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Creating a Modularized Graduate Curriculum in Chemical Engineering

Dr. Mary E. Besterfield-Sacre, University of Pittsburgh

Dr. Mary Besterfield-Sacre is Senior the Associate Dean for Academic Affairs and Nickolas A. DeCecco Professor in Industrial Engineering at the University of Pittsburgh. She is also the Founding Director of the Engineering Education Research Center (EERC).

Dr. April Dukes, University of Pittsburgh

April Dukes (aprila@pitt.edu) is the Faculty and Future Faculty Program Director for the Engineering Educational Research Center (EERC) and the Institutional Co-leader for Pitt-CIRTL (Center for the Integration of Research, Teaching, and Learning) at the

Prof. Susan K Fullerton Shirey, University of Pittsburgh

Susan Fullerton is an Associate Professor, Bicentennial Board of Visitors Faculty Fellow, and Vice Chair for Graduate Education in the Department of Chemical and Petroleum Engineering at the University of Pittsburgh. She earned her Ph.D. in Chemical Engineering at Penn State in 2009, and joined the Department of Electrical Engineering at the University of Notre Dame as a Research Assistant Professor. In 2015 she established the Nanoionics and Electronics Lab at Pitt as an Assistant Professor, and was promoted to Associate Professor with tenure in 2020. Fullerton's work has been recognized by an NSF CAREER award, an Alfred P. Sloan Fellowship, a Marion Milligan Mason award for women in the chemical sciences from AAAS, and a Ralph E. Powe Jr. Faculty Award from ORAU. For her teaching, Fullerton was awarded the 2018 James Pommersheim Award for Excellence in Teaching in Chemical Engineering at Pitt. For more information: http://fullertonlab.pitt.edu/

Dr. Götz Veser, University of Pittsburgh

Creating a Modularized Graduate Curriculum in Chemical Engineering

Abstract

U.S. graduate engineering programs traditionally follow a "one-size-fits-all" approach that prioritizes research skills, is slow to adapt to industry trends, and defaults to training students for academic careers. Further, these programs implicitly assume that students start at the same knowledge level, disregarding differences in educational preparation and students' backgrounds. The University of Pittsburgh Swanson School of Engineering is creating and validating a five-component personalized learning model (PLM) for graduate education within its Chemical Engineering Department. This model aims to modernize graduate STEM education through a student-centered approach, advancing existing knowledge on the relationship between personalized learning and student outcomes.

This paper reports on the methodology and results of the second of the five components of the PLM, the *Task Environment*. This component purposefully breaks the traditional three-credit coursework into modular, stackable single-credit classes, building from fast-paced reviews of fundamentals over traditional graduate-level core content to graduate-level specialized content. This change provides a flexible and personalized learning experience, allowing students to customize their education to align with their interests.

To create the modularized curriculum, we leveraged the collective expertise of our chemical engineering faculty and external subject matter experts (SMEs) from industry, government, academia, and start-ups. Starting with our existing course-specific learning objectives, we employed group concept mapping to (1) brainstorm additional graduate-level learning objectives, (2) group them into one of three levels of increasing specialization within each course topic, and (3) rate their importance. Two sets of learning objectives were produced. The first is a prioritized set of learning outcomes for each content area organized into these three levels. The second set comprises non-traditional technical and non-technical learning outcomes for graduate students to succeed post-graduation. For the first set, faculty have formed a learning community to interpret the results and collectively work on restructuring course content and pedagogy. For the second set, the same SMEs rated the importance of each learning objective to prioritize incorporation into the modularized curriculum. From the results, we have formed a faculty learning community and have begun redesigning the curriculum into single-credit classes.

1. Introduction

Traditional graduate STEM education primarily focuses on research outputs, academic publications, and preparing students for academic careers. While this approach has yielded substantial advancements in research, it often overlooks graduate students' diverse career goals and varying educational backgrounds. Additionally, the traditional "one-size-fits-all" structure of graduate programs is slow to adapt to emerging industry trends and evolving societal needs.

Recent reports, including the National Academies of Sciences, Engineering, and Medicine’s 2018 publication *Graduate STEM Education for the 21st Century* [1], emphasize the importance of transforming graduate education to address these gaps. This transformation requires programs to incorporate communication, teamwork, leadership, and adaptability skills, essential for success in academia, industry, and entrepreneurial endeavors. At the University of Pittsburgh’s Swanson School of Engineering, the Department of Chemical and Petroleum Engineering has pioneered this transformation by developing a Personalized Learning Model (PLM) for graduate education.

The PLM, funded by the National Science Foundation Innovations in Graduate Education award, introduces a five-component framework to personalize graduate learning. This paper focuses on the second component of the PLM, *the modularized Task Environment*, which enables students to customize their learning experiences through single-credit modules categorized as fundamental, graduate core, and specialized topics. Breaking traditional coursework into flexible modules gives students greater control over the breadth and depth of their education.

This paper outlines the methodology used to design and implement the modularized curriculum, the outcomes of the concept mapping process, and the broader implications for graduate STEM education. Through this initiative, the department aims to modernize graduate chemical engineering education, ensuring students are equipped for a dynamic and interdisciplinary professional landscape.

1.1. Overview of the Personalized Learning Model (PLM)

The Personalized Learning Model (PLM) for STEM Graduate Education is a comprehensive, student-centered approach designed to enhance graduate education through tailored instruction and professional development. It is rooted in Watson and Watson's [2] principles of personalized learning and integrates Deci's Self-Determination Theory [3] to align educational experiences with individual career goals. The PLM emphasizes a holistic approach to graduate education by embedding customized learning throughout the academic journey. An overview of the model is provided in Figure 1. The model complements earlier work conducted by Mistree [4,5] for individual courses and extends the work to an entire graduate-level engineering program.

The PLM begins with students establishing I**nstructional Goals**, where students and faculty collaborate to develop Individual Development Plans (IDPs) using tools like the CliftonStrengths [6] and myIDP [7] platform by the American Association for the Advancement of Science (AAAS). The students’ instructional goals are designed to align modular curricula with both short and long-term career aspirations. To create a dynamic **Task Environment**, the model replaces traditional three-credit courses with single-credit modules, offering students the flexibility to customize their education and lowering the faculty's barrier to adapting course content to emerging trends. Additionally, the inclusion of Professional Development Streams tailored to industry, academia, and entrepreneurship equips students with practical skills beyond technical expertise and broadens their professional readiness. This structure is inspired by programs like North Carolina State’s A2i initiative [8], which successfully integrates real-world competencies into academic training.

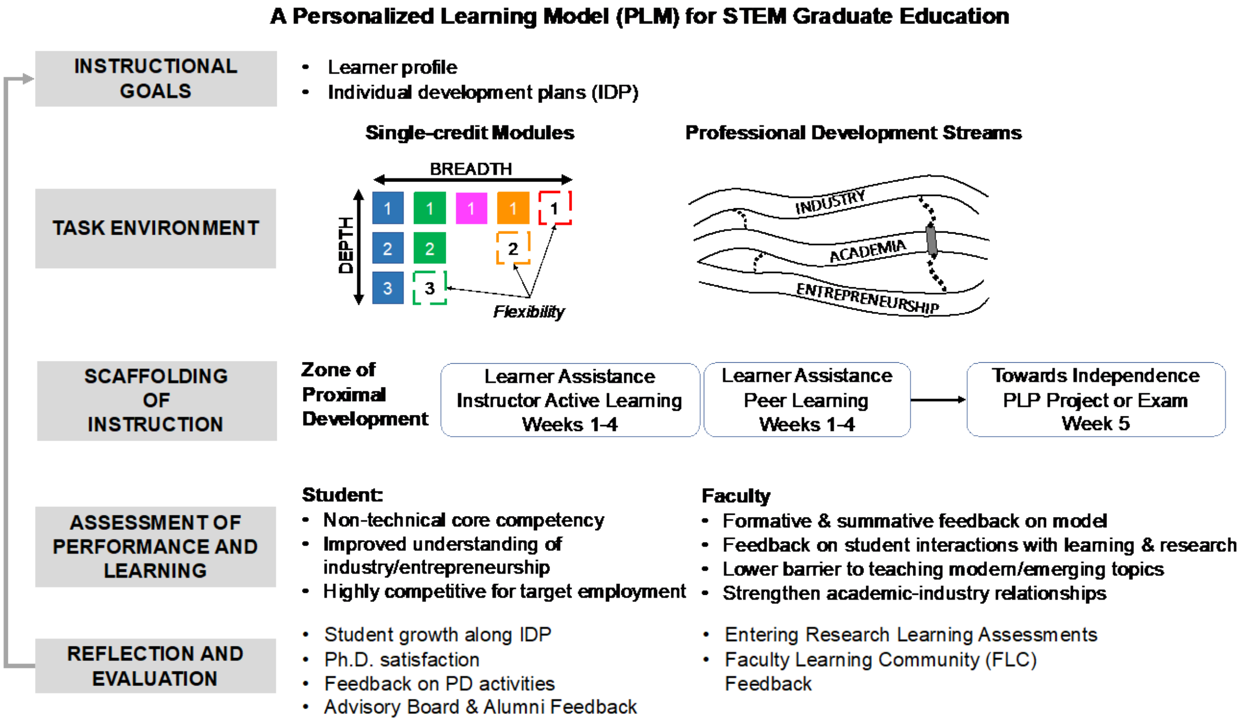

Figure 1: Overview of the Personalized Learning Model (PLM) for STEM graduate education being developed and deployed to innovate graduate education. (Here, we depict three separate streams from the onset of our program; however, other STEM programs may look different.)

The model incorporates pedagogical strategies focused on active learning and **Scaffolding Instruction** to ensure students master the course material. Faculty members, supported by the Engineering Education Research Center (EERC), help students progress toward independence and mastery through learner-assisted activities and individual projects. This approach benefits minoritized students by adopting an asset-based framework [9] that identifies and builds on their strengths rather than focusing on deficits.

Assessment and reflection are integral to the PLM. Student learning is tracked through portfolios, projects, and competency exams, while faculty and students continuously provide feedback to improve instructional strategies and learning outcomes. **Reflection** further helps students refine their goals and adapt their approach, fostering a mindset of continuous growth.

The PLM seeks to revolutionize STEM graduate education by providing an inclusive and adaptable framework that meets students where they are and empowers them to achieve their full potential. By documenting and assessing its implementation, the model aims for broader adoption across institutions to transform graduate education nationwide.

1.2. Focus on the Task Environment

As mentioned, the task environment consists of redesigning the core curriculum from three-credit courses into single-credit modules and developing three professional streams of industry, academia, and entrepreneurship. The purpose of modularization is multi-fold: (1) it allows flexible and personalized learning, (2) it aligns with individual student goals and interests, (3) it provides student agency in intellectual development, and (4) it provides content adaptability to emerging trends.

For example, our first-year Chemical Engineering graduate curriculum comprises five courses: Thermodynamics, Kinetics and Reactor Design, Transport Phenomena, Mathematical Methods, and Safety and Ethics (taught in one course together). Although this curriculum is reasonably standard in Chemical Engineering graduate education, its structure leaves little room for customization, specialization, and flexibility on emerging topics. In contrast, one-credit modules enable students to adapt to their prior knowledge level - for example, by testing out of specific content - and customizing their education while maintaining vital core training.

Specifically, the modules envisioned have three levels: fundamentals, graduate-level, and specialized learning. The first course modules (fundamentals) will be required across the topics, but students may test out by demonstrating mastery via an exam before the start of the semester. This assures a uniform starting point for students from varying undergraduate backgrounds; we seek to "level the playing field" by providing equity across students. The second module will be mandatory for all students, maintaining a core graduate-level ChE curriculum beyond undergraduate mastery. The third credit will be specialized content that remains within the scope of transport, kinetics, and thermodynamics but adds flexibility such that the instructor can focus on a topical area that is timely and potentially well-aligned with their research expertise.

This paper focuses on our project's methodology and results to create one-credit modules for our graduate chemical engineering curriculum. In doing so, we devised a body of knowledge (BOK) for graduate engineering education that drew upon the expertise of academia, industry, government, and start-ups. The resulting BOK comprised both core technical and non-technical learning objectives. Faculty formed a learning community to collectively interpret findings, restructure content, consider pedagogy associated with 1-credit courses, and begin developing the new curriculum.

2. Methodology

2.1 Collaborative Development Process

To design the modularized curriculum, the University of Pittsburgh engaged a collaborative team of stakeholders comprising chemical engineering faculty and external subject matter experts (SMEs) from industry, government, academia, and start-ups. This diverse group contributed their collective expertise to ensure the curriculum addressed technical and professional competencies that met the needs of external entities.

Our subject matter experts come from diverse backgrounds because the body of knowledge must be sufficiently broad to support students as they transition to various careers post-graduation. Our SMEs were recruited from the department's Junior Advisory Board, the grant's Technical Advisory Board, the department's faculty members, the grant's Educational Advisory Board, and program alumni. In all, 25 SMEs participated in various stages of the development process, with 17 participating in all aspects. Table 1 provides the demographic composition of SMEs.

Table 1: SME demographics for all 25 participants

Organization	Job Focus	Disciplinary Background	Terminal Degree
Academia 45.8%	Client Service 3.0%	Chemical engineering 84%	BS/BA 25%
For Profit 41.7%	Administration 6.3%	Chemistry 4%	MS 20.8%
Gov/NGO/Other 12.5%	Operations 21.9%	Other engineering 8%	PhD 54.2%
	R&D 50%	Other 4%	
	Other 18.8%		

2.2 Group Concept Mapping

Group Concept Mapping (GCM) is a participatory, structured method that combines qualitative and quantitative techniques to generate, organize, and visually represent ideas around a specific topic or issue. Developed by Trochim and further refined by Kane and Trochim [10], GCM is widely used for planning, evaluation, and decision-making in various fields, including healthcare, education, and organizational development. This methodology was selected because it allowed us to (1) engage a diverse set of stakeholders, (2) combine quantitative methods while preserving the richness of qualitative feedback from the SMEs, and (3) facilitate the results for direct use by the faculty. GCM consists of three primary interactive phases. Idea generation or brainstorming is the first stage. Participants contribute ideas (here, learning objectives) specific to a focus question or prompt. For our project, SMEs received the following focus prompt throughout the development of the BOK.

> *The objective is to create a body of knowledge for graduate chemical engineering education focusing on six topics: Thermodynamics, Kinetics and Reactor Design, Transport Phenomena, Mathematical Methods, Ethics, and Safety. We desire to group the learning outcomes from these six topics into three levels:* ***fundamentals, graduate,*** *and* ***specialization****. Lastly, we want to know the importance of each learning outcome.*

These ideas form the basis for subsequent steps. The second and third phases involve structuring the ideas. Specifically, participants sort the ideas into groups based on similarity and rate them on dimensions such as importance or feasibility. The sorting and rating phases provide the raw data for quantitative analyses. Concept Systems, Inc. GroupWisdom [11] concept mapping software was employed to facilitate the brainstorming and analysis of learning objectives.

To develop the BOK, we began by assimilating the current learning objectives for the six topics. Because the learning objectives were from different courses and may not be action-oriented, the faculty engaged in a workshop hosted by the EERC to develop detailed learning objectives for their courses based on Bloom's revised taxonomy [12]. Faculty were informed on how learning objectives were integral to the project and the importance of writing them to cover the depth of learning for both assessment and industry use. Faculty were then instructed on Bloom’s revised taxonomy and provided step-by-step instructions for writing clear objectives, practice examples, and in-workshop time to revise specific course learning objectives. The exercise yielded 96 learning objectives across the six topics. Each outcome was labeled so that SMEs could identify which course it belonged to (e.g., Transport: Split PDEs into two or more ODEs and solve them via separation of variables).

We met with our SMEs via Zoom three times during the late fall of 2023 through the spring of 2024. At our initial meeting, we reviewed the project goals and provided an overview of how we intend to collaborate with the SMEs. We reviewed the GCM technique at our second meeting and discussed the above focus prompt. Next, we provided a timeline with the three phases (brainstorming, sorting, and rating), specific instructions, approximate time commitments, and completion deadlines for each phase. Lastly, we provided an instructional tutorial on the GroupWisdom software.

During the **Brainstorming/Idea Generation** phase, the SMEs reviewed existing learning objectives from six core chemical engineering courses. Further, participants brainstormed additional objectives that reflected graduate-level competencies and professional skills. The resulting set of learning objectives exceeded the software limit for sorting. The additional contributed objectives were analyzed into two sets: (1) core content areas and (2) non-core content areas (e.g., communication skills, project management, etc.). The second set was set aside for a secondary rating after completing the GCM method on the core content areas. One hundred sixteen learning objectives were used for sorting and rating phases (see Table 2-A).

For the **Sorting** phase, SMEs grouped learning objectives into conceptual categories. They were instructed to sort and group each outcome into one of three "piles" that made sense according to whether the learning objective was fundamental, graduate-level, or specialized. SMEs could also create a pile for learning objectives that did not need to be taught (e.g., Discard Pile) and a pile for items that the SME was unsure about or did not have the background to sort appropriately (e.g., Unsure Pile).

Finally, during the **Rating** phase, SMEs rated each learning objective based on its importance to their field and graduate education. The learning objectives were presented randomly on a five-point Likert scale (1—Not at all important, 2—Slightly important, 3—Moderately important, 4—Very important, and 5—Extremely important).

Once the data were analyzed (see forthcoming section), we met with our SMEs in late spring 2024 to explain the analysis used to obtain the results. We had an open discussion with the SMEs as they reviewed the results, asking if anything was surprising or incorrect.

Later in the year, the SMEs participated in an additional survey to rate the various additional objectives. As listed in Table 2-B, eight areas emerged from the Brainstorming phase. Cross-disciplinary topics include law, entrepreneurship, electrical, materials, biology, and renewables. The SMEs were then asked to rank the categories from most to least important based on their field and graduate education.

Table 2: Learning objectives for traditional core content and non-core content

A		B	
Traditional Core Content	**# of Learning Objectives**	**Non-Core Content**	**# of Learning Objectives**
Kinetics	24	Communication	8
Transport	25	Project Management	9
Thermodynamics	20	Interpersonal Skills	2
Mathematics	24	Business Finance	4
Ethics	11	Life Cycle Analysis	2
Safety	12	Programming	7
		Process Control and Process Design	3
		Cross-Disciplinary Topics	6

3. Analysis

3.1 GCM Analysis

The GroupWisdom platform processes participant input using advanced statistical techniques, including multidimensional scaling and hierarchical cluster analysis. This analysis generates visual output such as point maps, cluster maps, and cluster rating maps, providing clear insights into group perceptions and thematic structures.

First, a similarity matrix was created [13]. The matrix yielded learning objectives frequently sorted and placed closer together, indicating conceptual similarity. Multidimensional scaling was then applied. From the similarity matrix, learning objectives that were sorted closer together were plotted closer together; objectives that were not frequently sorted together were plotted further from each other. The results were plotted on an *X,Y* point map. This visual two-dimensional point map helped to identify thematic clusters.

Hierarchical Cluster Analysis was then implemented on the point map. This cluster analysis groups learning objectives on the point map into clusters that aggregate to reflect similar concepts. The clustering routine takes the *X,Y* coordinate matrix and produces a tree structure of all cluster solutions from one large cluster to multiple clusters that do not overlap [14]. GroupWisdom yielded different clusters based on the tree structure, ranging from 5 to 15. The team could review the visualizations, interpret the clusters, and refine them. Analysis of the clusters began with the 15-cluster solution, then to a 14-cluster solution where clusters 5 and 6 were merged. This was followed by a 13-cluster solution where the individual clusters of 10 and 11 merged. At each stage, the clusters were analyzed for the learning objectives in the cluster, and if the merging of the clusters made logical sense. The final cluster solution was a 6-cluster solution (see Figure 2), which included two clusters that comprised fundamental learning objectives (clusters 1 and 4), one graduate-level learning objectives cluster (cluster 3), one specialized-level learning objectives cluster (cluster 6), and two clusters that housed ethics, graduate thermodynamics and specialization topics (clusters 2 and 5). The final map reflected the research team's perspective.

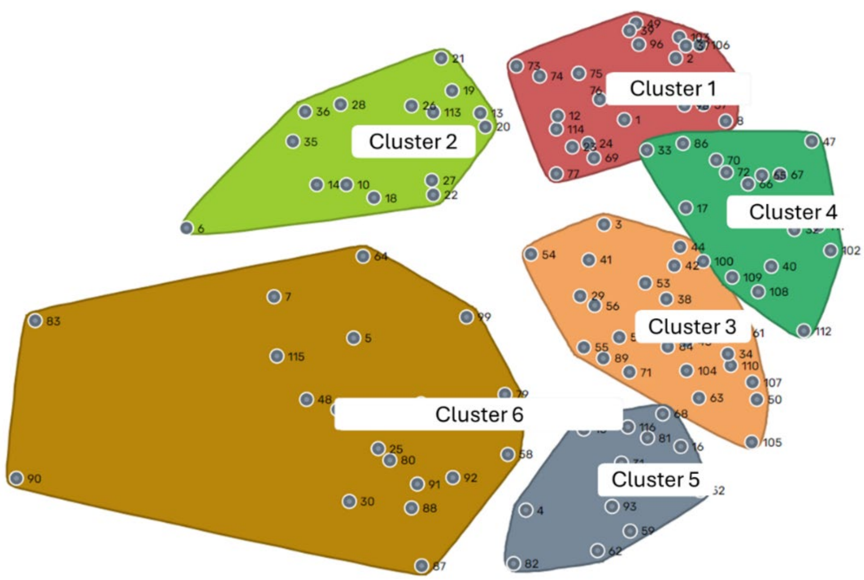

Figure 2: Resulting hierarchical cluster analysis with suggested clusters (numbers correspond to learning objectives).

3.2 Learning Objectives and Importance

Next, we parsed the learning objectives clustered into one-credit modules from the concept map first by organizing all the learning objectives by course (i.e., Math Methods, Transport, Thermodynamics, Kinetics, Safety, and Ethics) to a level (e.g., Fundamentals) in a spreadsheet; then, a second layer of organization was conducted for each course, whereby fundamentals, graduate level, specialized topics, and unsure organized learning objectives for the course. From here, each learning objective was sorted from highest (i.e., 5 – dark green) to lowest (i.e., 1 – dark salmon) according to the average importance rating it received from the third phase of the GCM exercise (see Table 3).

Table 3. Average rating value for learning objectives (5 Highest, 1 Lowest)

Rating Value	Average SME Rating Values
5	4.11 to 4.60
4	3.63 to < 4.11
3	3.14 to < 3.63
2	2.65 to < 3.14

1	2.17 to < 2.65

The ratings of academic and nonacademic SMEs were compared, and it was found that both types of SMEs shared 14 learning objectives with the same level of importance (i.e., ratings of 4 or 5). These 14 learning objectives are listed in Table 4. This analysis confirmed that one SME group did not favor a particular content over the other SME group.

Table 4. Shared importance between academic and non-academic SMEs on core learning objectives

Average Rating	Learning Outcome
4.5	**Transport:** Construct and deliver effective oral (presentation) and written (paper) communication regarding the background, theory, methods, results, and analysis of your problem and calculation.
4.5	**Safety**: Judge the hazards of a substance from its safety data sheet.
4.3	**Safety**: Identify and select the personal protective equipment (gloves, eyewear) suitable for a specific substance or operation.
4.3	**Safety**: Recognize personal, process, & community safety
3.8	**Math Methods**: Principles and applications of probability, statistics, analytics, and machine learning/AI
3.7	**Kinetics/ReactorDesign**: Solve material and energy balance equations for batch, semi-batch, stirred-flow, plug-flow, and packed bed reactors
3.7	**Math Methods:** Perform relevant statistical analyses, e.g., multivariate analysis, ANOVA, partial and full factorial designs
3.6	**Math Methods**: Restate the accuracy, assumptions, and extrapolation for modeling techniques
3.6	**Safety**: Perform common lab activities safely, e.g. using needles and syringes, replacing a gas cylinder and regulator, removing gloves safely.
3.6	**Math Methods**: Demonstrate familiarity with modeling techniques (including things to watch out for with respect to accuracy, assumptions, and extrapolation)
3.6	**Transport**: Describe and give examples of the three modes of transport
3.5	**Thermo**: Calculate changes in thermodynamic properties using the first and second laws of thermodynamics in conjunction with equations of state or departure functions
3.5	**Math Methods**: Apply parametric (t statistics) and nonparametric (U statistic; K-S statistic) tests to determine when significant differences exist between two or more sets of data.
3.4	**Safety**: Assess the safety of a laboratory operation.

3.3 Survey analysis of non-core learning objectives

We created and deployed a survey to facilitate the SME rating of the importance of the non-core learning objectives provided in the first phase of the GCM. These 41 learning objectives were separated into eight topic categories (listed in Table 2-B). The SMEs were then asked to rate the 41 additional objectives and then rank the categories from the most (1) to least (8) important relative to carrying out activities in their work.

Surveys were completed by 25 SMEs with backgrounds in three main areas: academia, industry, and other (entrepreneur activities and national labs). Holistically, the most highly rated learning objective for each category is listed in Table 5. The color of the rows indicates the level of importance, as demonstrated in Table 3.

Table 5. Most highly rated learning objectives for each additional non-core category

Category	Learning Objective	Average Rating of Importance
Communication	Recognize the technical level of your audience and use the appropriate amount of detail in written and oral communication.	**4.56**
Project Management	Articulate a clear understanding of a project's objectives (measurable) and final goals.	**4.64**
Interpersonal Skills	Practices skill development aligned with emotional intelligence, including listening, humility, and confidence.	**4.36**
Business Finance	Evaluate financial decisions using the concept of the time value of money.	**3.40**
Process Control and Process Design	Explain applied process design concepts and evaluate modern methods of techno-economic and feasibility analysis.	**3.40**
Programming	Identify key concepts and applications of machine learning.	**3.24**
Life Cycle Analysis	Define objectives, assumptions, and scope for life cycle assessments and assess process rates and product alternatives based on their life cycle impacts to inform decision-making.	**3.12**
Cross-Disciplinary Topics	**Law:** Demonstrate a working knowledge of patents, trade secrets, torts, insurance, licensing, professional engineering practice, regulatory requirements (federal, state, local, international), permitting, contracts, and procurement.	**3.00**

To make an informed decision on which non-core learning objectives to incorporate throughout the new chemical engineering graduate curriculum, we also asked the SMEs to rank the eight categories of learning objectives as most (1) to least (8) important overall relative to carrying out activities in their work.

Three learning objectives were ranked as most important: communication, project management, and interpersonal skills. The remaining five categories had similar ranking averages across all 25 SMEs (Table 6).

Table 6. Average importance ranking value for categories of non-core learning objectives by occupation (1 Most Important, 8 Least Important)

	Average Rank of Importance (1 Most Important, 8 Least Important)			
Category	**ALL SMEs (n=25)**	**Academia SMEs (n=11)**	**Industry SMEs (n=10)**	**Other SMEs (n=4)**
Communication	1.76	1.82	1.50	2.25
Project Management	3.00	2.36	3.50	3.50
Interpersonal Skills	3.36	3.00	3.40	4.25
Business Finance	5.20	5.27	5.20	5.00
Life Cycle Analysis	5.44	5.82	5.60	4.00
Programming	5.52	6.09	5.20	4.75
Process Control and Process Design	5.76	5.82	5.70	5.75
Cross-Disciplinary Topics	5.96	5.82	5.90	6.50

We also measured the level of SME agreement in the rankings and whether the SME's occupational background impacted agreement by calculating Kendall's Coefficient of Concordance (W) for the data as a whole and for each sub-group of SMEs. Overall, the data for the 25 SMEs showed a moderate but statistically significant agreement of the rankings (W = 0.409, p-value = 6.9E-13). When individual sub-groups of the SMEs were tested for agreement, we observed that the Academia sub-group had a higher W ratio than the complete data set, using a Bonferroni correction (p-value for significance ≥ 0.017) to account for the additional analyses. We found that Kendall's Coefficient of Concordance was statistically significant for the Academia (W = 0.532, p-value = 8.2E-7) and Industry groups (W = 0.400, p-value = 2.2E-4), indicating a moderate agreement. However, the "Other SMEs" group had the smallest Kendall's Coefficient of Concordance (W = 0.292), suggesting a low level of agreement, and it was not statistically significant (p-value = 0.318).

Since our SMEs also experienced different educational backgrounds, with 5 earning a BS degree, 4 earning an MS degree, and 16 earning a Ph.D. as their highest-earned degrees, we also wanted to determine whether educational background impacted the ranking of non-core learning objectives. When the data was sorted into three groups based on the highest earned degrees, we found similar levels of agreement in each group. BS and Ph.D. degree holders had statistically significant, moderate Kendall's Coefficient of Concordance (W = 0.606, p-value = 0.0035 and W = 0.474, p-value = 3.6E-9, respectively). MS degree holders had a low level of agreement, which was not statistically significant (W = 0.301, p-value = 0.297).

Like the rankings by occupation, grouping the non-core learning objective rankings by degree also demonstrated a separation into the three most important identical categories: communication, project management, and interpersonal skills. The remaining five categories had lower important ranking averages by degree group, ranging from 4.75 to 7.40 (Table 7).

Table 7. Average importance ranking value for categories of non-core learning objectives by degree (1 Most Important, 8 Least Important)

	Average Rank of Importance (1 Most Important, 8 Least Important)			
Category	**ALL SMEs (n=25)**	**BS SMEs (n=5)**	**MS SMEs (n=4)**	**Ph.D. SMEs (n=16)**
Communication	1.76	1.80	2.50	1.56
Project Management	3.00	2.60	2.75	3.75
Interpersonal Skills	3.36	3.40	3.75	2.69
Business Finance	5.20	4.80	4.75	5.44
Life Cycle Analysis	5.44	6.20	6.00	5.88
Programming	5.52	7.40	5.75	4.88
Process Control and Process Design	5.76	4.00	5.25	6.44
Cross-Disciplinary Topics	5.96	5.80	5.25	5.38

To further determine if there were any differences between the rankings by the SME subgroups for each non-core learning objective category, we completed Kruskal-Wallis H tests for each category of learning objectives, comparing the three occupation groups and the three degree-holder groups independently.

These analyses revealed no statistical difference between these occupational and degree groupings of rankings for individual categories.

4. Results

4.1 Outcomes of the Group Concept Mapping Process

As mentioned, the GCM exercise yielded two types of learning objectives: core learning objectives and non-core learning objectives. Each of the results is presented.

4.1.1 Core Learning Objectives

Appendix 1 provides the learning objectives sorted by topic for all six courses. Figure 4 illustrates the result for one of the six courses, Kinetics and Reactor Design. The figure provides the learning objectives in four columns representing fundamentals, graduate level, specialized, and unsure. Further, the learning objectives are ordered from high to low according to their importance rating. The course learning objectives were presented to the SMEs to review to see if there were any concerns with the results.

There were differences between the six courses. Specifically, Ethics contained no graduate-level learning outcomes, and Safety contained no graduate-level or specialized learning outcomes. The SMEs saw this and the faculty teaching the courses as reasonable, as the topics were fundamental, and the two classes would be taught as single one-credit courses (as opposed to one combined three-credit course).

	Fundamentals		Graduate Level		Specialized		Unsure
final		final		final		final	
1,2	Kinetics/ReactorDesign: Solve material and energy balance equations for batch, semi-batch, stirred-flow, plug-flow, and packed bed reactors	2	Kinetics/ReactorDesign: Given a set of empirical data relating reaction rate to temperature and convection, propose modifications to decrease the impact of rate-limiting mass transfer	2	Kinetics/Reactor Design: Interpret the results of linear/nonlinear fits to empirical measurements of composition/position/time data in chemical reactors (assumes the process of fitting the data is covered in math)	2	Kinetics/ReactorDesign: Use the most abundant reaction intermediate (MARI) method to simplify and solve surface catalyzed reaction sequences
1	Kinetics/ReactorDesign: Define selectivity, yield, space time, space velocity	2,3	Kinetics/ReactorDesign: Critically assess the validity of the Langmuir adsorption isotherm as a realistic model, given a set of physical conditions or an empirical dataset	3	Kinetics/ReactorDesign: Describe and critically assess the use of process intensification methods to improve efficiency and reduce the environmental impact of a chemical reactor system	3	Kinetics/ReactorDesign: Rationalize the unique design principles for complex multiphase reactor schemes (e.g., polymerizations, membrane reactors) on the basis of their unique molecular-scale properties
1	Kinetics/ReactorDesign: Explain the basic requirements of a reaction rate equation using language a first-year college student (near peer) would understand	2,3	Kinetics/ReactorDesign: Compute a Thiele modulus and effectiveness factor from a suitable set of empirical parameters	3	Kinetics/ReactorDesign: Use the principles of electrochemistry to explain the basic design of electrocatalytic reactors and corrosion processes	3	Kinetics/ReactorDesign: Describe the basic function of biochemical machinery (e.g., metabolic processes in bio-organisms AND human-made bioreactors) by analogy to the design of canonical chemical reactor units
1	Kinetics/ReactorDesign: Solve for the compositions in an equilibrium reacting mixture, given the equilibrium constant and initial conditions	2	Kinetics/ReactorDesign: Derive the Langmuir adsorption isotherm and critically assess its validity under a given set of physical condtions or an empirical dataset				
1,2	Kinetics/ReactorDesign: Predict the reactant/product composition exiting a reactor under conditions involving multiple reactions	2	Kinetics/ReactorDesign: Describe methods for identifying the number of active sites on a catalyst particle				
2	Kinetics/ReactorDesign: Schematically describe residence time distributions for ideal plug-flow, stirred-flow, and nonideal reactors						
2	Kinetics/ReactorDesign: Use the steady-state approximation to develop a valid rate equation for a multi-step reaction sequence						
2,3	Kinetics/ReactorDesign: Compare the differences between internal and external mass transfer limitations in catalytic processes						
1,2	Kinetics/ReactorDesign: Compare and contrast physisorption and chemisorption in terms of enthalpy of adsorption						
~2	Kinetics/ReactorDesign: Compute estimates for viscosity, thermal conductivity, and diffusivity of gases from expressions given by the kinetic theory of gases						
1	Kinetics/ReactorDesign: Differentiate between elementary and nonelementary reaction equations						
~2	Kinetics/ReactorDesign: Compute estimates of elementary reaction rates using transition state theory and collision theory						
~2,3	Kinetics/ReactorDesign: Differentiate between molecular, Knudsen, and single-file diffusion regimes when given a set of unlabeled cartoon schematics						

Figure 4. Resulting SME derived learning objectives for each module for kinetics and reactor design.

For Math Methods, SMEs rated many learning objectives as important (i.e., green shaded) for fundamentals and graduate-level, but rated the learning objectives with lower importance (i.e., salmon shaded) for specialized level and the unsure column. Again, this was found appropriate by the SMEs, given that Math Methods supports other areas of the chemical engineering curriculum.

Except for Kinetics and Reactor Design, the SMEs did not place high importance on learning objectives in the specialized columns. This result was intuitive, which is the purpose of the specialized module. The third credit is intended to be focused, flexible content, and likely a topical area that is timely and well-aligned with the instructor's research expertise. Students must take at least one specialized core credit as part of the new curriculum.

4.1.2 Non-Core Learning Objectives

The survey results from 25 SMEs provided valuable insights into the perceived importance of the non-core learning objectives created during the brainstorming session for the BOK creation. Overall, Communication emerged as the most highly rated category, with average importance rating scores for individual learning objectives ranging from 3.20 to 4.56 on a scale where 5 was the highest possible rating. Similarly, Project Management and Interpersonal Skill learning objectives were also rated highly, with average importance scores ranging from 2.76-4.64 and 4.12-4.36, respectively. The remaining categories—Business Finance, Life Cycle Analysis, Programming, Process Control and Design, and Cross-Disciplinary Topics—received comparatively lower ratings, with their *highest-rated* learning objectives averaging between 3.00 and 3.40 (Table 5). However, this finding does not discount the relative importance of individual learning objectives within these categories. Notably, some learning objectives in Business Finance, Process Control, and Process Design were rated, on average, as moderately important, highlighting their potential value.

The ranking data for the eight categories further underscores the perceived importance of Communication, Project Management, and Interpersonal Skills in professional settings, with a scale of 1 as the most important and 8 as the least important. These three categories were ranked the highest overall when analyzing the complete data set and when examining rankings by SME sub-groups by occupation and degree. Specifically, Communication consistently emerged as the most important category across all sub-groups and the overall data set (Table 6).

While statistical significance was not achieved when comparing the average ranking of the categories by SME sub-groups, the data suggests a notable difference in how SMEs from Academia perceive Programming compared to Industry and the Other (entrepreneur/National Labs) sub-groups. Academia SMEs ranked Programming relatively low (6.09), while it received higher average rankings from SMEs in Industry and the Other sub-groups (5.30 and 4.75, respectively; Table 6). We observed a similar difference in the ranking of Programming across degree groups with Ph.D. SMEs ranking Programming at an average of 4.55 and BS SMEs averaging a rank of 7.40 (Table 7). This difference may reflect differing expectations and practical demands across these occupational and degree contexts. This perception gap highlights the need for better alignment between academic preparation and workforce expectations. Incorporating programming skill-building opportunities into the curriculum could help bridge this gap and ensure students are better equipped for diverse career pathways.

Overall, this analysis reveals a clear priority for incorporating communication, project management, and interpersonal skills into the curriculum and professional development streams, underscoring the critical role of professional activities for ChE Ph.D. graduates. While there were some variations in agreement within sub-groups, the overall ratings and rankings of the additional learning objectives reflect broad alignment among SMEs. These findings provide a robust foundation for curriculum development, emphasizing specific skills and knowledge sets that are a high priority for integration into our ChE curriculum.

4.2 Faculty Learning Community (FLC)

To interpret and implement the results of the concept mapping process into one-credit graduate modules, a Faculty Learning Community (FLC) was established in the early Fall of 2024. Monthly, faculty teaching the courses collectively engaged in iterative discussions. Our first meeting focused on the overall review of the results and beginning discussions of how we will transform the three-credit classes into one-credit modules for Fall 2025. Faculty returned the following month after reviewing their GCM results for their course with questions and concerns regarding how the modules could be structured and taught.

Faculty participated in a Quality Evaluations Design (QED) Innovation Support Survey (QISS) following the November meeting. Our external evaluator created this survey based on two strands of research: Rogers' Diffusion of Innovation and Henderson & Froyd's work on Increasing the Impact of Learning Innovations [15-17].

The survey aimed to obtain a baseline from the faculty regarding how they viewed the upcoming changes and the curricular innovation, and to identify initial "pain points" as faculty investigate and change their courses. The survey will be routinely administered throughout the grant as an assessment of the viability of this curricular innovation. A future paper will provide more details of this specific work and its results. As the one-credit modules unfold and are implemented, we hope to move the FLC to other areas of the engineering school, the chemical engineering community, and the engineering education community.

The faculty were asked to begin drafting their modules at the December meeting. Here, the faculty started deciphering the feasibility of teaching the learning objectives in the suggested module. There were some situations where the learning objective needed to be assigned to a different module, such as insufficient time to address all goals in a single module.

The spring FLC meetings have focused on assisting faculty in transitioning their courses into modules that take advantage of Vygotsky's Zone of Proximal Development [18]. Using this scaffolding principle as an overarching pedagogy, students are first exposed to content in a learner-assisted mode; then, as students develop competency, they will move toward independent learning. During the last week of the module, students will demonstrate independence via an exam or a project. In doing so, faculty teaching each course have reviewed the learning objectives that form the body of knowledge (provided in the appendix) and verified the modules in which these learning objectives will be taught. Faculty are identifying the structure within the first (5-week) one-credit course. For each learning objective, faculty are determining the requisite pre-knowledge, providing examples for understanding, guiding in-class practice opportunities, and determining independent practice opportunities (e.g., homework, project, etc.). Over the summer, they will repeat this process for the other two modules. Hence, by fall 2025, a complete day-to-day plan (the cornerstone of the syllabus) for the three modules will be completed.

5. Conclusion and Ongoing Work

The study employed subject matter experts (SMEs) and a group concept mapping technique to develop two distinct sets of learning objectives for graduate chemical engineering: core and non-core learning objectives. The findings reveal a surprising agreement among experts regarding the learning objectives and their relative importance. However, while the FLC has widespread enthusiasm and awareness about the need to modernize, challenges arise when transitioning from conceptual support to actionable implementation. This resistance highlights potential obstacles in the diffusion process and underscores the need for strategic approaches to guide the FLC by effectively adopting these modernized objectives and course structure.

Our modularized graduate curriculum in ChE, guided by the PLM, is an ambitious and transformative project. Several ongoing efforts are underway to advance this initiative and address emerging challenges. The first is finalizing the modular content. Faculty are refining the modular content by aligning learning objectives with appropriate modules, ensuring consistency in instructional approaches across modules, and addressing gaps identified during the GCM exercise. We are also investigating pedagogical techniques for the new curriculum that promote student mastery.

The Faculty Learning Community continues to play a vital role in refining the curriculum. Overcoming their barriers is key to success. Plans are in place to expand the FLC model to other departments and institutions to foster interdisciplinary collaboration and innovation in graduate education.

Transitioning from a traditional, rigid graduate curriculum to a modularized, personalized learning framework represents a significant innovation in graduate education. Key takeaways and anticipated impacts include enhanced flexibility and personalization, alignment with industry and societal needs, and improved pedagogical practices. The project aims to inspire similar transformations across disciplines and institutions by documenting and sharing development practices.

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Appendix 1 Resulting Core and Non-Core Learning Objectives

Kinetics and Reactor Design

proposed	Fundamentals	proposed	Graduate Level	proposed	Specialized	proposed	Unsure
1,2	Kinetics/ReactorDesign: Solve material and energy balance equations for batch, semi-batch, stirred-flow, plug-flow, and packed bed reactors	2	Kinetics/ReactorDesign: Given a set of empirical data relating reaction rate to temperature and convection, propose modifications to decrease the impact of rate-limiting mass transfer	2	Kinetics/Reactor Design: Interpret the results of linear/nonlinear fits to empirical measurements of composition/position/time data in chemical reactors (assumes the process of fitting the data is covered in math)	2	Kinetics/ReactorDesign: Use the most abundant reaction intermediate (MARI) method to simplify and solve surface catalyzed reaction sequences
1	Kinetics/ReactorDesign: Define selectivity, yield, space time, space velocity	2,3	Kinetics/ReactorDesign: Critically assess the validity of the Langmuir adsorption isotherm as a realistic model, given a set of physical conditions or an empirical dataset	3	Kinetics/ReactorDesign: Describe and critically assess the use of process intensification methods to improve efficiency and reduce the environmental impact of a chemical reactor system	3	Kinetics/ReactorDesign: Rationalize the unique design principles for complex multiphase reactor schemes (e.g., polymerizations, membrane reactors) on the basis of their unique molecular-scale properties
1	Kinetics/ReactorDesign: Explain the basic requirements of a reaction rate equation using language a first-year college student (near peer) would understand	2,3	Kinetics/ReactorDesign: Compute a Thiele modulus and effectiveness factor from a suitable set of empirical parameters	3	Kinetics/ReactorDesign: Use the principles of electrochemistry to explain the basic design of electrocatalytic reactors and corrosion processes	3	Kinetics/ReactorDesign: Describe the basic function of biochemical machinery (e.g., metabolic processes in bio-organisms AND human-made bioreactors) by analogy to the design of canonical chemical reactor units
1	Kinetics/ReactorDesign: Solve for the compositions in an equilibrium reacting mixture, given the equilibrium constant and initial conditions	2	Kinetics/ReactorDesign: Derive the Langmuir adsorption isotherm and critically assess its validity under a given set of physical condtions or an empirical dataset				
1,2	Kinetics/ReactorDesign: Predict the reactant/product composition exiting a reactor under conditions involving multiple reactions	2	Kinetics/ReactorDesign: Describe methods for identifying the number of active sites on a catalyst particle				
2	Kinetics/ReactorDesign: Schematically describe residence time distributions for ideal plug-flow, stirred-flow, and nonideal reactors						
2	Kinetics/ReactorDesign: Use the steady-state approximation to develop a valid rate equation for a multi-step reaction sequence						
2,3	Kinetics/ReactorDesign: Compare the differences between internal and external mass transfer limitations in catalytic processes						
1,2	Kinetics/ReactorDesign: Compare and contrast physisorption and chemisorption in terms of enthalpy of adsorption						
~2	Kinetics/ReactorDesign: Compute estimates for viscosity, thermal conductivity, and diffusivity of gases from expressions given by the kinetic theory of gases						
1	Kinetics/ReactorDesign: Differentiate between elementary and nonelementary reaction equations						
~2	Kinetics/ReactorDesign: Compute estimates of elementary reaction rates using transition state theory and collision theory						
~2,3	Kinetics/ReactorDesign: Differentiate between molecular, Knudsen, and single-file diffusion regimes when given a set of unlabeled cartoon schematics						

Transport

Fundamentals: proposed	Fundamentals	Graduate Level: proposed	Graduate Level	Specialized: proposed	Specialized	Unsure: proposed	Unsure
1	Transport: Describe and give examples of the three modes of transport	2,3	Transport: Construct and deliver effective oral (presentation) and written (paper) communication regarding the background, theory, methods, results, and analysis of your problem and calculation.	Kinetics?	Transport: Develop a model for a defined chemical engineering transport problem involving at least two modes of transport that can be solved using the base package of COMSOL. Transport models can include steady-state, unsteady transport processes, irregular geometry, and nonlinear transport.	3	Transport: Classify and apply process intensification principles
~1	Transport: Specify and apply boundary conditions	2	Transport: Reason how developing (unsteady) or developed (steady state) temperature or concentration profiles interact with developing or developed velocity profiles	3	Transport: Apply knowledge of fundamental electrokinetic phenomena, such as the flow past charged surfaces and electrophoresis, to analyze and predict the behavior of charged particles and fluids in various electrochemical and biotechnological applications.	3	Transport: Rigorous and sophisticated understanding of the fundamental physics, transitioning to integrated applications in bio, materials, reactors, and separations.
1	Transport: Write out the constitutive equations for momentum, thermal energy and mass transport. Be able to explain each term.	2	Transport: Solve and physically interpret (i.e., evaluate) one-dimensional unsteady state transport problems and multi-dimensional steady-state transport problems.			1	Transport: Contrast Eulerian and Lagrangian viewpoints
~1	Transport: Improve understanding of underlying transport processes by carrying out dimensional analyses	~2	Transport: Solve and physically interpret simple steady-state conduction, diffusion, and fluid flow problems in rectangular, cylindrical, and spherical geometries, with and without zero-order and first-order generation/loss using shell (i.e., integral) balances.				
~1	Transport: Calculate heat flux due to radiation	2	Transport: Compare macroscopic, microscopic and molecular approaches to solving transport problems				
1	Transport: Given a stress-strain relationship, categorize the behavior as Newtonian or non-Newtonian	2	Transport: Construct and simplify differential balances for momentum, thermal energy, and species mass in rectangular, cylindrical and spherical geometries, accounting for convective and diffusive (molecular-scale) transport and generation/loss.				
~2/Math	Transport: Solve PDEs and visualize numerical results in Matlab	Kinetics?	Transport: Compute temperature profiles using the finite difference method				
~2/Math	Transport: Perform vector and tensor operations		Transport: Recall and explain each term in the combined momentum flux tensor, the combined energy flux vector, and the combined mass flux vector				
		Kinetics?	Transport: Split PDEs into two or more ODEs and solve via separation of variables				
		Kinetics?	Transport: Convert PDEs to ODEs using combination of variables and solve				
		??	Transport: Analyze the behavior of materials using constitutive equations in tensor form and invariants.				
			Transport: Derive the Hagen-Poiseuille equation				

Thermodynamics

Fundamentals		Graduate Level		Specialized		Unsure	
proposed		proposed		proposed		proposed	
1	Thermo: Calculate changes in thermodynamic properties using the first and second laws of thermodynamics in conjunction with equations of state or departure functions	3	Thermo: Calculate chemical compositions in reaction equilibria involving multiple independent reactions in nonideal systems	3	Thermo: Create computer codes in Python or a similar language to solve problems such as computing changes in thermodynamic properties, phase equilibria, etc.	2	Thermo: Calculate thermodynamic properties of ideal gas polyatomic molecules using statistical mechanics
3	Thermo: Read quantitatively and interpret two-and three-species phase diagrams in mixtures involves solids, liquids, gases, compounds/alloys, and critical phenomena	2 or 3	Thermo: Calculate electrolyte equilibrium, e.g. acid base equilibrium, partioning of ions between phases, charge distribution near surfaces	2	Thermo: Solve the Schrodinger equation and calculate the eigenfunctions for the following model systems: particle-in-a-box, harmonic oscillator, and rigid rotor	3	Thermo: Analyze basics of interfacial thermodynamics (e.g. adsorption equilibrium, Gibbs dividing surface, interfacial excess, Gibbs Thompson equation) and self assembly (e.g. micellar equilibrium)
1	Thermo: Calculate pure fluid and mixture phase equilibria	2	Thermo: Describe how intermolecular potentials give rise to non-ideal fluid and solid behavior			?	Thermo: Establish precise logical structure of classical, nonmolecular Gibbsian thermo and its key appln to pure & mixture property relations and equilibrium & stability; link to molecular origins of thermochemical & substance properties (stat mech).
3	Thermo: Compare and contrast the origins and limitations of various equations of state	2	Thermo: Define the purpose of a partition function and give examples of how it is used			2	Thermo: Describe how statistical mechanics can be used to compute thermophysical properties of macroscopic systems
1	Thermo: Calculate phase equilibria using activity coefficient models					2	Thermo: Identify partition functions for different ensembles
3	Thermo: Calculate basics of electrochemical equilibrium, e.g. Nernst equation					3	Thermo: Derive the Gibbsian functions and the Gibbs-Duhem equation using Legendre transforms
1	Thermo: Compute property changes on mixing using partial molar properties						
3	Thermo: Compute fluid properties from two and three parameter corresponding states						

Math Methods

Fundamentals	Graduate Level	Specialized	Unsure
roposed	proposed	proposed	proposed
Math Methods: Demonstrate familiarity with data evaluation techniques (e.g., data quality, applicability, completeness, bias)	Math Methods: Perform relevant statistical analyses, e.g., multivariate analysis, ANOVA, partial and full factorial designs	Math Methods: Demonstrate in-depth experience with analysis and programming (e.g., from a research project) [including version control]	Math Methods: Implement forward Euler, backward Euler and Runge-Kutta numerical ordinary differential equation solver algorithms in Python.
Math Methods: Principles and applications of probability, statistics, analytics, and machine learning/AI	Math Methods: Apply parametric (t statistics) and nonparametric (U statistic; K-S statistic) tests to determine when significant differences exist between two or more sets of data.	Math Methods: Quantifiably assess which ordinary differential equation solver algorithm is most appropriate for specific mathematical models.	Math Methods: Implement bootstrap and Markov Chain Monte Carlo resampling approaches for estimating parameter confidence bounds of ordinary differential equations.
Math Methods: Demonstrate familiarity with modeling techniques (including things to watch out for with respect to accuracy, assumptions, and extrapolation)	Math Methods: Explain the working principles of time stepping, convergence, and stability in numerical methods.	Math Methods: Manipulate ODEs to satisfy the condition for exactness and assess for consistency with the original ODE.	Math Methods: Analyze the dynamic response landscape of complex, coupled, 2nd order, ordinary differential equations using phase plane and eigenvalues/vectors analysis.
Math Methods: Restate the accuracy, assumptions, and extrapolation for modeling techniques		Math Methods: Analyze/consider the role of hysteresis in reactor design when dealing with exothermic reactions or chemostats using bifurcation analysis.	
Math Methods: Define linear regression using least squares and compare the results of linear regression when applied to continuous versus categorical data		Math Methods: Implement gradient descent algorithm in Python to estimate the parameters values of nonlinear ordinary differential equations.	
Math Methods: Solve ordinary differential equations with established analytical methods		Math Methods: Formulate a robust statistical analysis of healthcare data (or data from preferred research area) to determine the major factors driving outcomes between different populations.	
		Math Methods: Dissect the long-term dynamical responses of arbitrarily complex, first order, ordinary differential equations using flow analysis.	
		Math Methods: Decide on the appropriate operating ranges of a chemostat reactor using flow or phase plane analysis of dynamical systems	
		Math Methods: Create new statistical tests to analyze non-normally distributed data using brute force approaches.	
		Math Methods: Apply Bessel function to solve various chemical engineering problems	
		Math Methods: Apply interaction effect analysis to identify important (possibly deleterious) synergistic responses using healthcare data.	

Safety

Fundamentals	Graduate Level	Specialized	Unsure
roposed	proposed	proposed	proposed
Safety: Judge the hazards of a substance from its safety data sheet.			Safety: Establish a basic knowledge of plant process control concepts, risk assessments, safety audits, and quality management systems.
Safety: Recognize personal, process, & community safety			Safety: Review major codes / regulations that chemical engineers students might encounter across a variety of industries.
Safety: Identify and select the personal protective equipment (gloves, eyewear) suitable for a specific substance or operation.			Safety: Prepare safety documents: PHA (Process Hazard analysis), LOPA (Layers of protection analysis), MRA (machine risk assessment), MOC (management of change).
Safety: Assess the safety of a laboratory operation.			Safety: Explain the basic processes in fault tree analysis.
Safety: Perform common lab activities safely, e.g. using needles and syringes, replacing a gas cylinder and regulator, removing gloves safely.			Safety: Identify components of a fault tree.
Safety: Recall key facts about the safety system of the University. For example, the phone number for campus police; the names of individuals to contact within the department, school, and university in case of safety-related questions; basic rules of storing chemicals.			
Safety: introduction to the Elements of OSHA's Process Safety Management and EPA's Risk Management Program			

Ethics

Fundamentals	Graduate Level	Specialized	Unsure
roposed	proposed	proposed	proposed
Ethics: Formulate ethical decisions applied to engineering case studies using their "ethical toolbox"		Ethics: Differentiate between the range of context-specific expectations and mechanisms to establish/ensure technical rigor, intellectual credit, and rights of ownership in the dissemination of R&D results.	Ethics: Assess common forms of ethical misconduct in research by delineating responsible and questionable research practices
		Ethics: Compare and contrast basic ethical theories (e.g. moral absolutism vs. relativism, utilitarianism, virtue ethics)	Ethics: Basic business ethics. Bribes, insider trading, market manipulation, fair pricing and quoting.
			Ethics: Summarize compasses & challenges; Triple bottom line of sustainability; Personal, process, & community safety; Finding your career passions; Time planning & management; ChE's core & transdisciplinary culture
			Ethics: Contrast and asses environmental ethics and economic considerations in chemical products and processing
			Ethics: Cultural competence for equity and inclusion. Depending on the region of the job, this is going to make a difference (i.e. Native American, Appalachian, Black, Hispanic, etc.) but all are important to recognize
			Ethics: Demonstrate understanding of basic data ethics considerations, including ownership, privacy, and licenses
			Ethics: Describe the safety, quality, productivity triangle. (Work examples of excursion cases where productivity and quality faceoff. Work examples of customer demand cases where productivity and safety faceoff.)
			Ethics: Relate the key elements found in professional codes of ethics issued by professional organizations, highlighting their relevance for chemical engineers. (example organizations: AIChE, ACS, ABET, BMES)

Complete list of non-core learning outcomes and color-coded based on ratings from Table 3

Cross-Disciplinary Topics

Law: Demonstrate a working knowledge of patents, trade secrets, torts, insurance, licensing, professional engineering practice, regulatory requirements (federal, state, local, international), permitting, contracts, and procurement.
Renewables: Describe the promise and challenges of each topic below in regard to decarbonizing the (chemical) industry, including unit operations, equipment, systems, applications, design sizing and selection, and integrations into plant design for renewable energy.
Materials: Examine advanced concepts in polymer chemistry, and chemical compatibility.
Electrical: Explain basic electrical processes as industries transition from fossil fuels to electricity.
Biology: Utilize knowledge of molecular, cellular, and systems biology to explain biological processes in microorganisms and humans.
Entrepreneurship: Describe the structure, legal requirements, logistics (insurance, liability), and funding options (stages, equity versus debt) for new company formation.

Process Control and Process Design

Explain applied process design concepts and evaluate modern methods of techno-economic and feasibility analysis.
Analyze piping and instrumentation diagrams (PIDs) to interpret system components and their functions.
Design, select, and size the safeguards and protections required for control of industrial processes.

Programming

Identify key concepts and applications of machine learning.
Use applications modeling processes (e.g., AspenPlus)
Use Python or MatLab to solve differential equations
Explain algorithmic principles and program logic and structure.
Use applications for visualization of molecules (e.g., GaussView)
Solve problems using finite element modeling (e.g., COMSOL)
Describe the interactions between different types of hardware (e.g., CPU, GPU, quantum computer) and software.

Life Cycle Assessment

Define objectives, assumptions, and scope for life cycle assessments and assess process rates and product alternatives based on their life cycle impacts to inform decision-making.
Conduct a life cycle analysis on a chemical plant, using commercial or open-source software (e.g., OpenLCA or Simapro) and incorporating principles of the Resource Conservation and Recovery Act (RCRA) for waste storage.

Business Finance

Evaluate financial decisions using the concept of the time value of money.
Explain the principles and processes involved in creating budgets, forecasts, and contracting costs.

Apply fundamental accounting principles, including cost, revenue, margins, and accrual, to various business scenarios.
Analyze profit and loss statements and balance sheets to interpret financial health and performance.

Interpersonal Skills

Practices skill development aligned with emotional intelligence, including listening, humility, and confidence.
Select conflict resolution strategies that incorporate the needs of all parties, take into account power dynamics, and utilize empathy.

Project Management

Articulate a clear understanding of a project's objectives (measurable) and final goals.
Formulate a problem, identify key points, and extract relevant data for analysis.
Analyze a problem from a perspective that is broader than your focused area of expertise.
Apply basic project management skills including developing Gantt charts (setting project milestones, defining a project schedule, planning tasks), managing stakeholders, setting milestones, and communicating progress to multiple stakeholders.
Evaluate and justify when to exit a project, based on performance and outcomes.
Determine when project deliverables meet acceptable standards of completeness and quality.
Estimate the time required to complete tasks with accuracy.
Evaluate the quality of a proposed solution by assessing potential sources of error and reliability.
Apply established business processes (e.g., Six Sigma Methodology, and the Front-End Loading (FEL) model)

Communication

Recognize the technical level of your audience and use the appropriate amount of detail in written and oral communication
Communicate effectively and respectfully with operations personnel.
Apply ethical guidelines when producing figures for publication to ensure accuracy and prevent misleading representations.
Apply effective scientific communication techniques in short pitches, presentations, technical writing, and editing, including effective visualization of data where appropriate.
Construct an outline that communicates expected outcomes, work-in-progress, and completed work.
Communicate by documentation, a multi-step technical procedure that others can replicate accurately without requiring additional information.
Communicate the motivation, value, and potential financial impact of a project to non-technical business partners effectively.
Write a proposal for funding using government research agency formatting, and/or for internal funding for industry.