AC 2011-2134: EVALUATION AND RESULTS FOR AN INTEGRATED CURRICULUM IN CHEMICAL ENGINEERING

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Evaluation and Results for an Integrated Curriculum in Chemical Engineering

Abstract

Increasing knowledge integration has gained wide-spread support as an important goal in engineering education. The Chemical Engineering Pillars curriculum is one of the first fully integrated curricula in engineering, and is specifically designed to facilitate knowledge integration. This curriculum, in use for just over 5 years, is unique for its use of block scheduling. Block scheduling, in its simplest form, is transforming multi-semester courses into a single-semester course via extended, concentrated contact time. Among other things, the flexibility afforded by extended and more frequent contact time allows (and encourages) greater opportunity for active and collaborative learning. The specific adaption of this technique to chemical engineering has resulted in a curriculum comprised of 6 "Pillar" courses which are taken individually in 6 consecutive undergraduate semesters and are accompanied by vertically integrated laboratory experiences.

Introduction

In this paper, we present the basics of implementing a pillars-style curriculum and report on our ongoing assessment of student learning and knowledge integration using this framework. The assessment is "ongoing", in part, because the new curriculum has been evolving with time. Also, and more importantly, as this curriculum is one of the first of its kind, our somewhat unique assessment requirements necessitate development of new tools as we go. Specifically, it is critical that our curriculum be evaluated not only for its effectiveness in enhancing the ability of students to engage in systems thinking (knowledge integration), but also to specifically assess the impact of this type of curriculum on students' performance in conceptualizing (chemical) engineering principles. We report results from two assessment vehicles in use toward these ends: concept mapping exercises and concept inventories. Finally, based on our current assessment results, we suggest a few adaptation strategies that may be fruitful for cohort institutions to use to enhance knowledge integration in similar (chemical) engineering curricula.

Integrated Curricula and Block Scheduling

Prevailing wisdom from engineering educators both within the US[1–3] and in the European Chemical Engineering Universities, Working Party Education Group[4] is that the ideal engineering curriculum focuses on the following three issues:

1. Giving the students a strong fundamental foundation by concentrating on the essential core of scientific and engineering basics, including biological applications and molecular insight[5;6].

2. Enhancing systems thinking[7] by helping students to integrate their knowledge across courses and disciplines[8] so that they are better prepared to address open-ended problems.
3. Preparing and providing for continuing education and life-long learning[4].

The strong focus throughout engineering on establishing broad-based systems thinking within a discipline[1;9;10] has led the National Science Foundation to fund a number of Coalitions that primarily championed the "integrated curriculum". Until recently[11], there have been no educational efforts that have extended this (successful) approach beyond the Freshman[1;10;12] or Sophomore[13;14] years of undergraduate engineering programs. Furthermore, to our knowledge, no such curricula have been developed for graduate programs, despite the fact that the potentially multifaceted/multi-disciplinary nature of many graduate programs is arguably in greater need of this type of approach than undergraduate programs.

In the work discussed here, we report on the development and assessment of an integrated curriculum that spans the upper-class years for an undergraduate chemical engineer. Our fully integrated chemical engineering curriculum is unique for its use of block scheduling[15] — a technique with a strong literature base and proven track record in K-12 education — for the first time in a traditional higher education engineering curriculum. Block scheduling, in its simplest form, is transforming multi-semester courses into a single-semester course via extended, concentrated contact time. These courses have considerably longer contact hours than a traditional university course so that: (1) students may gain systems insight through integration of their core knowledge across traditional course and discipline boundaries; (2) the instructors have the time to include truly multi-scale (from molecular to continuum to macroscopic) descriptions of chemical engineering content; and (3) the instructors have the flexibility to accommodate diverse learning styles and incorporate active learning more effectively[16]. The ideal outcome is students gaining systems insight earlier in the educational cycle by integrating core knowledge across traditional course boundaries. The instructors also have the time to include multi-scale descriptions of Chemical Engineering content and the flexibility to accommodate diverse learning styles, especially active learning. In this way, we hope that the Pillars Curriculum can serve not only as a better Chemical Engineering curriculum, but also as a better engineering model in general.

The Pillars Curriculum

Current engineering instruction is often compartmentalized within a traditional 3-4 credit per course schedule, so that knowledge is disconnected and well-defined relationships are established across a curriculum only during the senior year, if at all[10]. By moving to a block-scheduled curriculum, we have integrated complementary subject-matter along with experiments and open-ended problems, so that students see connections across the discipline *during each course*. While individual concepts within the discipline were redistributed for the purposes on enhancing integrated insight, the overall content covered in the curriculum remained largely unchanged.

Logistically, the Pillars are a series of six high credit-count (5 or 6-credit) courses with complementary 1-credit laboratories in the areas of Foundations (Mass/Energy Balances, simple Separations), Thermodynamics, Transport Phenomena, Reactive Processes (including more Complex Separations) and Process Systems Engineering I (Modeling/Control) and II (Design). Students typically are enrolled in one Pillar class each term for six consecutive terms – from sophomore through senior year. These courses are scheduled during predictable time-windows (even when two sections are necessary; i.e., the two sections are coincident) in order to facilitate scheduling of supporting (math, physics, chemistry, etc.) courses. Students receive a single grade for each of these Pillar courses, however, the laboratory is graded separately each term. As the overall content for these six courses is quite similar to the traditional (approximately) twelve courses in chemical engineering, the pre-requisites and total credit count is essentially the same. Thus, instructors for Pillars courses receive course-load "credit" equivalent to two traditional classes. A brief description of each of the Pillars is included below.

The *Foundations of ChE* pillar course combines elements of mass and energy balances, thermodynamics, separations, and product design. This course introduces chemical engineering problem solving techniques from both a (traditional) process-centric viewpoint as well as a product-centric viewpoint. The course spans from theoretical (basic thermodynamics) to applied (separations) allowing a simple route to problem-based learning of difficult theoretical concepts.

The *Thermodynamics* pillar course combines ideas from both pure and multi-component thermodynamics. It introduces molecular insight and the tools (including commercial software) for solving both simple and complex problems in phase and chemical equilibria. The course has a strong focus on multi-scale analysis, for example, covering intermolecular potentials (molecular-scale) to aid students in choosing equations of state for novel materials (macro-scale).

The *Transport Phenomena* pillar course stresses analogies between momentum, mass, and heat transport. Content spans from the molecular origins of transport up through continuum descriptions, as well as macroscopic balances.

The *Reactive Processes* pillar course integrates reactor design, reaction kinetics, and advanced separation processes to allow the comprehensive study of systems ranging from polymerization reactors to enzyme-catalyzed metabolism to (bio-)artificial organs.

The *Dynamics and Modeling* class is the first of a two-part *Systems Engineering* pillar sequence. This course covers dynamical analysis of process systems, process control fundamentals, feedback, basic process modeling, and optimization. The second course in this sequence is the *Design* course which formally combines topics from all other pillars to allow both product and process design.

Assessment Plan for the Pillars Curriculum

In order to illustrate the educational impact of the new curricular structure, this section includes examples and results of our two primary assessment tools: (1) concept inventories; and (2) concept maps. As discussed further below, we use concept inventories (CIs) to probe a student's understanding of difficult concepts. In contrast, we use concept maps as a measure of our students' "system thinking" capability.

Assessment: Concept Inventories

While the traditional exams used in engineering courses are well-suited to gauging a student's problem-solving skills, they are often not aimed at measuring conceptual understanding[17]. Moreover, the variability in test questions from term-to-term and instructor-to-instructor makes it difficult to use student grades to distinguish between student learning and inherent differences across semesters even within the same course[18].

Concept inventories (CIs)[17–20] are standardized "multiple-choice tests" that are specifically designed to evaluate students conceptual understanding. We have administered CIs to cohort groups before transitioning to the new curriculum (referred to as "traditional" students), during the transition process (referred to as "transitional") and after adopting the new curricular structure (referred to as "Pillars" students). These results are used to: 1) establish the baseline conceptual understanding in our non-Pillars students prior to implementation, and 2) measure changes in conceptual understanding for students who participate in Pillars.

All CI results quoted here used past and/or present versions of the TTCI inventories developed at the Colorado School of Mines (CSM)[19;20] – which are now available on-line (www.thermalinventory.com). This well-written and extensively validated CI[19] has been in use over several years at a number of institutions. By splitting this CI, as suggested by the developers[20], into parts corresponding to Thermodynamics, Fluid Mechanics, and Heat Transfer, questions from this CI are appropriate for use with the Thermodynamics and Transport Phenomena (using the Fluid Mechanics and Heat Transfer questions) Pillar courses, respectively. One example of a concept inventory question used is found in Figure 1.

Our results are reported in three separate groups – thermodynamics, transport (fluids), and transport (heat). Due to the experimental and evolving nature of the TTCI during the window in which it was used (and the fact that our traditional curriculum cohort group was only available for the earliest versions of the CIs) our results show the raw scores for all of the concepts for which we have data across multiple cohorts. After statistical analysis of these results, we further highlight (in green or yellow, respectively) those results where there are statistically significant differences in persistent questions (green $p < 0.05$; yellow $p < 0.1$).

As the main purpose of the new curricular structure is to enhance integrated insight – and *not* to increase understanding of individual concepts – we perform the CI analysis primarily as a means to ensure that we "did no harm". Figure 2 shows that there is no statistical difference in the conceptual understanding of our cohort groups for 11 of the 18 tested concepts in Thermodynamics. For those that did exhibit statistical differences, the Pillars cohort improved on 5 versus 2 concepts. In the Transport Phenomena pillar, we see that Figures 3 and 4 show largely the same results as Thermodynamics. That is, for 24 of 29 concepts there was no statistical difference noted. Of the remaining 5 concepts, the Pillars cohort performed better on 2 while the traditional cohort performed better on 3.

You are in the business of melting ice at 0 C using hot blocks of metal as an energy source. One option is to use one metal block at a temperature of 200 C and a second option is to use two metal blocks each at a temperature of 100 C.

All the metal blocks are made from the same material and have the same weight and surface area. Which option will melt more ice?

a. the 100 C blocks
b. the 200 C block
c. either option will melt the same amount of ice
d. can't tell from the information given

because:

e. 2 blocks have twice as much surface area as 1 block so the energy transfer rate will be higher when more blocks are used

f. energy transferred is proportional to the mass of blocks used and the change in block temperature during the process

g. using a higher temperature block will melt the ice faster because the larger temperature difference will increase the rate of energy transfer

h. the temperature of the hotter block will decrease faster as energy is transferred to the ice

i. the heat capacity of the metal is a function of temperature

Figure 1: *Concept Inventory Example Question – CSM test*$^{19;21;22}$ *Used by permission.*

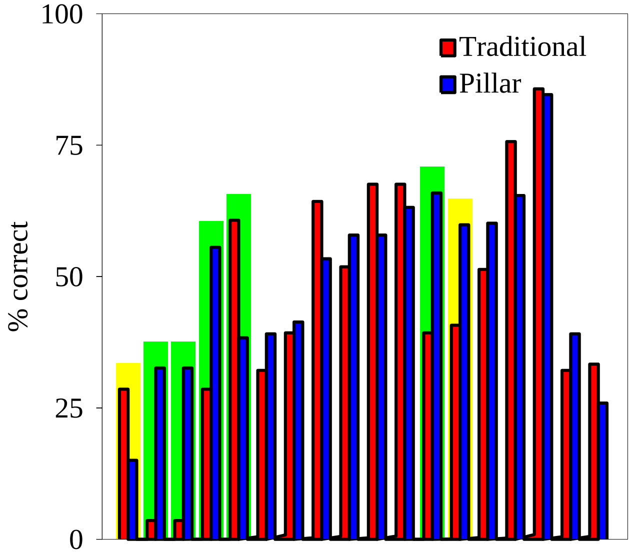

Figure 2: *Concept inventory results comparing both traditional and Pillar cohorts on thermodynamics concepts. Highlighted scores represent direct comparisons of concepts that had "significantly" differing scores between cohort groups (green* $p < 0.05$*; yellow* $p < 0.1$*). As may be noted the Pillar cohorts performed better on 5 versus 2 concepts.*

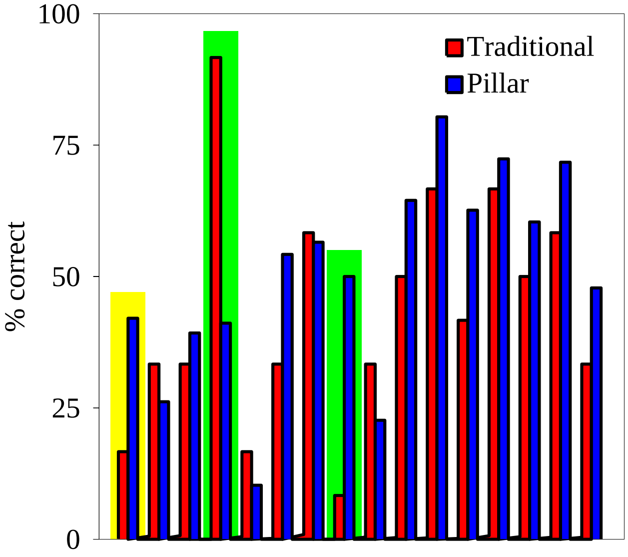

Figure 3: *Concept inventory results comparing both traditional and Pillar cohorts on transport (fluids) concepts. Highlighted scores represent direct comparisons of concepts that had "significantly" differing scores between cohort groups (green $p < 0.05$; yellow $p < 0.1$). As may be noted the Pillar cohorts performed better on 2 versus 1 concepts.*

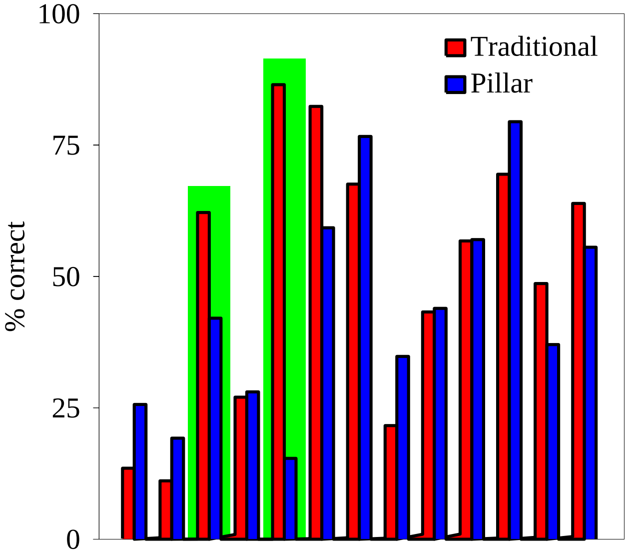

Figure 4: *Concept inventory results comparing both traditional and Pillar cohorts on transport (heat) concepts. Highlighted scores represent direct comparisons of concepts that had "significantly" differing scores between cohort groups (green $p < 0.05$; yellow $p < 0.1$). As may be noted the Pillar cohorts performed worse on 2 versus 0 concepts.*

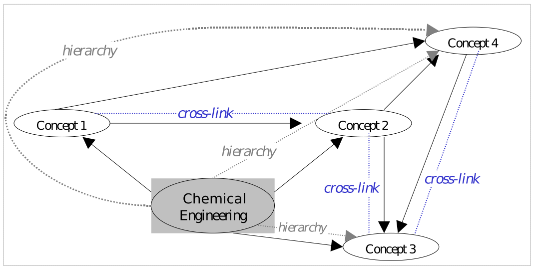

Figure 5: *Schematic of a Concept Map. Shown is an example concept map displaying links, branches and cross-links.*

Assessment: Concept Maps

Concept mapping was initially devised as a technique for measuring the assimilation of scientific knowledge in children[23] and has subsequently found a variety of uses in pedagogy including teaching, learning, planning, and assessment[24]. Concept maps are graphical representations of a student/subject's thoughts, theories, and/or concepts and their relative organization[25]. In practice, when developing a concept map, the student/subject draws a diagram showing a hierarchy of ideas or concepts linked through branches between the sub-concepts, with further links showing interrelationships between inter-branch ideas/concepts, when necessary (i.e., cross-links). A critical feature of a concept map is that it includes not only a hierarchy of ideas linked and cross-links, but that those linkages are labeled in such a way as to clearly articulate the meaning of those relationships. A schematic of a concept map is shown in Figure 5 and two examples of student work is included as an appendix (Figure 9).

In the context of its use in the current work, concept maps have been shown to be a valuable assessment tool for evaluating the extent of knowledge integration exhibited by a student/subject[25–27]. This observation makes concept mapping an attractive tool for evaluating integrated curricula, and they are used in that capacity in the present work.

While there has been some question over the years as to the validity of various methods of interpreting or "scoring" concept maps[28;29] and the relationship of these scores to overall student achievement, it is of interest here that these maps can be evaluated both based on the included content as well as on the structure of the map itself[24]. Here, these maps are "scored" by a (consistent) panel of experts using a rubric[25] which gives independent scores for the elements of comprehension, organization, and correctness (see Figure 6). These mapping exercises are performed for each group of students in the Design Pillar (and preceding transitional capstone design class) and, occasionally, by spring-semester students in earlier levels of the curriculum. In this way we can assess the students' "knowledge integration" not only as a function of curriculum followed, but also temporally within the Pillars curriculum.

In order to ensure anonymity of the participants and unbiased scoring of the maps, it takes multiple years of data collection before comprehensive results are available. Therefore, a detailed analysis of the impact of our model curriculum on "knowledge integration" will be the subject of a future publication. Nevertheless, our concept map scores to date are reported in

	1	2	3
Comprehensiveness – covering completely, broadly	The map lacks subject definition; the knowledge is very simply and/or limited. Limited breadth of concepts (i.e., minimal coverage of coursework, little or no mention of employment and/or lifelong learning). The map barely covers some of the qualities of the subject area.	The map has adequate subject definition, but knowledge is limited in some areas (i.e., much of the coursework is mentioned, but one of two of the main aspects are missing). Map suggests a somewhat narrow understanding of the subject matter.	The map completely defines the subject area. The content lacks no more than one extension area (i.e., most of the relevant extension areas, including lifelong learning, employment, people, etc. are mentioned).
Organization – to arrange by systematic planning and united effort	The map is arranged with concepts only linearly connected. There are few (or no) connections within/between the branches. Concepts are not well integrated.	The map has adequate organization with some within/between branch connections. Some, but not complete, integration of branches is apparent. A few feedback loops may exist.	The map is well organized with concept integration and the use of feedback loops. Sophisticated branch structure and connectivity.
Correctness – conforming to or agreeing with fact, logic, or known truth	The map is naive and contains misconceptions about the subject area; inappropriate words or terms are used. The map documents an inaccurate understanding of certain subject matter.	The map has few subject matter inaccuracies; most links are correct. There may be a few spelling and grammatical errors.	The map integrates concepts properly and reflects an accurate understanding of subject matter meaning little or no misconceptions, spelling/grammatical errors.

Figure 6: *Concept Map Scoring Rubric*[25]

Figures 7 and 8 where traditional, transitional, and Pillar cohorts are compared (and Pillar cohorts include results from sophomores and juniors as well as seniors). When comparing the average scores obtained, there is an encouraging trend that not only do Pillars students have a higher median score on each measure versus the traditional cohort group, but they are achieving comparable scores to the traditional cohorts earlier in their careers. Specifically, seniors that followed the traditional curriculum received a “Total” median score of 2.42, while students following the pillars curriculum received median scores of 2.92, 2.75, and 2.42 when compiling maps as sophomores, juniors, and seniors respectively. Perhaps more encouraging still is the results obtained when we compare the distribution of scores (Figure 8) for the traditional (senior) cohort to the Pillars’ Sophomore cohort. While there is an additional, small secondary mode at high scores for the seniors, for the vast majority of the distribution there is almost no difference between the scores of Traditional Seniors and Pillars Sophomores. Thus, we are encouraged that our goal of enhancing knowledge integration *early* in our students’ studies is being achieved.

Assessment Discussion and Pillars Outlook

An important observation from these results, to date, is that our acceleration of instilling integrated insight is such that the majority of the improvement is evident after only the first year in the Pillars curriculum[30] (see Figure 8). In other words, implementing only a portion of our block-scheduled model should be sufficient to facilitate an increase in integrated thinking. Not only does this suggest that other chemical engineering departments can adopt only a “limited set” of our Pillar courses, but also other disciplines – even those with more track-based curricula – can use this educational structure to enhance systems thinking in the first two years or so.

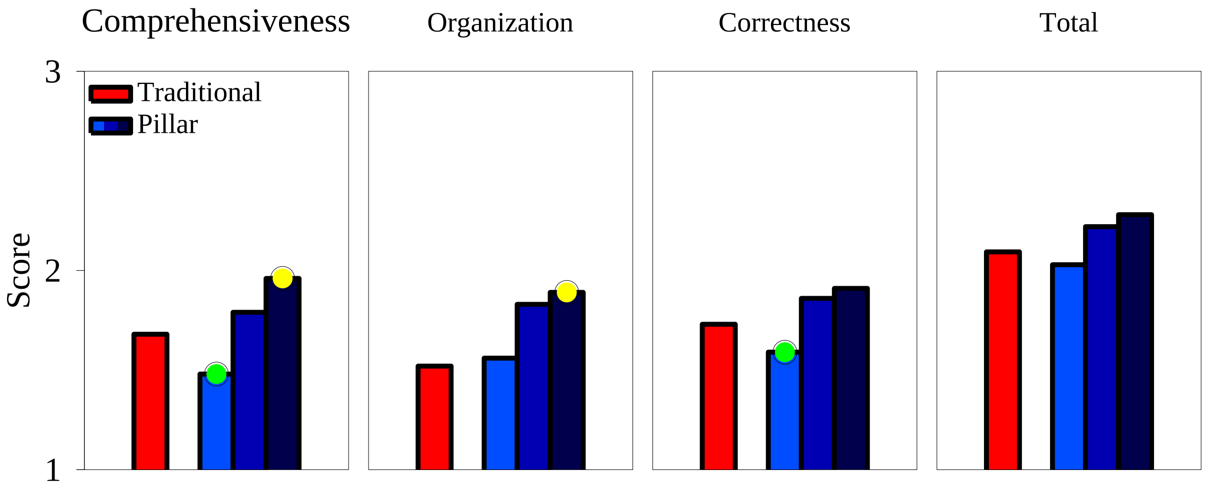

Figure 7: *Shown are the average concept map scores for all maps that have been scored to date. Note that the three shades of blue denote Pillars students that have completed sophomore, junior, or seniors years (light to dark), respectively. Also, the Pillars seniors are statistically significantly improved on both comprehensiveness and organization of their maps. Nevertheless, there is little statistical difference between the other results when examining the score averages.*

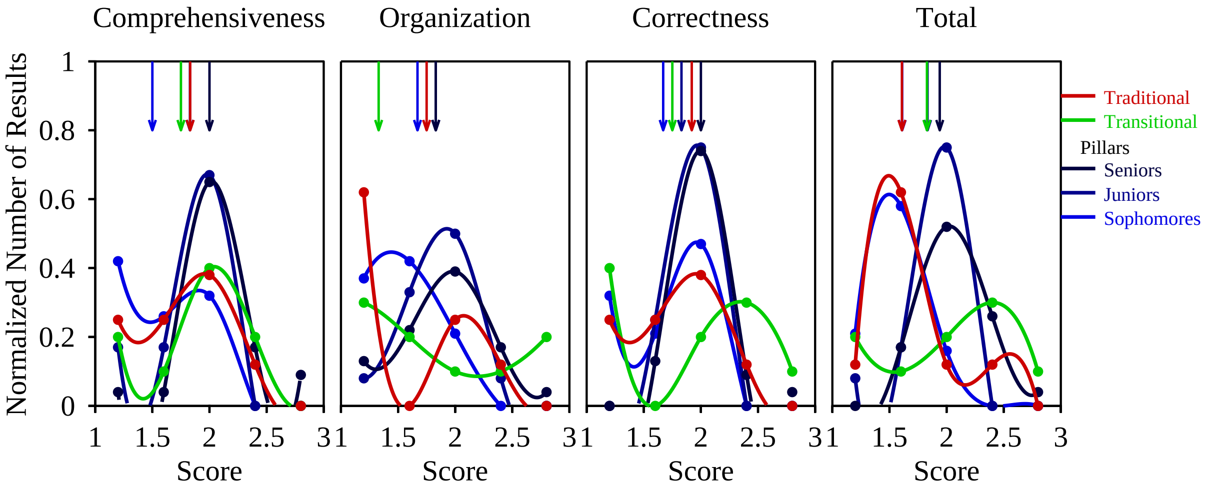

Figure 8: *Shown are the concept map score distributions for all maps that have been scored to date. Note that the three shades of blue denote Pillars students that have completed sophomore, junior, or seniors years (light to dark), respectively. Also, arrows at top denote the median of each distribution. Finally, note that the light blue (Pillar sophomores) scores are remarkably similar to those of the red (traditional seniors), when comparing the combined (Total) scores.*

One of the potential barriers to adoption of a pillars-style curriculum is that the non-traditional classes will not necessarily "map" cleanly onto existing educational materials. For example, unlike a traditional curriculum, there is no longer a class dedicated to chemical separations; instead this topic is covered in the Foundations Pillar, and revisited in subsequent pillars. Therefore, identifying textbooks may be difficult, and more than 1 textbook may be required for a single Pillar course. Instead of viewing this as a hurdle, the pillars team decided to turn this challenge into a strength. In other words, in order to facilitate adaption of this curriculum model to other chemical engineering departments, we have begun a fledgling effort at establishing an open-source courseware system and several accompanying e-Texts. This websuite, dubbed the "Pillars Website" (http://pillars.che.REDACTED.edu), currently hosts the web-notes developed for the first three courses in the curriculum: Foundations, Thermodynamics, and Transport Phenomena. Instead of passing on a static PDF of courseware that is difficult, if not impossible, to edit, our efforts to date are specifically designed to facilitate adoption and translation of course materials from one instructor to another by being a web-based content management/development/delivery system that allows web-standards-based notes (using HTML, MathML, Java and Javascript) to be edited, deployed, and organized with our WYSIWYG system.

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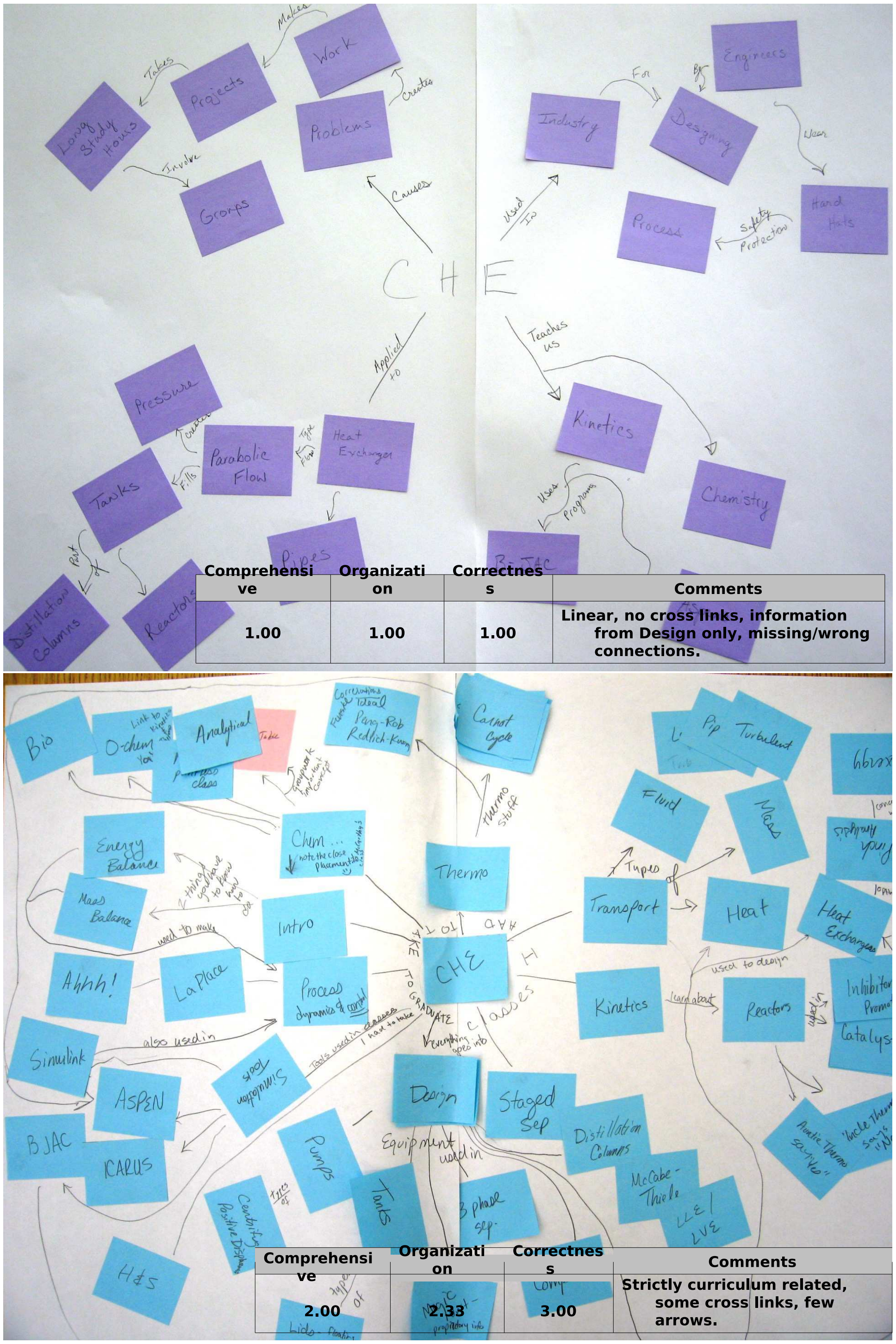

Comprehensive	Organization	Correctness	Comments
1.00	1.00	1.00	Linear, no cross links, information from Design only, missing/wrong connections.

Comprehensive	Organization	Correctness	Comments
2.00	2.33	3.00	Strictly curriculum related, some cross links, few arrows.

Figure 9: *Appendix: Two Example Concept Maps. (top) Shown is a map that lacks detail(focusing only on 1 course within ChE), is very linear in nature, and includes some mistakes in the linkages. (bottom) Shown is a map that is considerably more complete (but that still lacks societal, environmental, and industrial ChE context), has some cross-links between related branches of the map, and contains no glaring errors.*

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