Applying a Hierarchical Model of Mental Growth to Educate Undergraduate Engineering Students: Preliminary Assessment

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This presentation illustrates the framework for implementing a hierarchical model of mental growth as the basis for developing critical thinking skills and engineering judgment in engineering undergraduates. We adopt the hypotheses that mental growth constitutes a progression through a hierarchy of cognition, that the critical thinking and judgment required of engineers lies at an upper level in the hierarchy, and that to reach high levels, an individual must master cognitive skills and reorganize knowledge gained at lower levels. These hypotheses provide a roadmap for developing effective teaching and learning strategies to be applied to core engineering courses taught in the sophomore and junior years. It also suggests that the conventional approach of simply applying high-level instruction to educate sophomores and juniors does not necessarily produce seniors who can think critically. Our educational strategy, therefore, is to strengthen low-level cognitive skills in sophomores and juniors that provide a proper foundation on which high-level cognitive skills can be developed. We describe teaching and learning devices that exercise low-level cognitive skills and that support effective development of critical thinking. Assessment instruments that monitor student growth and evaluate the effectiveness of these teaching and learning devices are also described.

Introduction

Engineering undergraduates are expected to apply "critical thinking skills" to solve comprehensive problems. For example, ABET criterion 3c states that graduates must have "an ability to design a system, component, or process," which involves the integration of fundamental science and engineering concepts from a variety of courses and disciplines. As another example, engineering educators are becoming more aware of schema such as Bloom's taxonomy of educational objectives and are being encouraged to include work that pushes the higher-level thinking skills: analysis, synthesis, and evaluation. We agree that students should be provided opportunities and mentoring to develop their higher-level (critical) thinking skills, but we also espouse the following hypothesis:

> *Students must first master their lower-level thinking skills before they can apply higher-level thinking skills.*

This hypothesis may seem obvious, but it is not at all clear that new engineering undergraduates possess the lower-level skills or are explicitly given opportunities to develop them.[1,2] Therefore, the main objectives of this research are:

- To devise teaching and learning devices that provide a foundation of low-level cognitive skills that support rapid and effective development of critical thinking,
- To devise assessment instruments for monitoring the development of that foundation in individual students, and
- To devise teaching and learning devices that build on the foundation to exercise high-level cognition required for critical thinking and engineering judgment.

Hierarchical Model

Our goal is to develop high-level thinking skills in chemical engineering students that they will need to function as tomorrow's engineers. We hope to develop these skills among our students *before* they reach their senior years. To reach that goal, we are applying a hierarchical model of mental growth as the basis for developing teaching and learning devices that are used in core sophomore- and junior-level chemical engineering courses. The hierarchical model that we are applying is that of Egan[3]; it comprises five cognitive levels:

- Somatic—Tactile learning, toolmaking, communication by bodily gestures
- Mythic—Linguistic and oral learning, story telling
- Romantic—Graphic and written learning, generation of pictorial representations
- Philosophic—Inductive/deductive logic, reasoning, analysis and synthesis, critical thinking, creation of theoretical constructs, generalizations (skills required of engineers)
- Ironic—Sensitivity to anomalies among philosophic patterns, learning by modeling

In this model, development of high-level skills requires mastery of skills at lower levels. Therefore, before we can expect our students to develop the philosophic skills that they will need as engineers, we must exercise the somatic, mythic, and romantic skills that provide the foundation needed for those high-level activities.

Applying the Mental Growth Model to Engineering Curricula

To provide the foundation of low-level cognitive skills needed for students to develop high-level philosophic skills, we propose the following general curricular structure:

- Sophomore year: Exercise somatic and mythic skills; develop romantic skills; introduce simple philosophic skills.
- Junior year: Solidify and exercise romantic skills; start the transition to more complex philosophic modes of thinking.
- Senior year: Exercise philosophic skills; introduce ironic skills.

In our research to-date, we have designed activities to involve students in the lower levels in our sophomore courses. These activities include hands-on exercises as well as speaking and writing assignments. Additionally, specific opportunities are provided for the students to evaluate their metacognitive development, that is, their evaluation of the process(es) by which they learn material most effectively.

Five courses are involved in this study:

- ChE 211 – Material and Energy Balances
- ChE 220 – Thermodynamics I
- ChE 311 – Fluid Flow
- ChE 312 – Heat and Mass Transfer
- ChE 321 – Thermodynamics II

The 200-level courses are taken by sophomores and the 300-level courses by juniors. The specially designed activities related to the hierarchical model are implemented in "experimental" versions of the courses, while "control" groups are taught in the traditional manner. As shown in Table 1, the experimental (designated 'e') and control (designated 'c') courses are staggered over a 3-year period. The first four courses in the sequence are taught twice per year to accommodate the large number of co-op students in the department.

TABLE 1
Courses involved in the study. Experimental sections are labeled as 'e'; control sections are labeled as 'c'.

Year	**Spring**	**Fall**
2000	---	211c,e
2001	211c 220e	211e 220c 311e 321e
2002	211c 220e 311c 312e 321c	211e 220c 311e 321e
2003	 220e 311c 312c,e 321c	---

Ideally, a plan to assess the effectiveness of the interventions would involve forming parallel sections of each course, with some of the students enrolled in the control sections and the remaining students enrolled in the experimental sections. Also, the same professor should teach both sections of a given course, the cohorts of students should be similar in terms of defined criteria (e.g., GPA, fraction of commuting students, fraction of co-op students), and the students should not cross over from the control to the modified sections and vice versa. Once the two groups of students finished the course sequence, they would be evaluated through various means to determine if there is a significant difference between them. This ideal scenario is extremely difficult, if not impossible, to achieve. Therefore, we decided to proceed without forming special sections and to evaluate the program using several assessment instruments. These instruments allow us to track individual students. These data from individual students can then be used to identify populations with similar exposure to experimental activities (e.g., population A had five 'e' courses, population B had four…).

To evaluate the effectiveness of the cognitive-model approach, several instruments were adopted or developed.

- *Survey of Basic Information* (SBI) was used to obtain demographic information that we hope to relate to students' metacognitive, achievement, and goal-orientation scores. (The SBI can be viewed at http://www.ces.clemson.edu/chemeng/cog-mod/)
- *Professional Development Survey* (PDS) was compiled from items developed from the ABET EC2000 criteria and from published, validated instruments, which measure personality traits and learning versus performance goals. (The PDS can be viewed at http://www.ces.clemson.edu/chemeng/cog-mod/)
- *Motivated Strategies for Learning Questionnaire* (MSLQ) is a metacognitive survey that comes directly from the National Center for Research to Improve Postsecondary Teaching and Learning. It has been validated and used nationally for 10 years.[4]
- *Chemical Engineering Achievement Test* was developed to assess the degree to which a student has assimilated technical content and her/his current level on the hierarchy.

In addition, students in an experimental class were asked to maintain a portfolio, which was assigned homework credit if maintained satisfactorily. The goal of the portfolio was to give the students a place to organize their work. It also provides documentation to assess student growth over all years that the student participates.

Results and Discussion

During the first year of the study, ChE 211e,c was taught in Fall 2000 and 211c and 220e were taught in Spring 2001. Details concerning demographics, teaching and learning devices, grading scales, and results are presented in this section.

ChE 211e,c (Fall 2000): As shown in Table 2, Prof. Haile taught two sections of this course, one as a control and the other as an experimental section. It was a 4-credit course consisting of three 50-minute "lectures" and a 75-minute recitation per week. After the withdrawal period, approximately the same number of students populated each section. Table 3 outlines the differences between the two sections. In the control section, presentation of material paralleled the textbook, Felder and Rousseau.[5] The experimental section used a somewhat modified order but the same content was covered. The most important differences were in the recitation and metacogitive activities. The recitation in the control section was a typical session devoted to working example problems and reviewing homework problems. There was also no explicit discussion on the process of learning (metacognition); the professor professed and the students "learned." By contrast, the recitation activities in 211e were designed to involve the somatic, mythic, and romantic levels in the hierarchy, with emphases on calculations and relating plots and data. The students worked in groups of two (with a different partner each week) answering 5-10 questions from a worksheet on a particular topic (e.g., measurements, manometers, energy balances). Figure 1 shows an abbreviated example of a recitation exercise. The students collaborated within groups, across groups, and with the professor. The groups turned in their results, which were then graded and counted toward the course grade. The somatic level on the hierarchy is covered by the hands-on activity of achieving target flow rates. Group discussions hint at the mythic level, while the calculations hint at the romantic and philosophic levels.

TABLE 2
Course information. Experimental sections are labeled as 'e'; control sections are labeled as 'c'.

	ChE 211e Fall 2000	**ChE 211c Fall 2000**	**ChE 211c Spring 2001**	**ChE 220e Spring 2001**
Instructor	Haile	Haile	Kilbey	Husson
Time (50-min. lecture) (75-min recitation)	8:00 MWF 2:00 T	9:05 MWF 3:15 T	9:05 MWF 2:00 T	10:10 MWF none
Students Enrolled	30	24	18	40
Withdrawals	6	2	2	1

TABLE 3
Differences Between ChE 211 Experimental and Control Sections

	ChE 211e	**ChE 211c**
Order of Material	Modified	Followed textbook
Recitations	Meaning Data ↔ Plots Calculations	Calculations
Metacognition	Instructor Driven How to study Problem-solving strategy Educational goals Reflections Portfolios Pop quizzes	Student Driven

Lab Exercise 4: How much stuff is that?

I. Background Information

Equipment: Scale accurate to 1 lb_m with a range of 250 lb_m.
Stopwatch
Water delivery system, which has a single, unmetered control valve
55 gallon drum

Safety Precautions: Standard ChE Unit Operations Laboratory practices: safety glasses, bump caps, shirt sleeves, no open shoes. For this experiment only, we will relax the requirement that long pants must be worn; knee-length shorts will be acceptable. *Failure to comply will prevent a group from doing the experiment.*

Objectives: The student will gain familiarity with the bucket-and-scale technique for determining liquid flow rates.
The student should be able to analyze a particular design criterion and manipulate basic equipment in order to achieve the given target.

Logistics: Lab groups of 3 students
Each group will be scheduled for 7 minutes in the UO lab.

II. Target flow rates

The lab group will be asked achieve, in the allotted time frame, three of the following flow rates: 100 kmol/hr, 100 lbmol/hr, 100 mol/s, 5 gal/min, 25 gal/min, 50 gal/min.

The instructor will inform the group of the three target flow rates when they begin the experiment *and* the order of experimentation.

III. Flow rate determination

Using the equipment listed above, the group should execute a procedure for accurately determining the flow rate of water. The group should collect water long enough to prove that they established a particular flow rate. As part of your planning, decide on particular tasks for each person and a procedure that you will use.

IV. Report

1. Procedure for determining the flow rate of water.
2. Data obtained directly from experimental measurements in the laboratory.
3. Results: target flow rates and flow rates obtained (including error). Students are encouraged to display the data for target flow rates and results in consistent units.
4. Discussion of results and reasons for discrepancies between targets and experimental results.
5. Sample calculation(s) showing how data obtained in the laboratory was transformed into reported results.

Figure 1. Example lab exercise used in ChE 211 experimental sections.

As mentioned previously, students in the experimental section were asked to maintain a portfolio, which was assigned a small portion of the overall homework grade. The portfolio was to contain sections related to the course syllabus and objectives, personal learning goals, technical knowledge (homeworks, lab exercises, tests, etc.), metacognitive activities, and an open section ("*What can I add to make a more complete picture of how I have changed and what I have accomplished this semester?*"). The metacognitive activities were facilitated through reflective exercises in which students were assigned to write about their assessment of their learning and study habits. This form of reflection is extremely important for mental growth and plants the seeds for life-long learning.

Table 4 shows the grading scale and a summary of course grades. The percentages for each major category were intentionally kept the same, although there were slight variations in requirements in some of the categories, as indicated by the asterisks. The major part of the course grade came from the three 50-minute tests, which were identical for the two sections, and the final exam. The final exams were not identical since they were administered at two different times (by university rule), but they were very similar. The final course grades in Table 4 show that the grade-point ratio (GPR) was essentially the same for the two sections, which is not unexpected for just one course.

TABLE 4
Course grading scales. An asterisk identifies an item that was included in the homework grade.

	ChE 211e Fall 2000	**ChE 211c Fall 2000**	**ChE 211c Spring 2001**	**ChE 220e Spring 2001**
Homework	16%	16%	12.5%	15%
Problems	*	*	*	*
Out-of-class surveys	*	*	*	*
Reflective exercises	*			*
Portfolios	*			*
Recitation Exercises	16%	16%	12.5%	N/A
Project				10%
Tests	44%	44%	50%	36%
Quizzes				14%
Final Exam	24%	24%	25%	25%
Course Grades				
A	3	5	3	2
B	6	3	1	11
C	7	7	7	19
D	5	3	1	5
F	3	4	4	2
GPR	2.04	2.09	1.88	2.15

ChE 211c (Spring 2001): Another 211 control section was taught by Prof. Kilbey the following semester (details in Table 2). The class size was slightly smaller but the materials and methods were the same as those used for 211c in the previous semester. As shown in Table 4, the GPR was slightly lower than that from Fall 2000.

ChE 220e (Spring 2001): An experimental section of ChE 220 was taught by Prof. Husson in Spring 2001. As stated earlier, we did not have a specific cohort of students moving from one experimental course to another, rather we tracked the students' progression through the curriculum and assessed their development individually. There was no recitation associated with this course but the lower levels on the hierarchy were emphasized as well as the metacognitive activities of problem-solving strategies and reflective exercises.

Assessment: During this first year, we concentrated on the creation and validation of the assessment instruments. In particular, the research team created and tested a Professional Development Survey (PDS). Table 5 outlines the PDS domains, the sources of the assessment items for each domain, and the reliability indices for each domain. The reliability indices were calculated from data compiled from 92 chemical engineering students in the Fall of 2000.

TABLE 5
Creation and validation data for the Professional Development Survey (PDS).

Assessment Domain	**Source of Domain Items**	**Reliability Index**
Conscientiousness	International Personality Item Pool[6]	0.91
Intellect	International Personality Item Pool[6]	0.83
Learning Goals	Roedel, Schraw & Plake[7]	0.87
Performance Goals	Roedel, Schraw & Plake[7]	0.74
Subject Matter	Research team	0.65
Professional Development	ABET criteria	0.87
Chemical Engineering	Research team	0.76

A Psychometric analysis was also performed on the MSLQ data for these students. Of the 13 subdomains that comprise this questionnaire[4], we found that only one showed borderline significant differences between "e" and "c" groups:

- Intrinsic Goal Orientation showed that students in "e" groups were more likely than those in "c" groups to participate in a task for reasons such as challenge, curiosity, or mastery, i.e., participating as an end all to itself, rather than as a means to an end.
- These results, which are compiled from a scale of 1 to 7 (with 7 representing highly likely to participate in such tasks), are shown in Table 6.

TABLE 6
Pre- and post-course assessment data for Intrinsic Goal Orientation Domain of MSLQ.

	"c" average	"e" average	Standard error
Pre-course assessment	4.96	5.28	0.12
Post-course assessment	4.98	5.60	0.13

Summary for Year 1

Over the course of two semesters we have begun to test the effectiveness of a hierarchical cognitive model on learning processes of chemical engineering undergraduates. Thus far, two sophomore-level courses (Material & Energy Balances and Thermodynamics I) have been taught in a modified fashion by incorporating activities that specifically reinforce the lower levels in the hierarchical model. The goal is to build on the lower-level skills and progress to effective use of higher-level thinking skills to solve more complex problems. Results to-date indicated that there was little difference in technical growth (e.g., final exam performance on control versus experimental groups in Material & Energy Balances was virtually identical). However, instructors in experimental courses have reported a perceptible difference in students compared to students in control sections – students in experimental courses exhibited more confidence with material, higher frustration threshold, greater willingness to work, better perception of goals, and lower resistance to professor-student interaction. We will continue to emphasize activities related to the hierarchy in junior-level courses and quantitatively and qualitatively assess the students' technical and metacognitive growth.

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