Advances in Engineering Education

SUMMER 2011

Building an Evaluation Strategy for an Integrated Curriculum in Chemical Engineering

JOSEPH J. McCARTHY

ROBERT S. PARKER

ADETOLA ABATAN
Department of Chemical and Petroleum Engineering
And

MARY BESTERFIELD-SACRE
Department of Industrial Engineering
University of Pittsburgh
Pittsburgh, Pennsylvania 15261

ABSTRACT

Increasing knowledge integration has gained wide-spread support as an important goal in engineering education. The Chemical Engineering Pillars curriculum at the University of Pittsburgh, unique for its use of block scheduling, is one of the first four-year, integrated curricula in engineering, and is specifically designed to facilitate knowledge integration. As this curriculum is one of the first of its kind, conventional assessment strategies are not necessarily well suited for evaluation. In fact, our assessment strategy – by necessity – includes two separate measurement goals. First, we focus on measuring the effectiveness of the new curricular structure for enhancing the ability of students to engage in systems thinking (knowledge integration). At the same time, we specifically assess the impact of this type of curriculum on students' performance in conceptualizing (chemical) engineering principles. The goal of this paper is to outline an overall assessment structure suitable for measuring the efficacy of multi-year integrated curricula. Specifically, we describe the currently available assessment vehicles under use as well as discuss the methods – and results – for building the additional assessment materials required for a thorough vetting of this type of (chemical engineering) curriculum. While our specific assessment is still ongoing, we include a portion of the results to date and discuss their implications for the portability of integrated curricula in chemical engineering.

Keywords: integrated curricula, assessment, chemical engineering

INTRODUCTION

The challenge of developing a better chemical engineering curriculum, or indeed any engineering curriculum, is to build it such that it prepares students for the engineering needs of today, while enabling them – through a strong and well integrated core of engineering knowledge – to maintain versatility through life-long learning and continuing education. 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 or knowledge integration within a discipline [1, 9, 10] is not new; in fact, in the early to mid 1990's the National Science Foundation funded a number of Coalitions that primarily championed the "integrated curriculum". Until recently [11], however, 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. At the University of Pittsburgh, we have developed an integrated curriculum (the Pillars 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.

In accordance with the above-mentioned recommendations, the stated goals of the Pillars curriculum are to: (a) give students a strong fundamental foundation by concentrating on the essential core of scientific and engineering basics in a given discipline; and (b) enhance systems thinking by helping students to integrate core knowledge across traditional course boundaries so that they are better prepared to address open-ended problems.

As this curriculum is one of the first of its kind, it is critical that it be evaluated not only for its effectiveness in enhancing the ability of students to engage in systems thinking, but also to specifically assess the impact of this type of curriculum on students' performance in conceptualizing (chemical) engineering principles. In particular, while the use of block-scheduling in K-12 education has shown great promise for enhancing knowledge integration [16], it has been suggested that internalizing complex concepts like those in undergraduate engineering curricula requires repetition [17]. In this paper, we outline a multi-faceted evaluation approach for an integrated (chemical engineering) curriculum with the specific aim of informing this seeming disparity. This includes not only articulating a plan for assessing both the degree of knowledge integration (via the use of concept maps) and the depth of the students' conceptual knowledge (via the use of concept inventories), but also describing the details and results from the identification of target concepts for the development of new chemical engineering concept inventories, where necessary. This level of detail being devoted simply to an assessment *plan* is required because the general framework of the pillar classes is portable not only to other chemical engineering schools, but also to other engineering disciplines. Building a comprehensive body of data can then serve both as a validation of our own methods (and motivation for others to follow our model) and a road-map for evaluating the success of translation efforts.

BACKGROUND – 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 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. Students receive a single grade for each of these Pillar courses; however, the laboratory is graded separately each term. 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.

As mentioned, to properly assess this novel curricular structure we need to test not only for the, presumably positive, impact of block scheduling on knowledge integration, but ascertain whether the *lack* of content repetition has a negative impact on conceptual learning. To accomplish these two goals we employ Concept Mapping, to measure knowledge integration, and apply (and develop, as necessary) Concept Inventories, to measure conceptual understanding.

CONCEPT MAPS – KNOWLEDGE INTEGRATION

Concept maps are graphical representations of a student/subject's thoughts, theories, and/or concepts and their relative organization [18]. 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-linked, 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 1.

Concept mapping was initially devised as a technique for measuring the assimilation of scientific knowledge in children [19, 20] and has subsequently found a variety of uses in pedagogy including

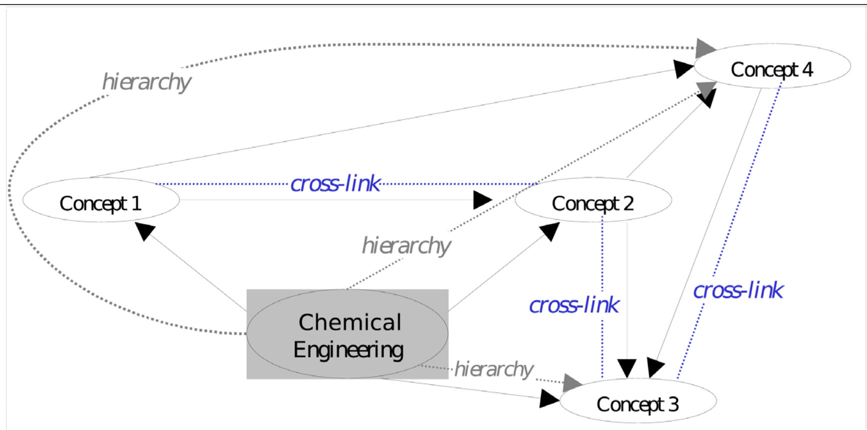


Figure 1. Schematic of a Concept Map. Shown is an example concept map displaying links, branches and cross-links.

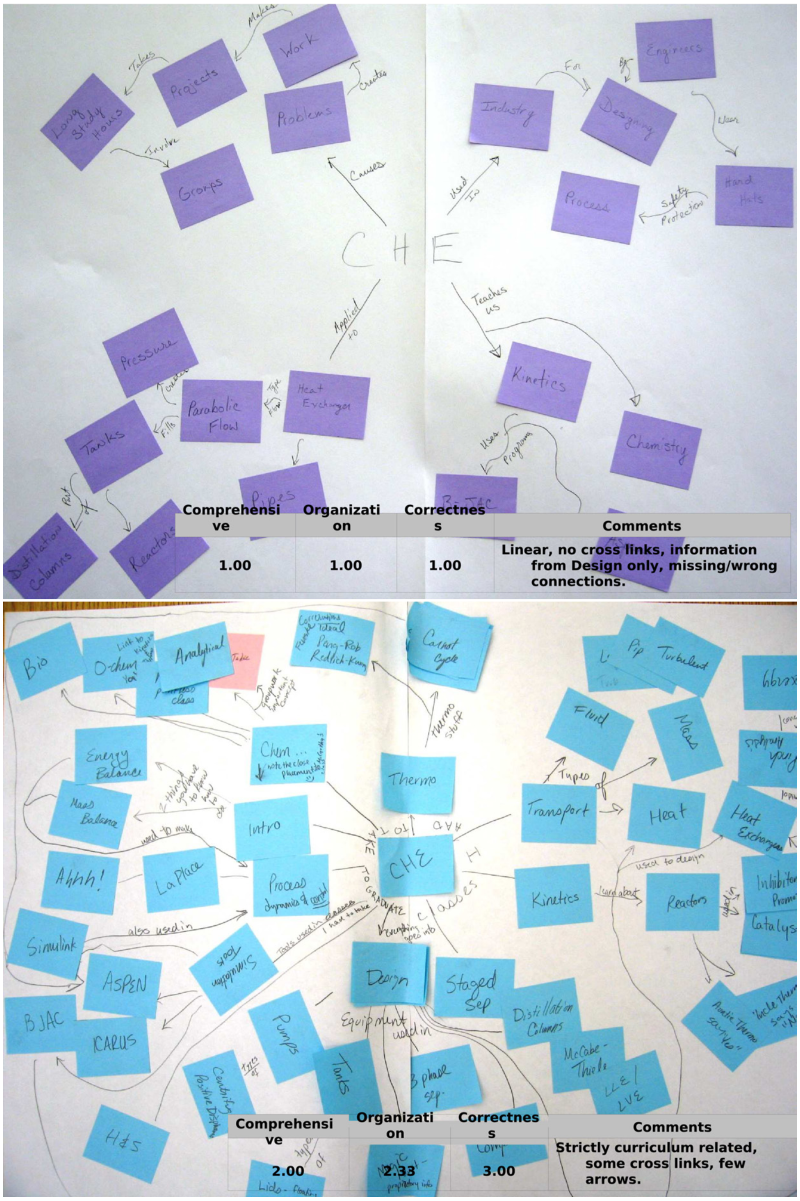
teaching, learning, planning, and assessment [21]. In the context of its use in the current work, concept maps have been shown to be a valuable assessment tool for evaluating the extent of knowledge integration exhibited by a student/subject [18, 22, 23]. This observation makes concept mapping an attractive tool for evaluating integrated curricula, and they are used in that capacity in the present work.

Scoring Concept Maps

While there has been some question over the years as to the validity of various methods of inter-

	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 2. Concept Map Scoring Rubric



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 3. 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

preting or "scoring" concept maps [24, 25] 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 [21]. In this way, there is a built-in control whereby the content-related score(s) can be compared to the content-related assessments (outlined in the next section). All of our maps are scored using a rubric [18] which gives independent scores for the elements of comprehension, organization, and correctness (see Figure 2). The mapping exercise can be at the end of each academic year or, alternatively, at the "capstone" or graduation stage. In our project, we have performed this exercise for both scheduling methods, traditional and integrated 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.

Preliminary Concept Map Results

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, included here are example maps from two students (Figure 3) and a summary of our concept map scores to date, reported in Figures 4 and 5. Note that, in scoring these maps, we distinguish between three cohorts of student – traditional (no Pillar courses), transitional (students have taken one or more Pillar courses), and Pillar cohorts – and further subdivide the Pillar cohort

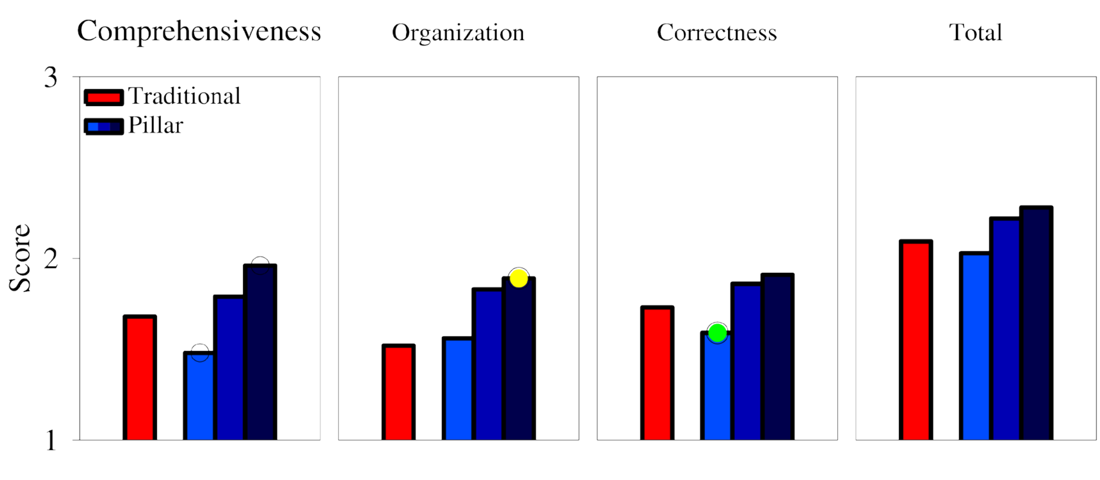


Figure 4. Shown are the mean concept map scores for all maps that have been scored to date. Note that the three shades of blue denote Pillars students that have completed sophomore, junior, or seniors years (light to dark), respectively

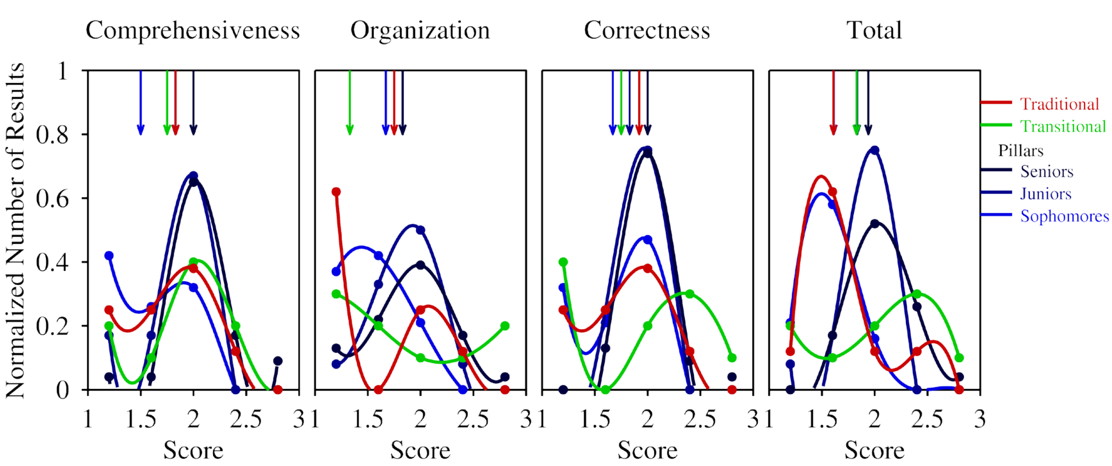


Figure 5. Shown are the concept map score distributions for all maps that have been scored to date. Note that the three shades of blue denote Pillars students that have completed sophomore, junior, or seniors years (light to dark), respectively. Also, arrows at top denote the median of each distribution. 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

into results from sophomores and juniors as well as seniors. When comparing the scores obtained, there is an encouraging trend that not only do Pillars students (seniors: 2.92 "Total" median score) have a higher score on each measure versus the traditional cohort group (seniors: median 2.42), but they are achieving comparable scores to the traditional cohorts earlier in their careers (sophomores: median 2.42; juniors: median 2.75). Perhaps more encouraging is to compare the distribution of scores (Figure 5). From Figure 5 we see that there is almost no difference between the distribution of the traditional (senior) cohort and the Pillars' Sophomore cohort . Thus, we are encouraged that our goal of enhancing knowledge integration *early* in our students' studies is being achieved.

Concept Inventories – Conceptual Understanding

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 [26]. Moreover, the variability in test questions from term-to-term and instructor-to-instructor make it difficult to use student grades to compare learning from inherent differences across semesters even within the same course [27].

Concept inventories (CIs) [26-29] are standardized tests that are specifically designed to evaluate students' conceptual understanding and thus are ideal as a tool for the evaluation of a student's fundamental mastery of the conceptual material within a curriculum. In addition to serving as a valid assessment of conceptual knowledge on its own [27], the fact that CIs focus on *misconceptions* – that is, incorrect world-views that block a student's ability to to make connections between basic concepts [26] – this method of assessment is particularly well suited to evaluating a curriculum whose goal is improving knowledge integration.

The Pillars curriculum consists of six Pillar courses – Foundations, Thermodynamics, Transport Phenomena, Reactive Processes, and a two-part Process Systems Engineering sequence – for which only two existing CIs are applicable. This section describes the few relevant CIs available as well as our efforts to construct the remaining required inventories. It is useful to note that, given the fundamental structure of the pillars curriculum, specific *application areas* of each of the pillar subject areas are purposely left fluid. In this way, concept inventories can be effectively built because the student achievement that is being assessed is their understanding/attainment of fundamental engineering principles, rather than the use of engineering knowledge in a specific application area. Thus, many of the CI questions should be portable within the discipline.

Existing Concept Inventories

A concept inventory study at the Colorado School of Mines (CSM) [28, 29] developed a CI focused on the Thermal and Transport Sciences. This well-written and extensively validated CI [28] has been in use over several years at a number of institutions. By splitting this CI, as suggested by the developers [29], into parts corresponding to Thermodynamics, Fluid Mechanics, and Heat Transfer,

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 6. Concept Inventory Example Question – CSM test [28, 31, 32]. Used by permission

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.

The CSM concept inventory [30] was developed using a rigorous "Delphi study" [30] (discussed in detail in the next section) and went through an extended beta testing period [28]. The CI questions derived using this procedure, an example of which is shown in Figure 6, were impressive enough that we modeled our CI development procedure after that followed at CSM. Of particular importance to note is how the question couples a test of the concept with the rationale behind the answers as an internal consistency check of student effort. Also, note that "reasonable" distractors are used based on the identified symptoms and rationale behind the misconception.

New Concept Inventories – Delphi Study

As mentioned previously, the Pillars curriculum aims to produce improvements in student understanding of major ChE concepts [33], which not only include Thermodynamics and Transport Phenomena, but also Reaction Kinetics (RK), Process Design and Control (PS) and Material and Energy Balances (plus Separations, MES). While the CSM concept inventory is aptly suited to the Thermodynamics and Transport Pillars, CIs for the remaining subject areas are yet to be developed. This section details the procedure – called the *Delphi method* [30] – that we have followed to collect the common misconceptions that should be tested in concept inventories aimed at these subjects.

The purpose of a Delphi study is to gather and condense the judgments of experts about a particular subject under conditions of anonymity, and therefore without bias [34]. In a Delphi study, the ideas generated by the participants are independent, isolated and anonymous. Thus, the impact of choice-shift (*i.e.*, the polarization of opinions due to strong personalities or name recognition) is minimized while the opinions are being collected.

In a conventional Delphi Study method, there is no communication between the participants. Rather, information flow is orchestrated by a director and occurs through feedback questionnaires

Dear Respondent:
Thank you for agreeing to participate in our Delphi study of difficult concepts in chemical engineering. As we previously indicated, the study will be conducted in four rounds. In this round, we would like you to list concepts in material and energy balances, reactive processes (kinetics, reactors, and advanced separations), and process systems that you think are either important or difficult for students. Please submit as many items as you would like in each of the categories.

We would like to have this round completed by MM/DD/YYYY so that we can promptly consolidate your responses and move on to the next round.

Figure 7. Delphi Study Round 0 Correspondence – Concept Gathering

Dear Respondent:
Thank you for your participation in our Delphi study. As a reminder, the purpose is to identify and rank difficult concepts for undergraduate students in chemical engineering. Based on your Round 0 responses, we have consolidated the important and difficult concepts. Your task now is to rank the consolidated concepts for understanding (U) and importance (I) on a scale from 0-10, where:

0 - No one understands OR it is not important to understand this concept
10 - Everyone understands OR it is extremely important to understand this concept

You will not have to rank any concept for which you do not feel you have sufficient expertise. You may "skip" the concepts that you do not feel comfortable rating. Please complete your ratings by MM/DD/YYYY.

Figure 8. Delphi Study Round 1 Correspondence – Concept Rating and Refinement

that are periodically sent to the participants. By structuring the group communication in this manner, the process is considered effective at allowing a group of experts to identify the specific characteristics of a problem, and ways to better deal with the problem [34]. In our case, the problem at hand is the identification of commonly misunderstood yet fundamental concepts relevant to each of the 3 Pillar subject areas under consideration (RK, PS and MES).

For our study, 15 external participants were chosen, representing nationally renowned chemical engineering faculty from highly ranked programs. The opinion-gathering was coordinated by three local subject area "champions" and was done in a series of rounds to first gather and then refine the data. The Round 0 correspondence requested participation in the study and stimulated interest by offering a small monetary incentive. At this stage, the participants were asked to identify a list of commonly misunderstood concepts which were of fundamental importance to any core undergraduate ChE curriculum. The particular invitation is included in Figure 7.

Round 0 yielded independent concepts in each of the subject areas as follows, 44 RK, 33 MES, 34 PS and 11 general or cross-cutting concepts (GEN). The responses to this round were refined by the local subject area champions in two ways. Concepts that could be coalesced were combined, while those that had been identified by only a single participant were eliminated.

For Round 1, the condensed questionnaire results (consisting of 36 RK, 26 MES, 26 PS, and 11 general or cross-cutting concepts) were electronically sent to the respondents in order to ascertain their opinion on the group responses. We specifically requested that they express the degree to which they agree or disagree that a particular concept was commonly misunderstood and of high importance on a scale of 0-10. This second invitation is shown in Figure 8. This initial ranking/scoring of the concepts for each subject area can be seen schematically in Figure 9, based on the mean score of the group.

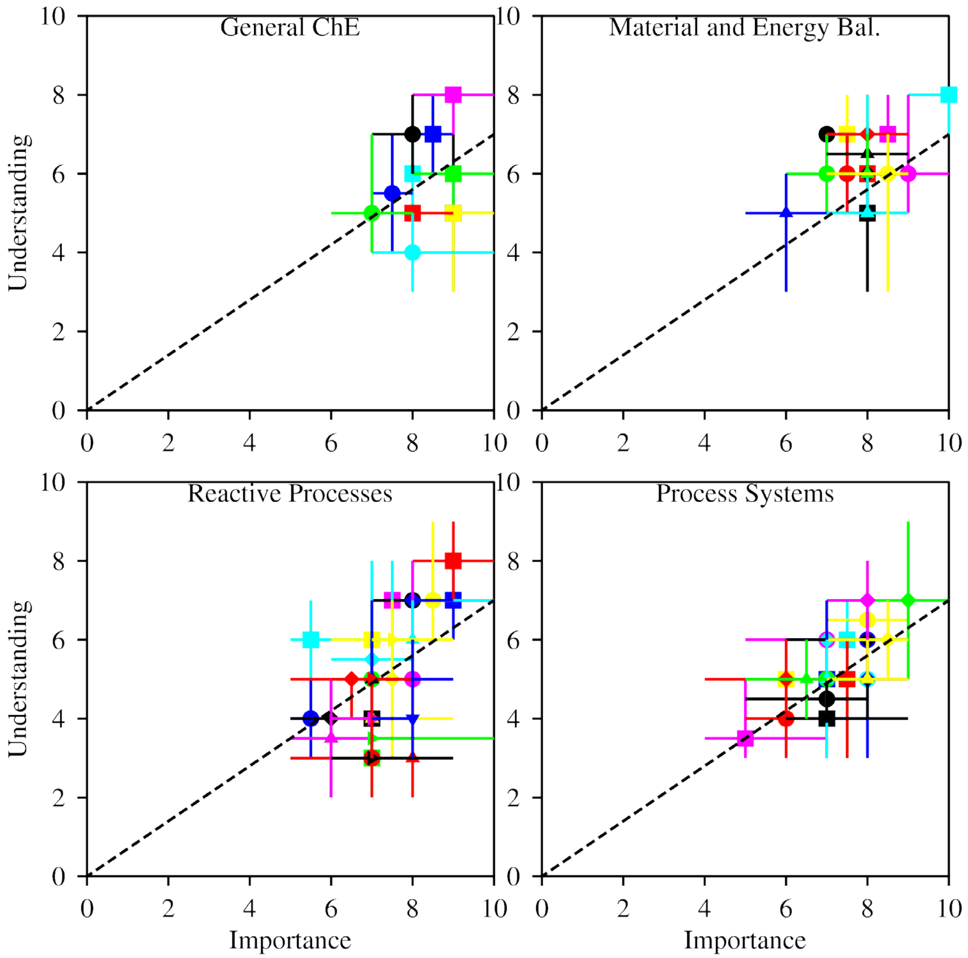


Figure 9. Round 1 responses. The dashed line represents the proposed cutoff for responses that are high in importance and high in misunderstanding (or low in understanding). The numbers correspond to a particular misconception

Round 2 was aimed at accounting for variation in absolute score values from participant-to-participant. As such, the participants were again asked to rate each concept both for "understanding" and "importance", but were now given the median score as well as the 50% range of the group for each concept. They were then asked to revise their responses based on the consensus scores of the group. They were specifically instructed to justify any of their scores that continued to fall outside of the 50% range. The third invitation is included in Figure 10 and the resultant spread of concept scores are shown in Figure 11.

Dear Respondent:
Thank you for your participation in our Delphi study. As a reminder, the purpose is to identify and rank difficult concepts for undergraduate students in chemical engineering. Based on your Round 0 responses, we have consolidated the important and difficult concepts. Your task now is to rank the consolidated concepts for understanding (U) and importance (I) on a scale from 0-10, where:

0 - No one understands OR it is not important to understand this concept
10 - Everyone understands OR it is extremely important to understand this concept

You will not have to rank any concept for which you do not feel you have sufficient expertise. You may "skip" the concepts that you do not feel comfortable rating. Please complete your ratings by MM/DD/YYYY.

Figure 10. Delphi Study Round 2 Correspondence – Further Concept Refinement

Comparing Figure 11 to Figure 9 shows the shift in importance and/or understanding of some concepts when the participants had access to the opinions of others within the group. These responses were further refined by defining a cut-off for how high in importance a concept could be while also being poorly misunderstood. Figure 11 shows how the cutoff line was used to cull the list of concepts at this stage of the process (the same line is shown on Figure 9 for illustrative purposes, it was not used at that stage). Implementing the cutoff line after the Round 2 results were obtained resulted in 18 RK, 13 MES, 15 PS and 8 general or cross-cutting (GEN) concepts that could be considered high in both importance and probability of misconception (i.e., conceptual difficult).

The progressive refinement of high-importance and hard-to-understand concepts as a function of Delphi round is shown in Table 1. By Round 3 (comprising only of our local champions), the final list was condensed to 5 RK, 6 MES, 6 PS concepts along with 2 GEN misconceptions covering all 3 Pillar areas. It should be noted that this final list was built from a local champion's translation of the expert participants' responses, and the reductions were confirmed in a final, post-Delphi, correspondence. The reason that this step represented a rather dramatic reduction in the number of "concepts" is that the experts' responses in the previous rounds often represented difficult topics or the symptoms of underlying misconceptions rather than actual concepts that gave students difficulty. In this post-Delphi round, the champions, therefore, combined many of these student issues under the heading of more general misconceptions.

Student misconceptions

The misconceptions that were identified in each of the subject areas are outlined here, including the underlying student misconception as well as the "symptoms" that lead to each of the misconceptions. As with the CSM concept inventory, questions derived from this list will be aimed at probing

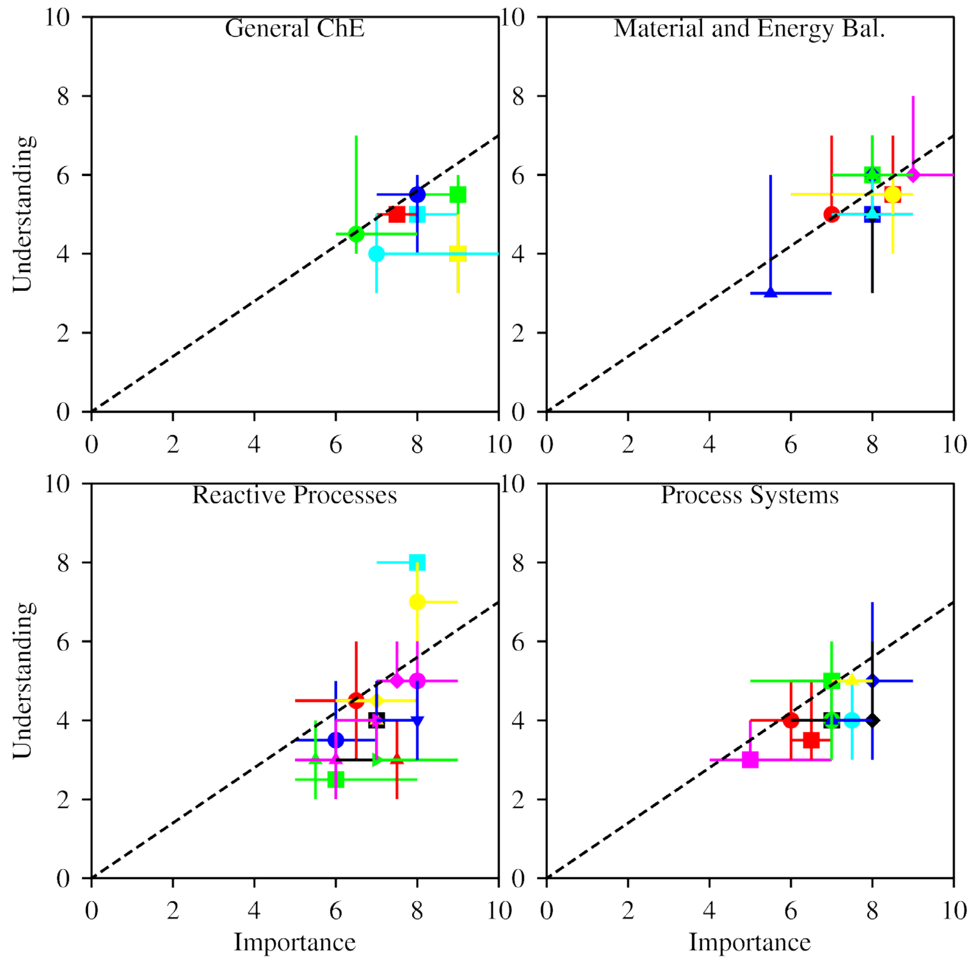


Figure 11. Round 2 responses. Dashed line represents the proposed cutoff for responses which were high in importance and high in misunderstanding (or low in understanding)

the misconception and will include distractors inspired by the listed symptoms. Also, in analogy to the work at CSM, we will pilot the questions with a number of different focus groups to tease out biases within the wording or question construction.

The general or cross-cutting misconceptions include:

1 Misconception: All questions are answerable and have one "right" answer.

- Students do not realize that assumptions are necessary in order to evaluate data.
- Students do not realize that assumptions and measurement variability will lead to open-ended problems/solutions.

Round	RK	MES	PS	Reduction Mechanism
0	44	33	34	Initial Responses
1	36	26	26	Consolidation by champions
2	18	13	15	Cutoff line implemented
3	5	6	6	Refinement by champions

Table 1. This illustrates the refinement of the number of truly fundamental yet misunderstood concepts with each successive round.

- Students do not realize that a "degree of freedom" analysis is necessary to evaluate whether enough information is even available to make a solution possible.

2 Misconception: Math and core sciences do not directly impact "engineering problems".

- Students do not know where to start in tackling open-ended problems.
- Students have difficulty translating ChE problem solving from a "petrochemicals" viewpoint to other fields (biological applications, energy, etc.).

The misconceptions related to the Material and Energy Balances (with Separation, MES) subject area include:

MES - 1. Misconception: all/no processes run at unsteady state.

- Students confuse recycle/bypass with unsteady processes.
- Students do not know how to write unsteady balances.

MES -2. Misconception: flow work only applies to "piston problems".

- Students do not understand when flow work must be considered (open v. closed).

MES -3. Misconception: state variables are similar to process variables.

- Students do not understand the intrinsic path-independence of state functions.
- Students do not understand the need for reference states.

MES- 4. Misconception: explicitly calculating the degrees of freedom is unnecessary.

- Students are unclear on (in)dependence of balance equations.
- Students are unclear on (in)dependence of reactions.
- Students do not understand how thermodynamics (phase behavior) impacts the degrees of freedom of a system.
- Students are not clear on how/when to choose appropriate control volumes for performing balances.

MES- 5. Misconception: The ideal gas law is always appropriate (even for liquids/solids).

MES- 6. Misconception: Significant figures are unimportant, two decimal places is about right.

The misconceptions identified in the Reactive Processes (RK) area include:

RK -1. Misconception: Reaction kinetics and rate expressions must be known *a priori* rather than derived or measured.

- Students have difficulty determining the relationship between reaction rate expressions/laws and molecular, stochastic and chemical kinetics.
- Students struggle to extract intrinsic kinetics from reactor modeling.

RK -2. Misconception: Transport phenomena impacts reactor behavior in mass-transfer limited cases.

- Students have trouble predicting/analyzing residence time distributions.
- Students cannot reconcile the behavior of non-ideal and multiphase reactors (e.g. bubble columns, fluidized, packed, fixed and entrained beds) with the idealized cases they can analytically describe.
- Students have little intuition regarding the appropriateness of correlations given acceptable error.
- Identifying the proper experimental/theoretical tests for heat and mass transfer limitations in reactors is often difficult.

RK -3. Misconception: Mass balances are only useful for overall material accounting due to the presence of reactions.

- Students struggle to translate and reconcile molecular and atomic or elemental species balances on reactive systems (including selectivity, yield, and extent of reaction concepts).
- Students can often not identify/determine linear independence of chemical reactions, rate determining step, elementary and non-elementary reactions, and complex reaction pathways.
- The physical meaning of operating and equilibrium lines is elusive.

RK - 4. Misconception: Biological system applications (e.g. metabolic engineering, controlled drug delivery, bio-separations) are analyzed in a completely different manner than purely "chemical" applications.

RK - 5. Misconception: Reactor stability and safety are the same thing.

The misconceptions identified in the Process Systems (PS) area include:

PS -1. Misconception: Optimization of processes and flow-sheets is straightforward.

- Students have difficulty defining, differentiating, and formulating objectives and constraints (includes incorporation of environmental, sustainable, and efficiency issues within objectives and constraints).

- Students have difficulty converting word problems with data to a formal mathematical (optimization) statement (true of continuous, batch, and synthesis problems).
- Students have only a limited introduction to optimization as undergraduates; topic is often covered only late in the degree.
- Students do not understand changes in solution required to handle multivariable optimization (search vectors) vs. 1-dimensional problems.

PS -2. Misconception: All details are equally important all the time; there is no hierarchy in design.

- Students do not understand how to simplify process descriptions without losing process characteristics.
- Students cannot identify when to employ rigorous (formal) optimization vs. heuristic decisions.
- Students do not understand the impact of economics on decision-making (magnitude and timing in design procedure).

PS -3. Misconception: With suitable simplification, processes can be treated as single-phase and ideal.

- Multi-phase processes (heterogeneous catalysis, packed/fluidized beds) and spatially inhomogeneous processes (bubble columns) are underutilized in class due to complexity, leading to students not grasping the fundamental challenges of these systems.
- PS -4. Misconception: Designers lay out plants, control engineers make and keep them running.
- Students do not connect network principles (reactor-separation-recycle or “pinch” systems) with control challenges.
- Impact of process dynamics on (in)feasibility, especially for highly integrated systems, is poorly grasped.
- Students do not differentiate concepts of “design” and “synthesis”.

PS -5. Misconception: Time-domain models are difficult to construct and do not provide insight.

- Linear algebra and ODE skills are weak due to lack of use (time since taking the courses, if taken at all).
- State space modeling is introduced only in the dynamics and control class (in general).
- Dynamical analysis concepts (time constants, gains, zero and delay dynamics) and synthesis concepts (closed-loop rates of response, effect of parameter tuning) are not taught in the time domain (students lack the math skills/motivation to explore these effects without suitable motivation (homework, exam) in a course).

PS -6. Misconception: Models and/or processes generate data, and data is "truth" that cannot be changed.

- Students cannot identify root cause of output from process data (troubleshooting and need for/benefit from retrofitting).
- Students do not grasp impact of (or correction for) change in process scale on dynamics or feasibility.
- Students cannot identify process data characteristics that suggest the need for and benefit from particular advanced control strategies.

Having rigorously identified the important misconceptions in each of the three subject areas that are unrepresented by CIs, the next step is to develop and test candidate questions targeting these concepts. Using questions geared toward the aforementioned concepts in each of the CI focus areas, we will employ the strategy used by Miller *et al.* [28] whereby focus groups of students will provide feedback via "thinking aloud" interviews after attempting the candidate questions to aid in question refinement. The results of these exercises will be the subject of a future communication.

SUMMARY AND CONCLUSIONS

Assessment is without doubt a critical component to the successful development and growth of pedagogical innovation. The difficulty in developing a truly novel curriculum is that the strategies used to assess a traditional curriculum are not necessarily well suited to its evaluation. The Pillars curriculum at the University of Pittsburgh is perhaps the first fully integrated engineering curriculum. Through the coordinated use of both concept mapping – in order to evaluate the degree of knowledge integration – and concept inventories – to evaluate the students' conceptual understanding – we have developed a strategy tailored specifically for the evaluation of integrated engineering curricula. A unique difficulty of our approach is that assessment vehicles and techniques needed to be developed in parallel with the development, implementation, and initial assessment of the curriculum. In particular, over the course of our project we have identified the misconceptions and begun to build concept inventories in the subject areas of Reaction Kinetics, Process Design and Control and Material and Energy Balances (plus Separations). Through this paper, we expect that others considering integrated engineering curricula may have a road map for how to build a comprehensive assessment strategy. At the same time, we hope that chemical engineers will find the misconception database of use, while other engineering disciplines can find utility in the methodology used to identify same.

ACKNOWLEDGMENTS

The authors wish to thank the Delphi panel of experts that participated in the identification of student misconceptions and, especially Goetz Veser (one of the local champions, for RK). This material is based upon work supported by the National Science Foundation under Grant No. EEC-0342713.

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AUTHORS

Joseph J. McCarthy is a Professor in the Department of Chemical and Petroleum Engineering at the University of Pittsburgh. His educational interests focus in technology-enhanced teaching/learning and integration of core knowledge early in the curriculum, primarily through curricular innovation. With regard to technology-enhanced teaching/learning, Dr. McCarthy has teamed with Dr. Parker to design/develop the Pillars website, aimed at building open-sourced course notes for an integrated chemical engineering curriculum (http://pillars.che.pitt.edu). The focus of Professor McCarthy's disciplinary research is transport phenomena in particulate and/or discrete systems.

Robert S. Parker is currently an Associate Professor in the Department of Chemical and Petroleum Engineering at the University of Pittsburgh. He received his chemical engineering degrees from the University of Rochester (BS, 1994) and the University of Delaware (PhD, 1999). Curricular innovation through accommodating diverse learning styles, with a focus on theory-practice (laboratory) integration, and the use of computing in engineering design/analysis are his educational research interests. His disciplinary research is in systems medicine, with foci in cancer, diabetes, and inflammation.

Mary Besterfield-Sacre is an Associate Professor and Fulton C. Noss Faculty Fellow in Department of Industrial Engineering, a Center Associate for the Learning Research and Development Center, and the Director for the Engineering Education Research Center at the University of Pittsburgh. Her principal research is in engineering education assessment, which has been funded by the NSF, Department of Education, Sloan Foundation, Engineering Information Foundation, and the NCIIA. Mary's current research focuses on three distinct but highly correlated areas – innovative product design, entrepreneurship, and modeling. She has served as an associate editor for the *JEE* and is currently associate editor for the *AEE Journal*.

Adetola Abatan graduated with a PhD in Chemical Engineering from the University of Pittsburgh in 2006. She currently works as a production engineer with Shell Oil Co, and has experience in Unconventional Resources such as oil shale, heavy oil and tight gas assets in North America. Her research interests include reservoir characterization using thermal models and technologies.