the need to select criteria for outcomes according to general disciplinary principles, then assuring, through testing, that these criteria have been met after a design has been detailed and constructed. For L2 students, the process obviously must be greatly simplified. For the camp, the design process was amended and implemented as follows:

- Design criteria were pre-specified. It was decided that a scoring scheme appropriate for the L2 to L3 transition should be based on two variables (requiring L3 understanding of relationship) rather than just maximized performance on one variable (something that L2 finds easier to understand).
- Testing procedures were pre-specified and campers received explicit training on data collection and analysis methods.
- Materials and equipment were rigorously limited.
- Campers were shown a prototype that was built by the mentors before they began. This was intended to instill a sense of craftsmanship attainable through proper use of conventional shop equipment, but it also limited creativity. This also reduced the time required for iteration.
- Campers were apprised of safety issues and consequences of unsafe behavior in an introductory session.
- Campers were led, step by step, through the first iteration of the design and testing processes.

Even with all these precautions and guidelines, the campers loosely adhered to the design process. Their planning tended to be limited to the next step—each step being addressed as a separate problem, which led to coordination and integration issues as well as dead-ends. They used some materials that were not on the pre-specified lists and often ignored previous results in brainstorming the next design. They would predict success wishfully (based usually on aesthetics rather than theory) and then, upon failure, make random and irrational design modifications. Perhaps most surprising, several teams abandoned competition goals altogether and pursued whimsical designs which were very non-competitive. Despite formal plans to do so, team mentors were reluctant to enforce strict adherence to the design criteria, design process, and design evaluation because they believed that this would be not fun or boring for the campers.

Discussion

The difficulties and successes that the campers had with both content and process resemble those experienced by most undergraduates. These can be traced to differences in conformity and decision-making between L2 and L3. At L2 there is adherence to rules when someone is looking. At this level, one tends to act to protect oneself from punishment, either by supervisors or peers. L2 design behaviors include:

- permitting motivated team members shoulder most of the load, unaware of missing roles
- making guesses in component selection and sizing, but unable to justify these
- constructing prototypes that mimic known designs, but often fail to meet important criteria
- evincing little interest in assessing design decisions, even after prototype failure

At L3 there is voluntary use of thinking and social practices because the actor believes it is the best thing to do. L3 design behaviors are consistent with those expected of graduating seniors. These include:

- displaying unprompted cooperation and delegation of most important tasks
- attempting to control interacting variables with knowledge why this is important
- generating prototypes that incorporate features that meet most design criteria
- asking for assessment before and after testing to ensure correctness

During the camp approximately 90% of classroom observations were matched to L2 behavior and 10% were traced to L3 behavior. These percentages are likely to shift throughout the college experience and become inverted by the time of graduation. Best practices for facilitating teamwork, comprehension, and problem solving in a way that promotes the L2-L3 transition are summarized in Table 3.

Conclusions

Because engineering students are very bright, their ability to follow directions and to memorize a large amount of information fools instructors into thinking that students understand, and therefore can apply, what they have been taught. However, most undergraduate students, like the campers in this study, have not yet attained formal operations (L3 and L4) but are still in transition from L2. The qualitative research presented in this work supports the hypothesis that by assessing a student's cognitive and social complexity using the Crux Developmental Model (CDM), educators can forecast the degree to which students will be challenged or frustrated by alternative educational methods and curricula. The model illustrates how cognitive, social, and affective activities complement one another and reinforce development during the college years. Implications for design education are summarized below.

- Build factual knowledge (e.g. elements of the design process and supporting engineering concepts) through explicit learning activities at the beginning of a mini-project. This generates shared understanding and provides a context for assessing learning.
- Use teaming to promote affective and social skills such as connection with the discipline, valuation of the design process, and active listening to diverse perspectives.
- Recognize that manipulating and linking abstract concepts at L3 requires anchoring in many concrete experiences in the cognitive, social, and affective domains. Expect this to be an ongoing challenge that requires close instructor/mentor observation and intervention.
- Hold individual learners, rather than teams, accountable for concept mastery associated with a design project. Clearly identifying expected competency levels provides guidance and closure for students in the transition to L3.
- Do not expect lower-division students to independently use and understand all the elements of the iterative design process. Take each step independently, assess explicitly, and allow time for multiple iterations within the design experience.

The authors of this paper have found the CDM framework to be a valuable tool for checking perceptions about design proficiency and formulating more student-centered interventions associated with design projects. The CDM model also complements performance levels for self-growers found in the Process Education literature (Myrvaagnes, 2007).

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Table 3 Teaching Strategies that Promote Growth from L2 to L3

Teamwork

1. Enforce a "rule" that any suggestion is followed by a request for feedback.
2. Ensure that every criticism is followed by a rationale and a constructive alternative, and that the recipient of the criticism is able to reiterate what was said to the critic's satisfaction.
3. Relinquish temporary leadership to every member of the team, so that each member has an opportunity to experience the accountability and satisfaction of leadership.
4. Provide structured reflection on leadership in light of actual performances that arose, and hypothesize alternatives that might be more constructive. Questions such as "What's happening here?", "Why didn't this design work?" or "Who feels frustrated that their ideas weren't considered?" are appropriate, but L2 doesn't have much patience for extensive reflection. Debriefing must be done in small doses, but with high repetition.
5. Assert authority from the beginning by rewarding exemplary behavior and disciplining transgression of interpersonal contracts so appropriate behaviors are reinforced.

Comprehension

1. Engage the students' with concrete, relevant situations.
2. Require "deep" active thinking by asking and requiring answers to critical thinking questions that force students to abstract from the concrete. Pose these questions in language that students use themselves.
3. Encourage accountability by insisting upon validation of answers using checking algorithms (such as unit analysis) and verify accountability by using a random call list.
4. Simplify or eliminate higher-level concepts.
5. Compare lists of examples and ask for clarification of similarities and differences in different contexts that could affect interpretation.

Problem-Solving

1. Make adherence to scientific and engineering methods "fun".
2. Require performance predictions and analysis of test results surrounding each prototype.
3. Construct design metrics based on interaction between multiple variables.
4. Use gaming to unite desired product and process qualities.
5. Support rapid iteration involving strategic checkpoints.

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