Conceptual Framework to Help Promote Retention and Transfer in the Introductory Chemical Engineering Course

MICHAEL E. HANYAK, JR
Bucknell University
Lewisburg, PA 17837

ABSTRACT

In an introductory chemical engineering course, the conceptual framework of a holistic problem-solving methodology in conjunction with a problem-based learning approach has been shown to create a learning environment that nurtures deep learning rather than surface learning. Based on exam scores, student grades are either the same or better than the course taught using a lecture-based format. Based on pre- and post-course scores for an in-house concept inventory, average learning gains were within one standard deviation of the average gain reported by Hake for interactive engagement. After nine months, chemical engineering majors essentially retain their knowledge of the concepts. By successfully integrating the major cooperative learning elements discussed in this article, undergraduate engineers will be able to enhance their long-term retention of the fundamental principles for a particular engineering discipline and potentially transfer that knowledge to solve future problems

Key Words: problem-based learning, retention and transfer, material and energy balances

INTRODUCTION

Based on their qualitative research study, Jonassen, Strobel, and Lee state that "for professional engineering programs, the clearest purpose for learning is preparation for future work, which includes the ability to solve problems and to learn independently and collaboratively [1]." They recommend guidelines for revising the nature of problem-solving instruction in engineering programs that would have students practice (across the curriculum) workplace transfer, problem-based learning, and cooperatively-based teamwork, while solving fixed-structured to ill-structured problems. As defined in their research study, workplace transfer is "the ability to generalize solution methods from one problem (typically a decontextualized word problem) to another, similar word problem embedded in a different context [1]," while acquiring life-long learning skills in communication,

teamwork, and decision making. These recommended guidelines are reinforced by Woods' article on authentic problem-based learning (aPBL), where he makes a distinction between problem-based learning and project-based learning [2]. In an aPBL approach, a problem is posed before the students acquire any knowledge to solve the problem, no lectures are given by the instructor, and all students in the group must obtain the necessary knowledge. In project-based learning, a problem is posed, the instructor lectures on the information necessary to solve that problem, and then the students apply that knowledge. In any aPBL implementation, projects can be used to pose and solve problems provided that no lectures are given by the instructor and the students acquire the needed knowledge on their own but with guidance from the instructor, and they share that knowledge with their group members. The focus of this article is on an aPBL implementation that uses projects.

From their review of the constructivist literature on learning and their experience as engineering educators, Mastascusa, Snyder, and Hoyt [3] present information on the most effective ways that students process knowledge in working memory, store it in their long-term memory, and how that affects learning for long-term retention and transfer. Furthermore, their book explores how to apply proven tools, techniques, and approaches to improve teaching using active learning concepts, such as cooperative learning and problem-based learning. Students must actively practice abstraction to enhance their long-term retention and transfer, using Bloom's high-order cognitive skills [4] of analysis, synthesis, and evaluation in addition to the lower-order cognitive skills of knowledge, comprehension, and application. Students must also engage in deep learning as opposed to surface learning, and educators must design instructional activities that promote active learning. Prince provides an extensive review of the research literature on active learning [5].

Several literature sources [1,2,3,5,6] concur that problem-based learning coupled with cooperatively-based teamwork can effectively help students develop their abilities at long-term retention and transfer, in order to solve challenging problems in later courses of the curriculum as well as the workplace. In this instructional framework, the team members must practice the five tenets [7] of cooperative learning—positive interdependence, individual accountability, face-to-face promotive interaction, appropriate use of teamwork skills, and regular self-assessment of team functioning— to enhance the retention of knowledge into their long-term memory and to build their schemata necessary for the transfer of that knowledge [3]. A well-functioning teamwork environment aids student members in actively constructing their new knowledge as opposed to passively receiving information through lectures and textbooks. As reported by Johnson, et al., a cooperatively-based team environment also fosters "greater intrinsic motivation to learn and achieve, better relationships with peers, more positive attitudes toward subject areas, lower levels of anxiety and stress, and higher self-esteem [7]." These attitudinal characteristics are what Bloom classifies as the affective domain of learning [4].

The first course in chemical engineering, often referred to as the stoichiometry or material and energy balance course, introduces the student to the basic principles that are used in later courses in the curriculum. Since enhancing the retention and transfer of these principles is desirable, this course could be a likely candidate to institute a problem-based learning (PBL) environment and create a student-centered classroom as opposed to an instructor-centered one. Although other active learning techniques—like muddiest point, one-minute paper, and think-pair-share [8]—can be used in this course, PBL coupled with cooperatively-based teamwork has the greatest potential to promote long-term retention and transfer [1,2,3]. Two major cognitive elements are usually emphasized in this introductory course—a problem-solving technique and the application of the concepts of material balances, phase equilibria, and energy balances. Most textbooks [9,10,11] for this introductory course present and use a problem-solving methodology that is some variation of Polya's method [12]—define the problem, devise a plan, carry out the plan, and review the solution—for solving well-defined problems. The traditional format for most of the example problem solutions tend to be a progression to identify a solvable equation or set of equations, supply the numbers and account for units, and calculate the results. This progression is repeated for the next set of solvable equations, until the problem has been solved.

In addition to teamwork, communication, and independent study, the strength of a PBL learning environment is that it requires team members to practice higher-order thinking skills in Bloom's cognitive taxonomy while solving ill-structured (or open-ended) problems, like "design a heating system for this classroom." Since the traditional focus of the introductory course for chemical engineering or any engineering discipline is to solve fixed-structured (or well-defined) problems, how can a PBL approach be applied as a learning environment in this course to promote long-term retention and potential transfer? This article describes a conceptual framework for a PBL implementation that incorporates a holistic problem-solving methodology (PSM) whose design fosters practice at all levels of Bloom's cognitive taxonomy. The unique format of this holistic PSM is not only conducive to a problem-based learning environment but has the added benefit of facilitating computer solutions as well as manual ones. First, the general format of the holistic PSM is presented. Second, its six sub-parts are described along with some of the cognitive strategies to complete them. Third, the integration of this methodology into a problem-based learning environment for the introductory chemical engineering course is described. Fourth, the cognitive benefits to the freshmen chemical engineering majors at Bucknell University are presented. Fifth, the scalability of the conceptual framework to other universities with larger class sizes is addressed. Finally, the article concludes with some recommendations to aid instructors who might want to adapt a PBL format for the introductory chemical engineering course. Although chemical engineering is used to present this conceptual framework, it is also applicable to other engineering disciplines for their introductory course.

PROBLEM-SOLVING METHODOLOGY

Since a decision-making plan is important in order to reach the goal state from the initial state of any ill-defined engineering problem, a plan or conceptual framework is also important to solve any well-defined engineering problem in the introductory chemical engineering course. A well-defined problem has an initial state, a goal state, and solution paths; however, its solution paths will all give the same correct answer, provided they are all based on the same assumptions. The conceptual framework in this article for solving well-defined problems is the holistic problem-solving methodology (PSM) shown in Table 1, which is also an adaptation of Polya's method. This methodology is a critical-thinking strategy called means-ends analysis [13]. Starting with the initial state called the <u>problem statement</u>, it breaks the problem down into smaller sub-problems, each with its own goal, called a sub-goal or outcome. The sub-goal of one sub-problem becomes the initial sub-state for the next sub-problem. Each sub-goal moves the engineering student closer and closer to the final goal, the <u>formal documentation</u> for the problem solution.

Although these steps or stages are sequential, feedback exists between stages. For example, while reviewing the numerical solution, a student might observe the need to calculate another quantity which was forgotten in the original mathematical model or add an assumption that is needed to complete the mathematical model.

The holistic methodology in Table 1 is designed to help students develop their critical-thinking skills rather than using memorization to solve well-defined engineering problems. Students are required to think prudently before they act; that is, before they "plug and chug". Furthermore, its design supports the Kolb learning cycle [14]. Kolb's research indicates that students have a preferred learning style based on how they perceive information into short-term memory and how they process that information into long-term memory [3]. Since perceiving as well as processing can be done actively or passively, four preferred styles of learning exist that focus on a different question—Why?, What?, How, and What If?—or four quadrants of learning. For students to become effective learners and

Activity	Outcome	Kolb Cycle
	Problem statement	Why?
Understand the problem	Conceptual model	
Model the phenomena	Mathematical model	What?
Devise a plan	Mathematical algorithm	How?
Carry out the plan	Numerical solution	
Review the problem solution	Heuristic observations	What If?
Report the problem solution	Formal documentation	

Table 1. The Holistic Problem-Solving Methodology (PSM).

problem solvers, they must develop their cognitive skills in all four learning quadrants of the Kolb learning cycle, even though they have a preference to one of those quadrants.

Why use the conceptual framework of Table 1 to help students develop effective problem-solving skills? Why not let the students discover these skills on their own with guidance by the instructor? First, since most freshmen or sophomore students are probably comfortable with an instructor-centered, lecture-based environment where they use memorization heavily, they will find it difficult initially to adjust to a student-centered, active-learning environment using the holistic PSM of Table 1. Second, in this new learning environment that uses retrieval-based and schema-building processes similar to experts, students must actively practice abstraction using Bloom's high-order cognitive skills to develop their mental abilities in long-term retention and potential transfer. All six of Bloom's levels—knowledge, comprehension, application, analysis, synthesis, and evaluation (in order of increasing mental activity)—are used to develop the outcomes in Table 1. Third, the students must learn the content matter for material balances, phase equilibria, and energy balance. Since all three of these challenges must be mastered simultaneously, the holistic PSM of Table 1 provides the conceptual framework to handle the workload and complexity without frustrating the students during the learning process. When instructors observe that students are reaching a higher level of confidence, they can reduce their imposed structure and let the students take more control over constructing their knowledge structures (i.e., schemata) that are stored in their long-term memory.

Of the six steps in the holistic PSM, the creation of the mathematical model and the heuristic observations are the most important activities because they develop the students' critical thinking abilities using Bloom's synthesis and evaluation levels, respectively. These two steps offer the students the opportunity to develop their conceptual understanding by practicing expert-like qualities that characterize a deeper approach to learning. As summarized by Nason, et al. [15], "students who adopt surface approaches are not as well equipped to answer [conceptual] questions, and efforts are necessary to encourage those students to adopt a deeper approach." Another consequence of surface learning is that it can potentially lead to incompetence in the workplace. As reported by Florman [16], at least eighty percent of engineering failures are caused by insufficient knowledge, underestimation of influence, ignorance, carelessness, negligence, forgetfulness, and error. The application of the holistic PSM is designed to foster discipline and help students develop their abilities to minimize these causes of failure at all stages in the development of a problem solution.

CONCEPTUAL MODEL

The holistic PSM is an outgrowth from the author's forty years of software engineering activities to develop instructional tools that support the educational process in chemical engineering. Based

on software engineering principles, one must resist the tendency to start immediately writing programming code until after the functional requirements and the software design have been developed. In the holistic PSM, you want to design the complete mathematical model before you contemplate doing the arithmetic and accounting for units. This holistic PSM is best illustrated by looking at the documented solution in Figures 1 to 7 for an example problem about a semi-batch reactor, which is similar to a problem presented by Hanyak and Raymond [17]. In Figure 1, the problem statement was purposely chosen as a typical textbook exercise to focus the reader's attention on the holistic PSM. Later, a contextualized version of this problem suitable for a problem-based learning experience will be presented.

The first problem-solving stage in Table 1 converts the initial sub-state of a problem statement into the sub-goal of a conceptual model. Using their abstract knowledge structure about the syntax and semantics of the English language and their basic knowledge of chemistry and physics quantities with their units, the students start to develop an abstract representation for the conceptual model as illustrated in Figure 1. Basically, this model helps students to visualize the problem, to organize information, to connect variables and numbers, and to clarify their thinking. Using this model, they leave the world of numbers and units and enter the world of variables. This abstraction is necessary because they will use the world of variables and equations to develop the mathematical model. They will come back to the world of numbers and units when they do the numerical solution. In the conceptual model, the process state of each material mixture is always labeled with its temperature, pressure, phase, amount (or flow rate) and composition. Whenever a process state variable is not known in the problem statement, it is labeled with a question mark in the diagram. Note that intensive quantities such as mass density, molar volume, and specific enthalpy can only be determined once the material state—temperature, pressure, and composition—of each chemical mixture is known. Whenever intensive quantities are needed during the mathematical model development, the students will have to assume values for those material state variables that happen to be labeled with question marks.

In Figure 1, the use of subscripted variables in the conceptual model alleviates overloading students' short-term memory and aids the pattern recognition capabilities of their brain. Our short-term memory, where we retain information for up to approximately one minute, is limited to 7 ± 2 items of information at one time [18]. Memory attention, organization, meaningfulness, and chunking are enhanced by mnemonic patterns [13]. For example, the volume of the liquid initially is represented by the pattern "Vi". The mnemonic "V" is easily associated with the concept of volume. The subscript mnemonic "i" represents the initial time, and its placement in the pattern "Vi" makes it subservient to the major concept of volume. Pattern "Vi" means "volume of liquid initially". Our short-term memory can easily handle the pattern "Vi", because it contains two characters of information. However, the

---

Problem Statement

A new catalyst has been found that will produce styrene monomer at 68.0ºF and 1.00 atm. The main reaction converts the reactants of toluene and methanol into styrene monomer, water, and hydrogen. A side reaction converts the reactants into ethylbenzene and water. The two reactants in stoichiometric proportion are placed into a capped reaction vessel with the catalyst, and they are allowed to react isothermally. All chemical components exist in the liquid phase, except hydrogen which exits as a gas through a pipe at the top of the vessel. How much total material in kilogram-moles is placed in the vessel initially to produce 3444.23 pounds of styrene monomer? What is the volume in cubic feet of the liquid initially in the vessel? The molar conversion of the toluene is 80.0%, while the molar yield of the styrene is 75.0%.
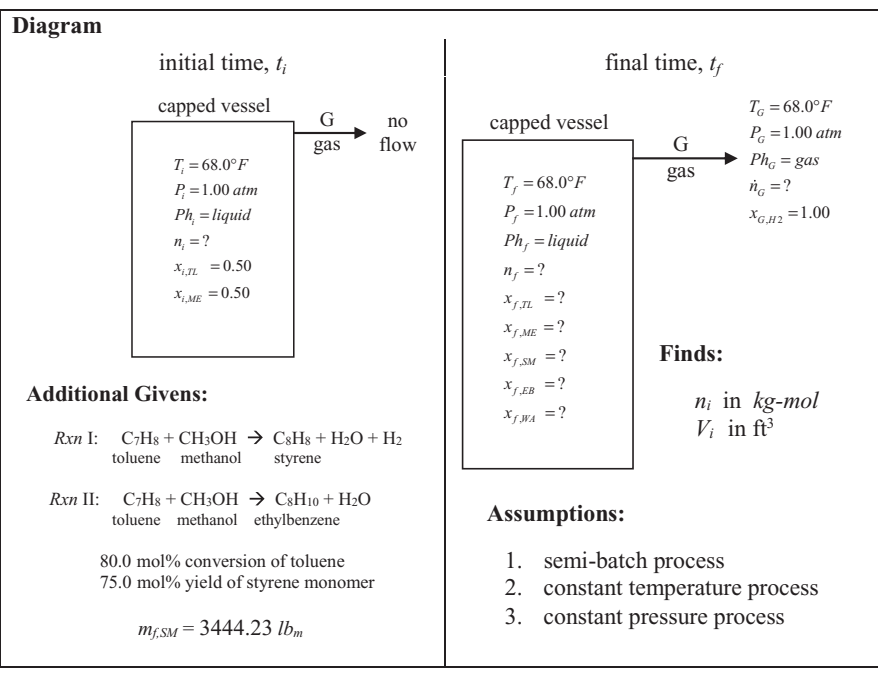
Conceptual Model

Diagram

initial time, t_i

capped vessel

$T_i = 68.0°F$
$P_i = 1.00\ atm$
$Ph_i = liquid$
$n_i = ?$
$x_{i,TL} = 0.50$
$x_{i,ME} = 0.50$

G — no flow
gas

final time, t_f

capped vessel

$T_f = 68.0°F$
$P_f = 1.00\ atm$
$Ph_f = liquid$
$n_f = ?$
$x_{f,TL} = ?$
$x_{f,ME} = ?$
$x_{f,SM} = ?$
$x_{f,EB} = ?$
$x_{f,WA} = ?$

G
gas

$T_G = 68.0°F$
$P_G = 1.00\ atm$
$Ph_G = gas$
$\dot{n}_G = ?$
$x_{G,H2} = 1.00$

Finds:

n_i in *kg-mol*
V_i in ft^3

Additional Givens:

Rxn I: $C_7H_8 + CH_3OH \rightarrow C_8H_8 + H_2O + H_2$
        toluene   methanol   styrene

Rxn II: $C_7H_8 + CH_3OH \rightarrow C_8H_{10} + H_2O$
        toluene   methanol   ethylbenzene

80.0 mol% conversion of toluene
75.0 mol% yield of styrene monomer

$m_{f,SM} = 3444.23\ lb_m$

Assumptions:

1. semi-batch process
2. constant temperature process
3. constant pressure process

Figure 1. Conceptual Model for the Example Problem of a Semi-Batch Reactor.

pattern "volume of liquid initially" contains 23 characters of information, and its appearance in the conceptual diagram has the potential to overload our short-term memory. In Figure 1, composition variables like $x_{f,TL}$ have a double subscript notation, where the left-most subscript identifies the time period and the right-most one identifies the chemical compound or component in the chemical mixture.

As reported by Halpern [13], only 25% of first-year college students have developed their mental abilities in logical abstract thought. Expert problem solvers are excellent at abstract thinking, because

they have highly-developed and rich schemata, which are necessary for long-term retention and transfer [3]. The development of a conceptual model is the initial step into the world of abstract thinking, and it is a knowledge and comprehension activity as defined by Bloom's cognitive taxonomy.

MATHEMATICAL MODEL

The second problem-solving stage in Table 1 converts the initial sub-state of a conceptual model into the sub-goal of a mathematical model. Using their presumed abstract knowledge about mathematics (in particularly algebraic equations), the students develop an abstract representation of the engineering phenomena occurring in the conceptual model. The mathematical model is that abstraction as illustrated in Figure 2 for the conceptual model in Figure 1, and it is always developed from first principles, such as the material balances, phase equilibrium relationships, and energy balances.

In Figure 2, the total and component material balances are written first, followed by the mixture equations of those process states where at least one component composition is not known. In the material balance equations, the variable name of R with a subscript is the extent of reaction. The last equation in this initial set is not linearly independent, thus it becomes the "check" equation to be used later after the numerical computations have been completed. This *check* must be based on using an equation that was not part of the mathematical model.

All amount quantities in Figure 2 are expressed as variables in the material balances and any mixture equations, even if molar amounts are given in the conceptual model. Whenever their mole fraction is known, component amounts are always expressed as their mole fraction value times the total amount variable, like *0.50 n_i*. Since these two conventions help to keep these equations in linear form, the component balances (Eqs. ② to ⑦) and the mixture equation (labeled "check") can be algebraically combined visually to form the total balance (Eq. ①), thus indicating that only seven of the first eight written equations are linear independent. Completing this visual inspection demonstrates that the linear independence for Eqs. ① to ⑦ is satisfied and eliminates the possibility of getting "1 = 1" or "0 = 0" when solving these equations in the "Numerical Solution" step later.

Using the linear independent equations (Eqs. ① to ⑦) of Figure 2, a preliminary degrees-of-freedom (*dof*) analysis is done by counting the number of variables in those equations (10) and subtracting the number of equations (7), giving a *dof* = 3. For this set of linear equations, three amount variables (whether mass, moles, or volume) are not given, only one is known in the conceptual model of Figure 1. If the *dof* (at this point in the development) does not match the number of knowns in the conceptual model, then additional equations must be written in the mathematical model until the proper degrees of freedom are obtained, as illustrated in Figure 2 by the addition

Mathematical Model

①   **total:** $-n_G \;+\; 1R_I \;\;\;\;\;\;\;\;\; = \;\; n_f \;\;\;\; - \;\;\;\; n_i$

②   **TL:** $-\; 1R_I \;-\; 1R_{II} \;=\; n_{f,TL} \;-\; 0.5\,n_i$

③   **ME:** $-\; 1R_I \;-\; 1R_{II} \;=\; n_{f,ME} \;-\; 0.5\,n_i$

④   **SM:** $1R_I \;\;\;\;\;\;\;\;\; = \;\; n_{f,SM}$

⑤   **EB:** $1R_{II} \;=\; n_{f,EB}$

⑥   **WA:** $1R_I \;+\; 1R_{II} \;=\; n_{f,WA}$

⑦   **H2:** $-n_G \;+\; 1R_I \;\;\;\;\;\;\;\; = \;\;\; 0$

check   **mixture f:** $n_f = n_{f,TL} + n_{f,ME} + n_{f,SM} + n_{f,EB} + n_{f,WA}$

⑧   **conversion:** $\dfrac{0.50\,n_i - n_{f,TL}}{0.50\,n_i} = 0.80$

# vars	= 10
# eqns	= 9
dof	= 1

⑨   **yield:** $\dfrac{n_{f,SM}}{0.50\,n_i - n_{f,TL}} = 0.75$

⑩   **mol wt:** $M_{SM} = \dfrac{m_{f,SM}}{n_{f,SM}}$

⑪   **mol wt:** $M_i = \dfrac{m_i}{n_i}$

⑫   **mol wt:** $M_i = 0.5 M_{TL} + 0.5 M_{ME}$

⑬   **density:** $\rho_i = \dfrac{m_i}{V_i}$

⑭   **density:** $\rho_i = dmix\left[T_i, P_i, \overline{X}_i \right]$

# vars	= 19
# eqns	= 14
dof	= 5

Figure 2. Mathematical Model for the Example Problem of a Semi-Batch Reactor.

of Eqs. ⑧ and ⑨ to get a *dof* = 1. If a molar amount were known for styrene monomer ($n_{f,SM}$), then Eqs. ① to ⑨ could be solved to determine all of the other unknown molar amounts. Because a mass amount is known for styrene monomer, Eq. ⑩ can be written to relate mass and moles for styrene monomer. Adding this equation increases the variable count by one, as well as the equation count by one. When doing the variable count, symbols that represent constants are never counted as variables. Thus, component molecular weights such as M_{SM} are considered to be constants. For the first ten numbered equations, the *dof* remains one, implying that one variable must be known

before this set of equations could be solved for the unknown variables. This known quantity is $m_{f,SM}$, the mass of styrene monomer finally. Thus, this set of equations is sufficient to determine the first "Finds" quantity (n_i), as listed in the conceptual model of Figure 1.

To find the second and last "Finds" quantity (V_i), additional equations must be added to the mathematical model. Since a molar quantity can be related to a mass quantity and the mass quantity can be related to a volume quantity, Eqs. ⑪ to ⑬ are the next ones to appear in the mathematical model of Figure 2. Since the liquid density of a chemical mixture is a function of its temperature, pressure, and composition, a functional form named *dmix* is written in Eq. ⑭. As a first principle, an equation for any intensity quantity, like mass density, molar volume, or specific enthalpy, is expressed abstractly as a function form. This form is a summarizing or chunking technique that helps to reduce complexity and thus not overload one's short-term memory. Functional equations are sufficient, while developing the mathematical model. The details behind any functional form are delayed to the "Numerical Solution" stage of the holistic PSM. Since the degrees of freedom for the fourteen equations in the mathematical model of Figure 2 are five, they are satisfied by the material state of the reactor initially—temperature, pressure, and two mole fractions—and the mass of styrene monomer finally.

In Figure 2, Eqs. ⑧ to ⑭ are always written using their basic definitions, because this strategy reinforces starting from first principles and requires that the English definition be translated into an equation equivalent. For example, the molar conversion in Eq. ⑧ is defined as the amount reacted of the limiting reactant (i.e., initial minus final) divided by the amount initially. Not starting with this basic definition for molar conversion but using an alternate one defined in terms of an extent of reaction can be problematic, because the alternate definition must be changed to account for when multiple reactions occur. Using the basic definitions for molar conversion and yield coupled with the material balances automatically handles multiple reactions. Once students build their confidence to synthesize a mathematical model, they can begin to create shortcuts in that model. For example, Eqs. ⑪ and ⑬ could be combined to form one equation ($\rho_i = n_i \cdot M_i / V_i$), thus reducing the number of equations by one. When practicing this technique, students should limit the number of variables and terms in the resulting equation to 7±2 items. This precaution is a guard against complexity and reduces the chance of overloading one's short-term memory. Keeping the equations used in a mathematical model simple in format also aids one's ability to discover potential patterns and sources of errors and helps the communication between students and instructors.
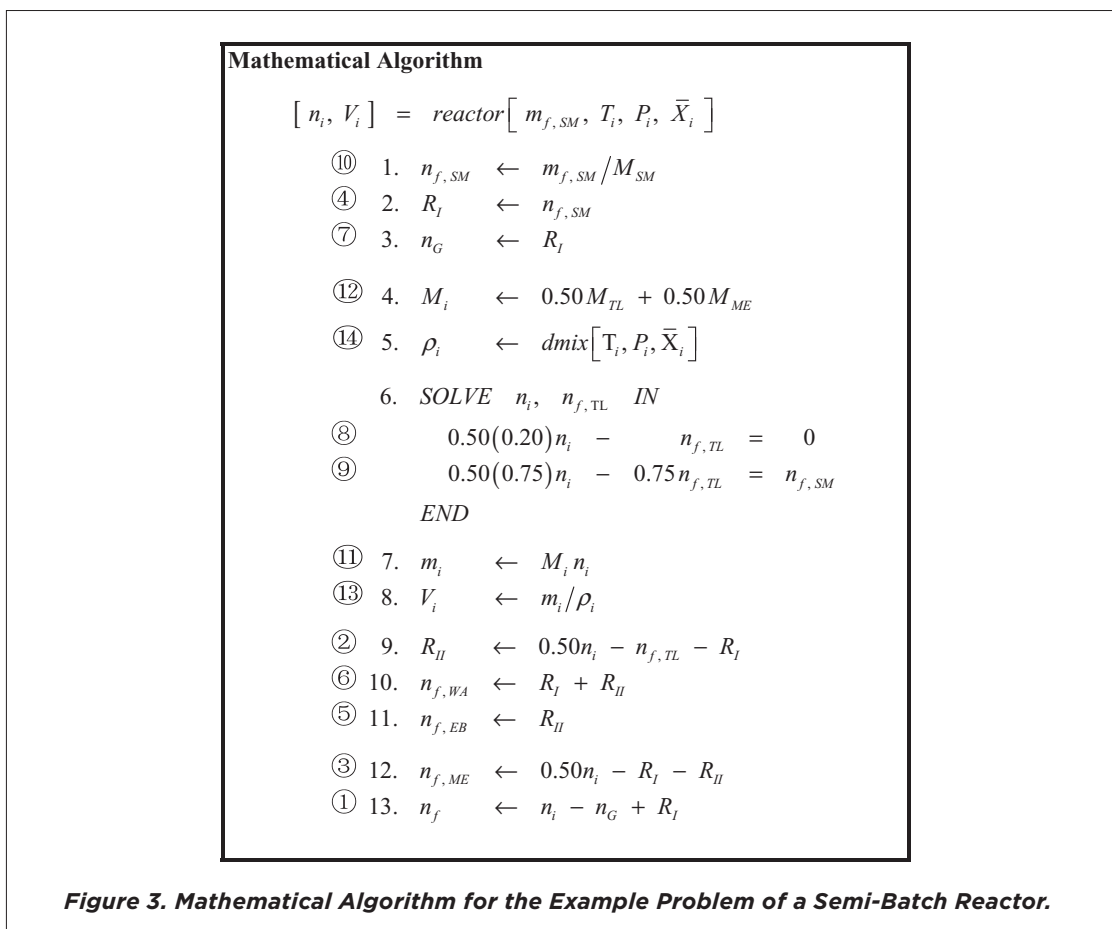
In summary, the development of the mathematical models requires a critical thinking strategy that uses the conceptual model and the "degrees-of-freedom" analysis, while working towards completing the set of necessary algebraic equations to model the engineering phenomena. The continual use of the "degrees-of-freedom" analysis provides the students with a meaningful mechanism to

complete the mathematical model. To help students build their schemata in long-term memory for this critical thinking strategy, they should be provided with a general checklist on how to development the mathematical model [19]. This developmental process is a synthesis activity as defined by Bloom's cognitive taxonomy.

MATHEMATICAL ALGORITHM

The third problem-solving stage in Table 1 converts the initial sub-state of a mathematical model into the sub-goal of a mathematical algorithm. Using their presumed knowledge structure about procedural algorithms, the students develop an abstract representation of how the equations in the mathematical model are to be solved, without substituting values for known variables. As illustrated in Figure 3, the mathematical algorithm is a plan that identifies the independent variables which satisfy

Mathematical Algorithm

$$\left[\, n_i,\ V_i \,\right] \quad = \quad reactor\left[\, m_{f,SM},\ T_i,\ P_i,\ \bar{X}_i \,\right]$$

(10) 1. $n_{f,SM} \quad \leftarrow \quad m_{f,SM}/M_{SM}$

(4) 2. $R_I \qquad \leftarrow \quad n_{f,SM}$

(7) 3. $n_G \qquad \leftarrow \quad R_I$

(12) 4. $M_i \qquad \leftarrow \quad 0.50\,M_{TL} + 0.50\,M_{ME}$

(14) 5. $\rho_i \qquad \leftarrow \quad dmix\left[\mathrm{T}_i, P_i, \bar{\mathrm{X}}_i\right]$

  6. $SOLVE \quad n_i,\ n_{f,TL} \quad IN$

(8) $\qquad 0.50\,(0.20)\,n_i \quad - \qquad n_{f,TL} \quad = \quad 0$

(9) $\qquad 0.50\,(0.75)\,n_i \quad - \quad 0.75\,n_{f,TL} \quad = \quad n_{f,SM}$

  END

(11) 7. $m_i \qquad \leftarrow \quad M_i\,n_i$

(13) 8. $V_i \qquad \leftarrow \quad m_i/\rho_i$

(2) 9. $R_{II} \qquad \leftarrow \quad 0.50\,n_i - n_{f,TL} - R_I$

(6) 10. $n_{f,WA} \quad \leftarrow \quad R_I + R_{II}$

(5) 11. $n_{f,EB} \quad \leftarrow \quad R_{II}$

(3) 12. $n_{f,ME} \quad \leftarrow \quad 0.50\,n_i - R_I - R_{II}$

(1) 13. $n_f \qquad \leftarrow \quad n_i - n_G + R_I$

Figure 3. Mathematical Algorithm for the Example Problem of a Semi-Batch Reactor.

the degrees of freedom (*dof*) and states the order in which the equations from the mathematical model are to be processed. After defining its functional form of [dependents] = *f* [independents], the students use a systematic partitioning procedure to move equations from the mathematical model to their proper places in the mathematical algorithm [19]. The general format of a mathematical algorithm is a function form followed by a set of equations that can be solved directly, then a set of equations that must be solved simultaneously (a SOLVE construct for a linear set or an NSOLVE construct for a nonlinear set), and finally a set of equations that must be solved last in the mathematical algorithm. The left arrow ($\leftarrow$) in an algorithmic step means assign a value to the variable.

When applying the partitioning procedure, which is an adaption of Steward's work [20], equations are moved to the mathematical algorithm based on structural factors (like an equation contains only one unknown variable or an unknown variable appears in only one equation) and not on their meaning. Once the mathematical algorithm is completed, some algorithmic steps can be moved based on the meaning of their equations. In Figure 3 for example, Step 4 could be placed just before Step 7, because the equations for these two steps are closely related and M_i is only a function of known constants. Similarly, Step 5 could be placed before Step 8, because ρ_i is only a function of know variables. Starting with the first algorithmic step, a final visual inspection of the mathematical algorithm can be done to examine it for correctness. If the unknown variables appearing in each step are determined in previous steps, other than the one or ones being calculated in that step, than the steps are in proper order. If not, then that step is in the wrong place, and it must be moved to somewhere else in the mathematical algorithm.

On close inspection of the mathematical algorithm in Figure 3, only Steps 1 and 4 to 8 are needed to find the two unknown quantities of interest—n_i and V_i. This mathematical algorithm reveals to a student why the material balance equations (① to ⑦) are not needed to find these two unknowns. However, the molar amounts calculated in Steps 3 and 10 to 13 are needed later to check the total mass balance under the Heuristic Observations. If the problem statement in Figure 1 had also requested finding the mole fractions finally in the reactor vessel, then all thirteen steps in Figure 3 would be required.

As indicated earlier, substitution of values for known quantities into the mathematical algorithm is not done, but a dimensional consistency analysis is required to identify the necessary unit conversion factors that will be needed for the "Numerical Solution" step in the holistic PSM. As illustrated in Figure 4, dimensional consistency checks need only to be done on certain equations in the mathematical algorithm. If the net units of any terms in any equation of the mathematical algorithm do not match, then unit conversions must be applied to that equation to make it dimensionally consistent.

As shown in Figure 4, the student lists the "base units" for amount, time, energy, and when necessary length and/or volume. Since the first three are the units of variables appearing in the material

---

Dimensional Consistency Analysis

$Basis: \quad kg\text{-}mol, \quad no\ time\ unit, \quad no\ energy\ unit, \quad volume\ in\ L$

⑩ 1. $\quad n_{f,SM} \quad \leftarrow \quad lb_m \left(\dfrac{lb\text{-}mol}{lb_m} \right) \left\langle \dfrac{kg\text{-}mol}{2.20462\ lb\text{-}mol} \right\rangle \qquad = \quad kg\text{-}mol$

④ 2. $\quad R_I \quad \leftarrow \quad kg\text{-}mol \Big/ \left(1 \dfrac{kg\text{-}mol}{kg\text{-}rxn} \right) \qquad = \quad kg\text{-}rxn$

⑭ 5. $\quad \rho_i \quad \leftarrow \quad dmix \left[20°C,\ 1\ atm,\ x_{i,TL} = 0.5\ \&\ x_{i,TL} = 0.5 \right] \quad = \quad kg/L$

⑬ 8. $\quad V_i \quad \leftarrow \quad kg \left(\dfrac{L}{kg} \right) \left\langle \dfrac{35.3147\ ft^3}{1000\ L} \right\rangle \qquad = \quad ft^3$

Figure 4. Units Consistency Analysis for the Example Problem of a Semi-Batch Reactor.

balances, mixture equations, composition equations (like $n_{f,TL} = x_{f,TL} \cdot n_f$), reaction conversion, reaction yield, reaction selectivity, and energy balance, no units analysis is required on these types of equations in the mathematical algorithm. All other remaining equations, except for mixture molecular weights, must be checked. Figure 4 displays those remaining equations that require units consistency analysis using the appropriate steps from the mathematical algorithm and the variable units from the "Givens" and "Finds" found in the conceptual model of Figure 1. Both number identifiers, like ⑩ and "1.", for the equation in the mathematical model and its corresponding algorithmic step must be included in this analysis. The student is to provide one more units check on a single algorithmic step that contains at least one extent-of-reaction variable. Once the student understands the proper units for the extent of reaction like *g-rxn* or *kg-rxn*, this check can be eliminated. In closing, the development of a mathematical algorithm with the check for dimensional consistency is an analysis activity as defined by Bloom's cognitive taxonomy.

NUMERICAL SOLUTION

The fourth problem-solving stage in Table 1 converts the initial sub-state of a mathematical algorithm into the sub-goal of a numerical solution. This solution could be done one of many ways—manually with a calculator, using a spreadsheet like Microsoft Excel, using an equation solver like E-Z Solve [9], or using any other computational software. The numerical solution determines the "Finds" quantities that appear in the conceptual model of Figure 1.

Manual Numerical Solution

Basis: $mks\ system\ with\ m_{f,SM} = 3444.23\ lb_m$

Givens: $T_i = \dfrac{5}{9} \cdot (68°F - 32) = 20°C;$ $P_i = 1\ atm = 1.01325\ bar = 101.325\ kPa$

$\overline{X}_i = x_{i,TL}\ \&\ x_{i,ME} = 0.5\ \&\ 0.5$

1. $n_{f,SM} = 3444.23\ lb_m \left(\dfrac{lb\text{-}mol}{104.152\ lb_m} \right) \left\langle \dfrac{kg\text{-}mol}{2.20462\ lb\text{-}mol} \right\rangle = 15\ kg\text{-}mol$

2. $R_I = 15\ kg\text{-}mol \Big/ \left(1\dfrac{kg\text{-}mol}{kg\text{-}rxn} \right) = 15\ kg\text{-}rxn$

3. $n_G = 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(15\ kg\text{-}rxn) = 15\ kg\text{-}mol$

4. $M_i = 0.50\left(\dfrac{92.1408\ kg}{kg\text{-}mol} \right) + 0.50\left(\dfrac{32.0419\ kg}{kg\text{-}mol} \right) = 62.0914\ \dfrac{kg}{kg\text{-}mol}$

5. $\rho_i = dmix\left[20°C,\ 1\,atm,\ 0.5\ \&\ 0.5 \right]\ \ see\ next\ page = 0.868141\ \dfrac{kg}{L}$

6a. $n_i = \dfrac{n_{f,SM}}{050(0.75)(0.80)} = \dfrac{15\ kg\text{-}mol}{0.50(0.75)(0.80)} = \dfrac{50\ kg\text{-}mol}{\boxed{50.0\ kg\text{-}mol}}$

6b. $n_{f,TL} = 0.50(0.20)\,n_i = 0.50(0.20)(50\ kg\text{-}mol) = 5\ kg\text{-}mol$

7. $m_i = 62.0914\ \dfrac{kg}{kg\text{-}mol}(50\ kg\text{-}mol) = 3104.57\ kg$

8. $V_i = 3104.57\ kg \left(\dfrac{L}{0.848381\ kg} \right) \left\langle \dfrac{35.3147\ ft^3}{1000\ L} \right\rangle = 129.231\ ft^3 = \boxed{129\ ft^3}$

9. $R_{II} = \dfrac{0.50(50\ kg\text{-}mol)\quad (5\ kg\text{-}mol)\quad 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(15\ kg\text{-}rxn)}{1\ kg\text{-}mol/kg\text{-}rxn} = 5\ kg\text{-}rxn$

10. $n_{f,WA} = 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(15\ kg\text{-}rxn) + 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(5\ kg\text{-}rxn) = 20\ kg\text{-}mol$

11. $n_{f,EB} = 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(5\ kg\text{-}rxn) = 5\ kg\text{-}mol$

12. $n_{f,ME} = 0.50(50\ kg\text{-}mol) - 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(15\ kg\text{-}rxn) - 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(5\ kg\text{-}rxn) = 5\ kg\text{-}mol$

13. $n_f = (50\ kg\text{-}mol) - (15\ kg\text{-}mol) + 1\dfrac{kg\text{-}mol}{kg\text{-}rxn}(15\ kg\text{-}rxn) = 50\ kg\text{-}mol$

Figure 5. Manual Numerical Solution for the Example Problem of a Semi-Batch Reactor.

For a manual solution, the students use the mathematical algorithm as a guide coupled with their presumed knowledge structure about arithmetic and units. In the example manual solution of Figure 5, the student identifies the base system of units and the basis for the calculation, either a given amount (or flow rate) in the conceptual model or an assumed one whenever no amount (or flow rate) is given in the problem statement. All "givens" are converted to the base system of units (if necessary), all calculations as prescribed by the mathematical algorithm are done in the base

system of units, and all important "finds" are finally converted from the base system of units to the desired units stated in the conceptual model. The dimensional consistency analysis in Figure 4 indicates the base system of units and identifies those algorithmic steps that must include the necessary conversion factors in the manual solution. Most or all of the calculations are completed manually with the help of a calculator, and the calculated values are recorded to six digits with their units always provided. For three or less unknown variables in a linear SOLVE construct, the student uses algebraic rearrangement and substitution to determine the algebraic expressions for the unknown variables, as illustrated in Figure 5 for Steps 6a and 6b. When the number of SOLVE unknown variables is greater than three, the student would use a software system that implements Gaussian Elimination, provide printed output of the computer solution as an additional page, write the answers in the appropriate step of the mathematical algorithm, and reference that additional page. For the "finds" only, precision is taken into account, and the final answers are boxed.

For functional equations like that for density in Step 5 of Figure 5, the numerical solution shows only the functional results with their units. How a function is resolved is indicated by a brief note like "see next page," "see Page 8," or "Table B.1 in F&R, 3rd Ed." A function like *dmix* can take one of four forms—either a table, a graph, a mathematical algorithm which states how equations are solved to transform the independent variables into the dependent variables, or a software program that implements a mathematical algorithm. For the last two forms, documentation must be presented on one or more separate pages to show the details—either the manual solution of the necessary equations with any assumptions or the printed output or graphics image from a software program showing the results and annotated with any assumptions. For the manual solution in Figure 5, the "next page" for *dmix* has purposely not been provided in this article for brevity. When any functional form can be represented by three or less equations, then those equations could be substituted for the functional equation in the manual solution. For example, when a gas mixture can be assumed to behave like an ideal gas, then the functional equation $\hat{V} = vmix[T, P, \bar{X}]$ could be replaced with $P\hat{V} = RT$. When an intensive quantity is not a function of composition like the ideal gas law, its functional equation in the mathematical model could be replaced by one simplifying equation, because it probably will help to eliminate the complexity caused by any composition dependency that would have occurred in the mathematical algorithm.

For a spreadsheet-based solution, the students use their presumed knowledge structure about spreadsheets and follow the procedure outlined above for a manual solution, again using the mathematical algorithm and dimensional consistency analysis as guides. However, a manual solution should be completed by the students first, in order to check the correctness of their spreadsheet programming.

For an equation solver software like E-Z Solve, students use their presumed knowledge of that software to input the mathematical model which includes any necessary conversion factors. As

E-Z Solve Numerical Solution

```
//   Semi-Batch Reactor Example, CinChE Manual, pp. 5-18

/* 01 - TM */      - nG  + R1        =    nf  - ni

/* 02 - TL */            - R1  - R2  = nftl  - 0.50*ni
/* 03 - ME */            - R1  - R2  = nfme  - 0.50*ni

/* 04 - SM */            R1          = nfsm
/* 05 - EB */                  R2    = nfeb

/* 06 - WA */            R1  + R2    = nfwa
/* 07 - H2 */      - nG  + R1        =    0


/* 08 - conv */    0.50*ni  - nftl  = 0.80*0.50*ni

/* 09 - yield */    nfsm  =  0.75*(0.50*ni - nftl)


/* 10 */  nfsm = mfsm/Msm/2.20462        // lbm -> kg-mol

/* 11 */    mi = Mi*ni                   // mi -> kg
/* 12 */    Mi = 0.50*Mtl + 0.50*Mme     // Mi -> kg/kg-mol

/* 13 */    Vi = mi/rhoi*(35.3147/1000)  // L -> ft^3

//    rhoi = dmix[20°C, 1 atm, 0.5 toluene & 0.5 methanol]
//    assume liquid mixture of Tol/MeOH is ideal solution

/* 14 */  rhoi = Mi/(Xtl*Mtl/Dtl + Xme*Mme/Dme)  // -> kg/L


/* given */  mfsm = 3444.23   // final styrene -> lbm

             Msm = 104.152    // styrene  -> kg/kg-mol
             Mtl = 92.1408    // toluene  -> kg/kg-mol
             Mme = 32.0419    // methanol -> kg/kg-mol

             Dtl =  0.8700    // @ 20°C & 1 atm -> kg/L
             Dme =  0.7918    // @ 20°C & 1 atm -> kg/L

             Xtl = 0.5        // mole fraction of toluene
             Xme = 0.5        // mole fraction of methanol
```

Givens:

```
mfsm = 3444.23 lbm

Msm  = 104.152 kg/kg-mol
mfsm = 92.1408 kg/kg-mol
mfsm = 32.0419 kg/kg-mol

Dtl  =  0.8700 kg/L
Dme  =  0.7918 kg/L

Xtl  =  0.50
Xme  =  0.50
```

Finds:

```
nfsm = 15 kg-mol
 R1 = 15 kg-rxn
 nG = 15 kg-mol

 Mi = 62.0913  kg/kg-mol
Rhoi = 0.848381 kg/L

 ni = 50 kg-mol
nftl =  5 kg-mol

 mi = 3104.57 kg
 Vi = 129.231 ft^3

 R2 =  5 kg-rxn
nfwa = 20 kg-mol
nfeb =  5 kg-mol

nfme =  5 kg-mol
 nf = 50 kg-mol
```

Figure 6. E-Z Solve Solution for the Example Problem of a Semi-Batch Reactor.

illustrated in Figure 6, the mathematical model of Figure 2 coupled with the units consistency analysis of Figure 4 were programmed into the E-Z Solve software to produce the results shown also in Figure 6. Students should be encouraged to include comments in their automated solutions, in order to help identify potential errors and to increase communication between the students and between the students and the instructor. The calculated values in Figure 6 should be listed in the order as given in the mathematical algorithm of Figure 3. Whether it is done manually or automated, the development of a numerical solution is an application activity as defined by Bloom's cognitive taxonomy.

HEURISTIC OBSERVATIONS

The fifth problem-solving stage in Table 1 is the development of the heuristic observations, which is an evaluation activity as defined by Bloom's cognitive taxonomy. From the students' experience of solving the well-defined problem, what heuristic observations can they discover that will give them a better understanding of both the technical subject matter and the application of the holistic problem-solving methodology? As illustrated in Figure 7, some heuristic observations must be made on the numerical solution, mathematical algorithm, mathematical model, and conceptual model. They are specific and/or general observations that students could apply to the solution of any well-defined problem.

The development of the heuristic observations is a reflection activity that seeks answers to "what if" questions. Those "what if" questions in Figure 7 represent a small sampling of what could be

Heuristic Observations

Numerical Solution

What if the "check" equation is not satisfied?

mixture f: $\qquad n_f = n_{f,TL} + n_{f,ME} + n_{f,SM} + n_{f,EB} + n_{f,WA}$ $\qquad$????

Computational Check: $\qquad 500 = 50 + 50 + 150 + 50 + 200$ $\qquad$ **OK!**

What if the total mass is not conserved?

The total mass balance for the semi-batch system is: $m_f + m_G = m_i$?

Note that $m_f = n_{TL}{\cdot}M_{TL} + n_{ME}{\cdot}M_{ME} + n_{SM}{\cdot}M_{SM} + n_{EB}{\cdot}M_{EB} + n_{WA}{\cdot}M_{WA} + n_G{\cdot}M_{H2}$

Thus, $\qquad 3104.57 \text{ kg} = 3104.59 \text{ kg}$ $\qquad$ **OK!**

Mathematical Algorithm

What if you know n_i instead of $n_{f,SM}$?

The mathematical algorithm would not have a SOLVE construct.

Could solve the problem assuming n_i and then scale the final answers.

Mathematical Model

What if the liquid mole fractions at the end of the reaction (time t_f) are to be found?

Add liquid composition equations as Equations 15 to 19 to the mathematical model.

Place these composition equations into the mathematical algorithm as Steps 14 to 18.

Change the computational check to be the sum of mole fractions instead of amounts.

Conceptual Model

What if no exit stream existed; that is, a batch system? What would the final pressure be?

Can the ideal gas law be used to find that pressure? What about safety considerations?

What if you were asked how much heat must be processed and how?

Are the chemical reactions overall endothermic or exothermic at 25°C and 1 atm?

How much heat must be removed or added to have the reactor operate isothermally?

Figure 7. Some Heuristic Observations for the Example Problem of a Semi-Batch Reactor.

observed by students. The instructor should require each student to generate at least one question per each of the four categories in Figure 7 and document their answers to those questions. Global learners will find this activity refreshing, while sequential learners will be challenged to develop their thinking skills in asking "what if" questions [21].

The heuristic observations step is the most important of the six steps in the holistic PSM, because a student gets to do retrieval practice that fosters the long-term retention of the material and gets to investigate contrasting cases that promote the potential transfer of that material [3]. By looking at variations on the originally-solved problem, students can easily develop contrasting cases without investing too much work. Retrieval practice is needed to construct the contrasting cases, and it helps to strengthen links between old and new schemata in one's long-term memory by getting a student to process the material at higher levels in Bloom's cognitive taxonomy. Examining contrasting cases helps to decontextualize the material by getting a student to observe the different solutions at each outcome in the holistic PSM and to extract the abstract representations for those outcomes from the contrasting problem solutions. This abstraction process starts to build expert-like schemata in one's long-term memory, which is necessary for transferring material from one situation to a completely different situation [3].

The heuristic observations step in the holistic PSM is a pivotal learning experience for the students. An incentive to get students to complete seriously the heuristic observations is to tell them that this activity provides them with a good opportunity to prepare for taking the major exams as an individual in the course. An instructor could provide "what if" questions initially, and have students answer them and thus begin the process of long-term retention and potential transfer. After the students build confidence, then the instructor could let the students develop their own "what if" questions and provide their answers to them, in order to complete the heuristic observations. Instructors should not underestimate how much students can learn on their own, as well as from and with other students, provided that they are given the opportunity to try and fail in a safe environment where feedback is provided when needed.

FORMAL DOCUMENTATION

The sixth and final step in Table 1 is the formal documentation of the problem solution. Because the solution is more than just the numerical answers, the students should be required to document their solution in a professional manner by following some prescribed standards. When graduates enter the professional world, documentation becomes important for legal reasons—regulatory

requirements, patents, and lawsuits. Thus, students should start early in the curriculum to develop good habits in this important area.

One way to emphasize the importance of documentation, as well as problem solving, is to have the students work for a fictitious consulting company that serves many clients. Problems can be contextualized to fit the company's organization and provide the students with meaningful reasons why they must solve the assigned problems. In the introductory chemical engineering course at Bucknell University, freshmen majors work for the Bison Engineering and Evaluation Firm, a consultant company known as BEEF, Inc. They are required to document their solution following the standards prescribed in the company's student handbook [22]. Figures 1 to 7 illustrate the documented results for the example semi-batch reactor problem, and they are based on the standards required by BEEF, Inc.

Because current textbooks on the introduction to chemical engineering do not support the holistic problem-solving methodology illustrated in Figures 1 to 7, the students, who are provisional engineers at BEEF, Inc., are provided with an instructional companion [19]. This document is designed to aid them in the development of their critical thinking skills as an engineering problem solver and report writer. The acronym for this instructional companion is CinChE, a Companion in Chemical Engineering. The holistic PSM of Table 1 is emphasized in CinChE. Numerous example problems are provided in CinChE for material balances, phase equilibria, and energy balances. Most of these examples are taken from the various editions of the Felder and Rousseau textbook [9]. The Acrobat portable-document-format (.pdf) version of CinChE contains numerous annotations and web links that aid the student in understanding the critical-thinking processes needed to develop the conceptual model, mathematical model, mathematical algorithm, numerical solution, and heuristic observations. This electronic version only contains those pages that have annotations and web links.

In summary, the holistic problem-solving methodology shown in Table 1 is a conceptual framework in which to solve any type of well-defined engineering problem. It is a systems strategy that heavily uses the mental processes of decomposition, chunking, and pattern matching to reduce complexity as one moves toward the solution for a problem. Furthermore, it has the potential to promote long-term retention and transfer of the material by constructing expert-like schemata in the student's long-term memory. It also reflects the Kolb learning cycle. The "Why?" part of this cycle is a knowledge and comprehension activity that produces the conceptual model. The "What?" part addresses synthesizing the mathematical model. The "How?" part is an analysis activity that produces the mathematical algorithm and an application activity that creates the numerical solution. Finally, the "What If?" part is the heuristic observations, an evaluation activity in Bloom's taxonomy and the highest-level of cognitive processing.

PROBLEM-BASED LEARNING

When using the holistic problem-solving methodology (PSM), students that solve problems by themselves can begin to cultivate abstract thinking habits and engage the cognitive processes to promote long-term retention and transfer of the material. However, a problem-based learning (PBL) environment that uses cooperatively-based student teams coupled with a problem-solving methodology possesses a stronger potential to promote these expert-like attributes [1,2,3]. In the Chemical Engineering Department at Bucknell University, the holistic PSM has been under development for the last thirty years. Initially, it was used minus the "heuristic observations" step in a lecture-based learning environment for the introductory course on chemical engineering. Over the last twelve years, all six steps have been fully incorporated into a problem-based learning environment [17]. What course design might the instructor employ to create this active learning environment? The components of this design are the course structure, a semester-long team project, two-week team projects, one-week team projects, summative exams, and best instructional practices. How would the components in this design promote long-term retention and potential transfer of the material? Both of these questions are addressed in this section.

Course Structure

In a three-credit-hour course that introduces the student majors to fundamental chemical engineering principles, the class might meet in fifty-minute periods, three times per week over a fourteen-week semester (assuming no break times). Students would be assigned to four-member teams. When the class size is not divisible by four, both four-member and five-member teams would be created. Oakley, et al. presents recommendations to minimize the likelihood of problematic team situations [23]. Students within teams would be assigned roles like coordinator, observer, monitor, assembler, and troubleshooter with specific duties [24], and these roles would be rotated through the five two-week projects in the course. In a four-member team, the coordinator would also be responsible for the troubleshooting role. Under the PBL format, the students could work for a fictitious company that has hired them at the entry-level position of provisional chemical engineer, similar to that in BEEF, Inc. Using a consulting company backdrop provides for many possible problem situations without being tied to a specific industry. This course structure provides the environment in which the students can interact and solve problems in the classroom.

In a cooperatively-based, problem-solving learning environment, the teams would have a semester-long project, four one-week projects, and five two-week projects. The first two weeks of the semester would have two one-week projects that focus on becoming acquainted with the holistic PSM and the PBL environment, drafting a team contract, and learning about the process state of

material—temperature, pressure, flow rate (or amount), and composition—and the intensive quantities associated with that material, like mass density, molar volume, and molar enthalpy. Two more one-week projects would occur, each during an exam week and after four weeks of material have been covered. Two in-class exams and a final exam are given over the semester, and students would take them as individuals. The two exams would occur on the Friday in an exam week. Table 2 incorporates this course design philosophy for the introductory chemical engineering course taken by freshmen majors at Bucknell University. Note that this course has a laboratory component, is assigned four credit hours, and meets three times per week in two-hour meeting sessions.

Topics		Source	Two-Hour Sessions
Project P0	{done independently}		
Problem-Solving Methodology		**CinChE:** Ch. 1	1
HYSYS Simulation and Process Streams		**HYSYS:** Ap. C	1
1-Week Project Ex1	{done as a team}		
Process Variables; Exp. Data Curve Fitting		**F&R:** Chs. 2, 3	1
Project Problems; Thermophysical Properties		**CinChE:** Ch. 3	1
Laboratory Preparation; Project Preparation		**handout**	1
Project P1	{done as a team}		
Material Balances (with and without rxn's)		**F&R:** Ch. 4	6
1-Week Project Ex2	{done as a team}		
Leclerc Food Plant Trip, Montgomery			1
Equations of State, 2-hr **Exam I** on Friday		**F&R:** Ch. 5	2
Projects P2 and P3	{done as a team}		
Material Balances, Recycle Processes		**F&R:** Ch. 4	6
Chemical Phase Equilibrium		**F&R:** Ch. 6	6
1-Week Project Ex3	{done as a team}		
Cherokee-Pharma Plant Trip, Riverside			1
Exam II Review, 2-hr **Exam II** on Friday		**F&R:** Ch. 4, 6	2
Projects P4 and P5	{done as a team}		
Energy and Energy Balances (no reactions)		**F&R:** Chs. 7-8	6
Material/Energy Balances (with reactions)		**F&R:** Ch. 9	6
Project P5 Lab Oral Presentations			1
		Total Sessions:	42

3-hr Final Exam, Week of Finals

F&R – the Felder and Rousseau textbook; **CinChE** – Companion in Chem. Eng. by Hanyak
HYSYS – Chemical Process Simulation and the Aspen HYSYS system by Hanyak

Table 2. Project Structure for the Introductory ChE Course at Bucknell.

Semester-Long Project

For this capstone project, teams would conduct a flowsheet simulation project to determine the material and energy requirements for the production of a major chemical product from some raw materials. At Bucknell, the team flowsheet project determines the process requirements and "best" operating conditions to manufacture styrene monomer from toluene and methanol using the Aspen HYSYS processor simulator. Each team member is assigned a different reactor inlet temperature with its molar conversion and yield, and the team must produce a memo report at the end of the semester recommending the reactor temperature that maximizes the net profit for the developed flowsheet. To handle the complexity of this capstone project, it is broken down into smaller problems that are assigned in the four one-week projects and five two-week projects. These assigned problems could be taken from a HYSYS manual that has been specifically-designed to be a self-study document [25]. This manual contains six tutorials that introduce the students to the HYSYS process simulation software, five process unit exercises that help them to develop their abilities and confidence to simulate individual equipment (like pumps, heaters, reactors, and distillation columns), and seven process flowsheet exercises that each member of the team simulates for a different reactor condition to manufacture styrene monomer from toluene and methanol. The six tutorials are done individually and completed within the first two weeks of the course (three per week). Students are to document their solution to each tutorial in their technical journal, as per the instructions in the HYSYS manual. The twelve exercises in the HYSYS manual have an individual component and a team component. The solution to each individual component is to be documented in the student's technical journal, while the solution to each team component is documented in the project memo report. No class time is spent on the HYSYS assignments, because the capstone flowsheet project is a self-learning activity. However, students are encouraged to consult with their teammates while doing these assignments. A teaching assistant is provided to answer any questions students might have about the HYSYS problems, once a week for about two hours. To ensure accountability for the individual components of the HYSYS exercises, a teaching assistant inspects and evaluates each student's technical journal at the end of the first week in each two-week project. After this inspection, the team meets and collectively answers the team questions about the HYSYS assignment during the last week of each two-week project.

Two-Week Projects

For each of these five projects, teams are assigned two HYSYS exercises and a number of analysis problems equal to the number of members in a team (e.g., four or five). The analysis problems are intended to help the students get a better understanding of the subject matter and how HYSYS does its calculations for individual process units. The analysis problems should be contextualized to

Problem Statement

Your first day on the job as a provisional engineer in the Process Engineering Department of our consulting company, BEEF, Inc., is filled with excitement and opportunity. Your boss, Rush T. Judgment, has received a request from Hawbawg Chemical Company to investigate the potential of using their 1000-gal Pfaudler glass-lined reactor vessel to produce styrene monomer from toluene and methanol using a new proprietary catalyst. This vessel has a diameter of six feet and a vertical height of seven feet.

Based on experimental studies conducted by our Research and Development Department, this new catalyst was able to facilitate the production of styrene monomer at ambient conditions. The main reaction converts the two reactants into styrene monomer, water, and hydrogen. A side reaction converts those reactants into ethylbenzene and water. The two reactants in stoichiometric proportion are to be placed into the capped reaction vessel with the catalyst, and they are allowed to react isothermally. All of the chemical components exist in the liquid phase, except hydrogen which exits as a gas through a pipe at the top of the vessel.

How much total material in kilogram-moles must be placed in the vessel initially to produce 3444.23 pounds of styrene monomer? Our Research and Development Department indicates that the molar conversion of the toluene is 80.0%, while the molar yield of the styrene is 75.0%. Will the reactor vessel be able to hold the volume of the initial reactants, as well as the volume of the final liquid mixture? If not, what would you recommend? As a general rule of thumb, about 3 to 5% of the reactor volume must be reserved for any gas that forms.

Please provide your boss with your memo report that summarizes your solution to the problem and attach your documentation for that solution. Your report is due in three days. In addition, your boss with be assigning you three more problems today that will also be due in three days. Please remember BEEF's company motto of "Results, not Excuses!"

Figure 8. Contextualized Statement for the Example Problem of a Semi-Batch Reactor.

motivate the students because they will ask the question "why," which is the first part of the Kolb learning cycle. Figure 8 illustrates a contextualized problem that is based on the textbook exercise of Figure 1 and has the students working for a fictitious consultant company. Instructors could craft their own contextualized analysis problems or take the end-of-chapter exercises from a textbook and update them. "To transform a textbook problem into a problem-based learning problem: think of the context in which the problem might arise; use some humor in the write-up, as appropriate; consider omitting some information, especially if students can easily find the information using library or network resources; consider adding extra information that is not necessary for the solution but that is embedded in the story; and try to use problems that require decision making [3]." Having students make a value judgment requires them to work at the highest level in Bloom's cognitive taxonomy. When creating contextualized problems, the instructor could consult Wood's book [26] on rules of thumb to develop realistic equipment characteristics and operating conditions. Chapter 1 of this book also provides guidelines on problem solving, communication, listening, and teamwork. The four or five contextualized problems in a two-week project should be designed not to be doable

by one individual in the allotted time to complete that project. This requirement ensures that the team members must work together to complete the assigned two-week project.

In problem-based learning, the classroom becomes an active learning environment where solving the problems drives what happens. The focus is the application of course content with limited feedback from the instructor rather than simply supplying the course content via lecture and having the student process that content outside the classroom through homework assignments. The presentation-processing found in the lecture-based format is inverted in the PBL environment. Students are expected to cover the course content outside the classroom and come prepared to process that content in the classroom cooperatively as they are mentored by the instructor in solving the problems. This inversion is often referred to as the "flipped classroom". Basically, the class periods become co-op sessions as opposed to lecture sessions. The format for a 50-minute co-op session might be as follows:

15-minute "content co-op",   20-minute "problem co-op",   15-minute "content co-op"

The first "content co-op" part could be an online survey to probe students' current understanding of assigned reading material, an activity where students complete a worksheet individually and/or in teams while the instructor circulates to ask and answer questions, or a brief exercise on a perplexing concept. The "problem co-op" part involves student review of their drafts of various parts of the solution for those analysis problems assigned in a two-week project. The last "content co-op" part could be an online survey to address any misconceptions identified by the instructor, a team challenge on important concepts using software like E-Z Solve or Aspen HYSYS, or a brief cooperative exercise on a new topic needed by the students in preparation for the next co-op session.

For the middle co-op part, each assigned analysis problem is to be solved using the six steps of the holistic PSM, which serves as the conceptual framework to foster communication and teamwork skills using the five tenets of cooperative learning. Using this holistic methodology, team members complete their assigned roles—coordinator, observer, monitor, assembler, and troubleshooter—while solving the contextualized analysis problems (labeled A1, A2, A3, A4, and for a five-member team, A5) in each two-week project. As stated earlier, team members rotate these roles from two-week project to two-week project to ensure over the semester that each team member experiences the responsibilities of each role at least once.

During the two weeks for a project, twenty minutes of each co-op session is devoted to each step in the holistic PSM, as illustrated in Table 3 for a four-member team. Note that a different rotation table would be needed for a five-member team. The specifically-designed structure in this table incorporates the five tenets of cooperative learning—positive interdependence, individual

Project Role	First Week			Second Week		
	Monday	**Wednesday**	**Friday**	**Monday**	**Wednesday**	**Friday**
Coordinator	Diagram, A1	Model, A2	Algorithm, A3	Recitation	Solution, A4	Heuristics, A1
Observer	Diagram, A2	Model, A3	Algorithm, A4	Recitation	Solution, A1	Heuristics, A2
Monitor	Diagram, A3	Model, A4	Algorithm, A1	Recitation	Solution, A2	Heuristics, A3
Assembler	Diagram, A4	Model, A1	Algorithm, A2	Recitation	Solution, A3	Heuristics, A4

Table 3. Four-Member Team Solving Problems A1, A2, A3, and A4.

accountability, face-to-face promotive interaction, appropriate use of teamwork skills, and regular self-assessment of team functioning—as defined by Johnson, et al. [7] At each co-op session, all students in a team are focusing on the same outcome step in the holistic PSM, but each is doing it on a different analysis problem. Before a co-op session, team members based on their assigned roles must develop a draft outcome outside of the classroom for that step in the PSM and bring it to that session (e.g., the coordinator is responsible for a Problem A1 draft of the conceptual model outcome (a.k.a. diagram) for the first Monday and the observer is responsible for a Problem A3 draft of the mathematical model outcome for the first Wednesday). These drafts are used to focus the "problem co-op" reviews conducted by the groups of students working on the same problem (e.g., all coordinators from each team would gather to compare and contrast their drafts of the mathematical model on the first Wednesday). The instructor monitors these group reviews and also provides guidance and feedback. When team members move to the next co-op session, they will all have the same focus but on a different problem as shown in Table 3. Because they have not seen the problem before, they will have to review the previously-drafted outcomes and possibly communicate with their teammates to draft their assigned outcome. At the end of the two weeks, all team members will have worked on all four analysis problems and interacted with their team members, as well as with students from other teams. In the sixth session, teams are required to spend time doing group processing; that is, doing self-assessment to examine and enhance their teamwork skills. The documentation or sixth step in the problem-solving methodology is done continuously over the two-week period, starting with the conceptual model and ending with the heuristic observations.

In Table 3, the second Monday might be a "recitation co-op" session. It could be used for in-class demonstrations, videos, laboratory simulations, additional team activities on the analysis problems, or as additional time to work example problems or address student questions. Completion of the individual parts of the HYSYS exercises could be inspected at this time. At Bucknell, the two-hour laboratory component occurs on the second Monday of each two-week project [17]. A second possible format for the second week is to have the "Numerical Solution" and "Heuristic Observation"

drafts moved to the second Monday and Wednesday and then add the "Formal Documentation" draft to the second Friday. This alternative would allow teams to complete the project assignment by the end of the second Friday, and they could then begin their work on the next project over the weekend.

One-Week Projects

The first two one-week projects were described earlier in this article. The other two one-week projects each occur during one of the two exam weeks, and one HYSYS problem is assigned per project. However, the first exam-week project contains a second assignment, known as a reflection exercise. In this reflection exercise, students must read the Felder and Silverman article [21] on learning and teaching styles in engineering education; complete the Learning Style Questionnaire [27]; read the first twelve pages in the "Teaching Through the Cycle" report [14] on the Kolb Learning Cycle; create their "Team Preferred Learning Styles" table based on their readings and their completed questionnaires; read the two-page article on the Tuckman Model [28] about the forming, storming, norming, performing, and adjourning of a team; and finally, reread the content at the web link "Building Blocks for Teams" [29]. After completing these six activities, each team is to revise their team contract, which they had drafted during the second week of the course. They were given limited guidance on preparing their first team contract (i.e., their draft needed to address three things—the rules of conduct, the roles of responsibilities, and the policies to handle detrimental issues). Before completing this reflection exercise, team members have experienced the dynamics of functioning as a team during the first four weeks of the course without much guidance. This purposely-designed scenario is called a desirable difficulty because of the limited guidance followed by the reflection exercise, and it enables students to understand better their responsibilities as team members and why the diversity of learning styles is important but challenging in their teamwork. To ensure individual accountability, students should be told that they must take a quiz after completing the reflection exercise. This quiz is a formative assessment tool and acts as a survey that retrieves from their long-term memory what they learned using questions like "What did you discover about learning and learning styles that impressed you the most?", "What did you discover about teaching and teaching styles that impressed you the most?", "What did you discover about learning styles and being (or becoming) an engineer?", and "What did you discover from writing the team contract?". By reviewing the answers to these questions, the instructor can discover the depth to which each student understands the importance of learning styles and teamwork.

Summative Exams

The three exams are administered as individual accountability pieces, where the primary objective of each exam for the instructor is a grading instrument that determines how much has been learned.

Students are responsible to know the material associated with the HYSYS and analysis problems, since the general content of that material will appear on the two in-class exams and the final exam. These exams could be opened-book tests, although they may be closed book to force students to practice complete retrieval of the material from their long-term memory. By design, students practice mostly partial retrieval in an opened-book exam; that is, they know where to find the material that they need to solve the problem. Practice at complete retrieval strongly correlates with long-term retention, making a secondary objective of a closed-book exam a potential learning experience [3]. Another possible format for each of the in-class exams is to have one closed-book problem that requires developing only the conceptual and mathematical models and one opened-book problem that requires completing the first five outcomes of the holistic PSM. The final exam could have two opened-book problems that require completing the first five outcomes of the holistic PSM. In the introductory chemical engineering course at Bucknell, all three exams are opened-book tests. These described formats for the exams promote long-term retention, and they should be used in place of the strictly true/false and/or multiple-choice type of exams [3]. However, these option-selected question types could be used on a limited basis in sub-parts of the closed- or opened-book exam formats, but the predominate cognitive activity should be partial and/or complete retrieval of the material.

Since the students are working for a fictitious consulting company, their promotion from the rank of provisional chemical engineer to a chemical engineer should be based on their individual contribution to and knowledge gained from the team projects (50%), the two in-class examinations (10% for the first and 15% for the second), and a final exam (25%). Their knowledge gained on their own and from their teamwork is graded on the three exams. Their contribution to the team effort needs to be evaluated periodically by surveying the students about the performance of their team members and then converting those survey results into a numerical score. Hanyak and Raymond [17] described a rubric strategy that incorporates suggestions by Oakley, et al. [24] to extract students' performances to their team effort. Having half of the course grade based on the team projects informs the students of the seriousness of the cooperatively-based team activities. Using a lower percentage contribution for the first exam does not overly contribute to the students' final course grades as they adjust to the problem-based learning environment. During the semester, students should receive individualized copies of their team and exam scores thus far, in order for them to gauge their progress in the course and take any necessary corrective action.

Best Practices

The pedagogical research literature indicates that active learning practices, if properly implemented and monitored, should foster deep learning that leads to long-term retention and transfer when compared to surface learning that usually occurs in a lecture-based environment where students

are passively receiving information in the classroom [3]. Six major factors must be addressed— misconceptions, material perception, retrieval practice, schemata construction, potential transfer, and formative assessment—to create the environment in which students can start to develop expert-like attributes for long-term retention and transfer.

Misconceptions

Misconceptions can hinder students from developing better schemata about the course subject matter, and they should be addressed by the instructor. In each of the first five stages of the holistic PSM of Table 1, students are presumed to have a particular abstract knowledge base on which they are expected to develop new schemata for a specific holistic PSM outcome, like basic chemistry and physics concepts for the conceptual model or algebraic equations for the mathematical model. Most likely, the students' presumed knowledge base may contain holes and probably misconceptions. Instructors need to identify the holes and provide the students with access to resources that help to eliminate those holes. Furthermore, they must conduct surveys to identify any misconceptions and create cooperatively-based exercises that will have students confront and resolve their misconceptions. When students complete these exercises in a group setting, they must try to defend their misconceptions and listen to other group members correcting those misconceptions. The give and take in the group activity helps students to restructure their schemata in long-term memory to overcome their misconceptions.

Misconceptions can also occur during the course about the course subject matter; for example, some students may apply the ideal gas law in any situation. Instructors will have to periodically evaluate the students to identify and help them to correct any of these misconceptions. Mastascusa, Snyder, and Hoyt summarize several techniques [3] to uncover misconceptions—like short-answer tests, concept inventories, and concept maps—and to correct misconceptions—like peer instruction, simulation, demonstration, and lab work. Instructors need to adopt those techniques that they are comfortable with and fit their teaching style and implement them in the "content" parts of the co-op sessions. Having correct retention of the material as schemata in one's long-term memory is a necessary requirement before transfer can occur.

Material Perception

In a problem-based learning environment, the responsibility for the initial awareness about the course material resides with the students, because the major focus of the 50-minute co-op sessions is the processing of that material under the guidance of the instructor. External to the classroom, students can be expected to complete reading assignments based on articles, textbooks, and online materials. Whatever resources are to be read before attending a co-op class session, students must be held accountable for that reading using a closed-book exercise in the first "content" part of a co-op session. This exercise acts as a retrieval event to bring material into the student's working

memory, since that material will be needed in later activities of the co-op session. Not all of these accountability exercises need to be graded, but the students should be informed at the beginning of the semester that randomly-selected exercises will be graded and contribute to their final course grade. These selected exercises should not be announced to the students.

The instructor can also provide specially-developed materials to enhance the student's outside preparation before the co-op sessions. For example, the author has developed seven resources for the students—the CinChE manual, the HYSYS manual, an interactive flowsheet demo, volume-of-mixing demo, test-yourself quizzes, eLEAPS sessions, and guided problem solutions. The CinChE manual [19] presents the holistic PSM and example problem solutions using that methodology. The HYSYS manual [25] serves as the self-learning activity for the capstone project of the course. The interactive flowsheet demo is completed individually by the students in the first week of the course. [30] It introduces them to the capstone flowsheet simulation project and to some basic concepts in chemical engineering. The volume-of-mixing demo illustrates the concept of the volume change that occurs when mixing two pure liquids [31] Test-yourself quizzes must be completed and documented by the students in their technical journal. These one-page quizzes with their solutions are accessed through a course management system like Moodle or Blackboard. Of the six to nine quizzes provided per two-week project, students are required to complete at least three of them. These quizzes are essentially drill-and-practice activities that require students to function at the knowledge, comprehension, and application levels of Bloom's cognitive taxonomy, examples of which can be found here. Note that the 50-minute co-op sessions are designed to have students function mostly at the application, analysis, synthesis, and/or evaluation levels in this taxonomy.

Another self-learning activity is one eLEAPS session per two-week project, where this session is accessed through the electronic version of the CinChE manual [19]. The **e**Learning **E**ngineering **A**nd **P**roblem **S**olving (eLEAPS) system is a surrogate coaching technique that leverages the power of Adobe Acrobat for script development by instructors and Adobe Reader for active learning by students. It was originally developed as a web-based, database-driven system, [32] but it was re-implemented as an Acrobat-based application because of the universal available of Adobe Reader. The eLEAPS system is used to coach students through the solution to a problem, derivation, proof, etc. Starting with a template solution created by the instructor, the student follows a coaching script that guides them through a solution in step-by-step increments called interactions. At the beginning of the coaching script, students are directed to print a copy of a template solution, which they fill in as they progress through the coaching script. An eLEAPS session is an external activity that replaces the content coverage usually done in a traditional lecture-format setting, an example of which can be found here. The four independent and external activities based on the HYSYS manual, an interactive web-based demo, one-page quizzes, and eLEAPS sessions are documented by the

students in their technical journals. To ensure individual accountability, a teaching assistant inspects and evaluates each technical journal at the end of each two-week project.

The guided problem solutions are only used in the first of the five two-week projects, where the students first encounter the holistic problem-solving methodology while solving the four or five analysis problems on material balances. These guided problem solutions serve to inform the students what is expected of them when they have to complete future analysis problems without the use of any guided templates. For the first two-week project, the contextualized problems have been solved manually by the instructor, their solutions have been scanned and stored as ".pdf" files, and portions of these files have been blanked-out using Adobe Acrobat. The ".pdf" file is a pre-developed solution that contains the problem statement and the template outcomes—a conceptual model with assumptions, a mathematical model, a mathematical algorithm, a numerical solution, and the heuristic observations. In these blanked-out ".pdf" files, annotated Acrobat notes have been added to guide the students through the application of the holistic PSM while they complete each template outcome for the problem solution. These template outcomes with their annotated notes are made available through Appendix E of the electronic CinChE manual, [19] an example of which can be found here. Using the rotation assignments in Table 3 and their assigned roles as team members in a two-week project, students draft their outcome by completing its template for a particular analysis problem before coming to a co-op session. Given the face-to-face promotive interaction between students and the positive interdependence among team members, students need to take seriously their responsibilities in preparing and reviewing their drafts. At the beginning of the course, students should be informed that if they do not prepare reasonable drafts as per the instructor's judgment, they will be assigned extra textbook exercises that they must complete within twenty-four hours (e.g., one extra for Project 1, two extra for Project 2, etc.). Failure to complete any of their extra exercises should result in their final grade being dropped by one or two letter grades. Basically, slackers should realize up front that their "under performance" comes with a heavy penalty and will not be tolerated by their team members. Being lazy and inconsiderate will cost them by having to do more work.

Retrieval Practice

When done as closed-book exercises, retrieval events require students to access material from their long-term memory and place it into the short-term area of their working memory to answer a question or complete an exercise, like a one-minute paper or a short quiz. Practicing retrieval events on the material in different contexts promotes learning and long-term retention [3]. As recommended by Felder and Brent, "Give the students something to do (answer a question, sketch a flow chart or

diagram or plot, outline a problem solution, solve all or part of a problem, carry out all or part of a formula derivation, predict a system response, interpret an observation or an experimental results, critique a design, troubleshoot, brainstorm, or come up with a question, …) [33]." These suggested retrieval events can take place in the two "content" parts of a 50-minute co-op session, and they can be at different levels of Bloom's cognitive taxonomy. Students are actively processing the material and strengthening links between their schemata about the material, particularly when processing that material at higher levels of Bloom's cognitive taxonomy—application, analysis, synthesis, and evaluation. A retrieval event is most effective when the material does not initially reside in short-term memory; that is, the student must retrieve it from long-term memory to working memory.

Another type of retrieval event is answering multiple-choice questions in a concept inventory. Mastascusa, Snyder, and Hoyt [3] recommend not using multiple-choice questions as retrieval events, because they "have incorrect answers designed to tempt students" and "choosing some of those wrong answers might reinforce incorrect learning." A concept inventory that requires students to explain why they selected their option for each question and then discussing their answers with peers can help to overcome these shortcomings and give the instructor a better picture of what the students are thinking. The web-based AIChE Concept Warehouse provides over 2,000 concept questions and 10 concept inventories pertinent to courses throughout the core chemical engineering curriculum [34]. Students not only select a multiple-choice answer, but they must explain why they made that selection in the AIChE Concept Warehouse. Although concept inventories are normally used at the start and end of a course to gauge what learning progress students have made, they can and should be used within a course. After the end of a two-week project at Bucknell, an online concept survey of about four to six questions has been administered to identify what the students have learned and to uncover any misconceptions about the material covered in that two-week project. Ngothai and Davis present a statistically-verified concept inventory of twenty questions for the introductory chemical engineering course on material and energy balances [35]. This inventory is designed for use at the start and finish of the course. Obviously, none of the questions in any pre- and post-concept inventory should be part of the short concept surveys used within the course.

Schemata Construction

The knowledge structures that students retain in their long-term memories are often called schemata. When new schemata are built, they are often linked with preexisting schemata. An effective technique to build and strengthen schemata is to get the students to defend their conceptions and misconceptions in an active learning activity, similar to the following example:

1. Have the students complete an exercise as a closed-book activity.
2. Have them partner with a team member and resolve any differences.

3. Have the team come to a consensus on the solution to the exercise.

4. Call on students randomly to respond to the solution for the exercise.

This example is a form of reciprocal teaching [36,3], and it is similar to the technique presented by Felder and Brent [33] and used in Mazur's peer instruction [37]. The first step is basically a retrieval event that helps to strengthen the neural links to the material. The next two steps force students to interact and thus construct or reconstruct their schemata. This "interactivity puts students into situations where they have to organize their thoughts and present and defend them and that is conducive to building richer schemata [3]." The fourth step provides for individual accountability and has the students retrieve and articulate their thoughts. This example technique can be used in the two "content" parts of the co-op sessions to reinforce important concepts and address any misconceptions. The effects of reciprocal teaching can also occur in the "problem" part of the co-op session when students compare and contrast their draft materials for the same solution outcome like the mathematical model for the same problem.

Contrasting cases and contextual interference are two other techniques that require students to resolve differences [3]. In comparing two or more cases, students have an opportunity to create a more abstract schema because they will have to extract the general principles involved. The "heuristic observations" outcome in the holistic PSM requires students to create contrasting cases, and reviewing those draft observations during the "problem" part of the co-op session can lead to abstraction as they compare and contrast their draft materials. In contextual interference, students must resolve the differences between two different organizations of the same material, which is an opportunity to create more abstract schemata similar to that in contrasting cases. The CinChE manual [19] presents solutions based on the holistic PSM for example problems taken from the Felder and Rousseau textbook [9]. Having students compare the two solutions to an example problem from these two sources is an exercise in resolving differences based on contextual interference.

Potential Transfer

"Teaching for transfer works best when it revolves around activities that give students practice at retrieval and activities at higher levels in Bloom's taxonomy," in order to enrich their schemata [3]. The first five outcomes in the holistic PSM address all six levels of Bloom's cognitive taxonomy, particularly the synthesis of the mathematical model and the evaluation to produce the heuristic observations. Retrieval practice and schemata construction are necessary for long-term retention of the material, and this retention is a prerequisite for material transfer. The techniques of decontextualization, judicious feedback, hugging, bridging, and analogies help to promote transfer by having the students build richer abstract schemata of the material [3], as described in the next two paragraphs.

Decontextualization means overcoming "place learning;" learning that is highly connected to the place of learning like the classroom or a study area. "Not only must students work in different physical locations—to reduce the effect of place knowledge—but they also must encounter the material in different problem contexts [3]." Completing the independent-study capstone project for the Aspen HYSYS simulation of a chemical process flowsheet requires the students to do their computer work outside the classroom. "Learning in different areas with different groups of people leads to better learning than always studying in the same place with the same people [3]." Having students working for a fictitious consulting company gives them meaning to why they must address solving the "contextualized" analysis problems and having them draft the solution outcomes for these problems and review them in the "project" part of the co-op sessions varies the conditions of practicing with different people. At Bucknell, the laboratory experiments in a two-week project provide a different location where students determine the relative imbalances for material and possibly energy. All of these instructional activities help students to begin developing more expert-like schemata.

The Aspen HYSYS simulation project is an example of judicious feedback and hugging. The students must construct their own knowledge about chemical process simulation, with limited feedback from the instructor. Judicious feedback creates desirable difficulties that "put learners in situations where they need to take more responsibility for construction of their schemata, and…this produces richer schemata, with more and stronger links to other knowledge structures [3]." The assigned HYSYS simulation problems are similar to (or hug) the four analysis problems that students address as a team in their two-week projects. Also, placing problems in the context of an imaginary company is another form of hugging. Bridging is instructional activities that encourage the formulation of abstractions, like the conceptual framework of the holistic PSM. An analogy that has a shared abstraction with some of the course material is another representation of the same concept; for example, material balancing and checkbook balancing.

Formative Assessment

Formative assessments should be used by the instructor to monitor how the students individually are progressing in their learning and how the team members are functioning in their teamwork. Since they are usually not grading instruments, the sole purpose of the formative assessments is to provide feedback for the instructor as well as the students. Most of these assessments can be done using the survey tools found in a course management system like Moodle or Blackboard, where an aggregated result, the class average, is sufficient for the instructor's purposes. During most co-op sessions at Bucknell University, electronic surveys are conducted solely in the web-based academic version of the Team 360 system [38] to assess students' knowledge based on reading assignments, outside learning activities, and conceptual understanding. The academic version of Team 360 was

Figure 9. Example Team 360 Survey on Precision and Units.

a joint software development project started in 2004 between Michael E. Hanyak and Ascendus Technologies. The Team 360 system provides the unique feature, not found in any course management systems, where team members can view their collated responses to the survey questions, along with the aggregated responses of their teammates and the class average for each scored survey question. As an example, students were to complete a reading assignment on precision and units before coming to a co-op session. At the beginning of that co-op session, they took as individuals the Team 360 survey shown in Figure 9.

Using their recorded responses on scrap paper, the team members collaborate and examine those responses, resolve any differences, and then complete the same survey for the team. After using Team 360 to administer these two surveys, the instructor allows each student to view the Team 360 collated results for the first survey, an example of which is shown in Figure 10. As a member of Team 2, Tederal Bank observes his responses, his partners' averaged responses, his team's averaged responses, and the class averaged responses to each question in the survey. A correct response to a questions has value of one, while an incorrect one has a value of zero. An averaged response to a question is in the range of zero to one. For the example survey in Figure 10, the class average for the first survey based on individual responses was 0.77. Although not shown, the class average for the second survey based on the collaboration of the team members was 0.88. To complete the cooperative exercise, the instructor discusses the survey with the class while randomly calling on students to explain their answers.
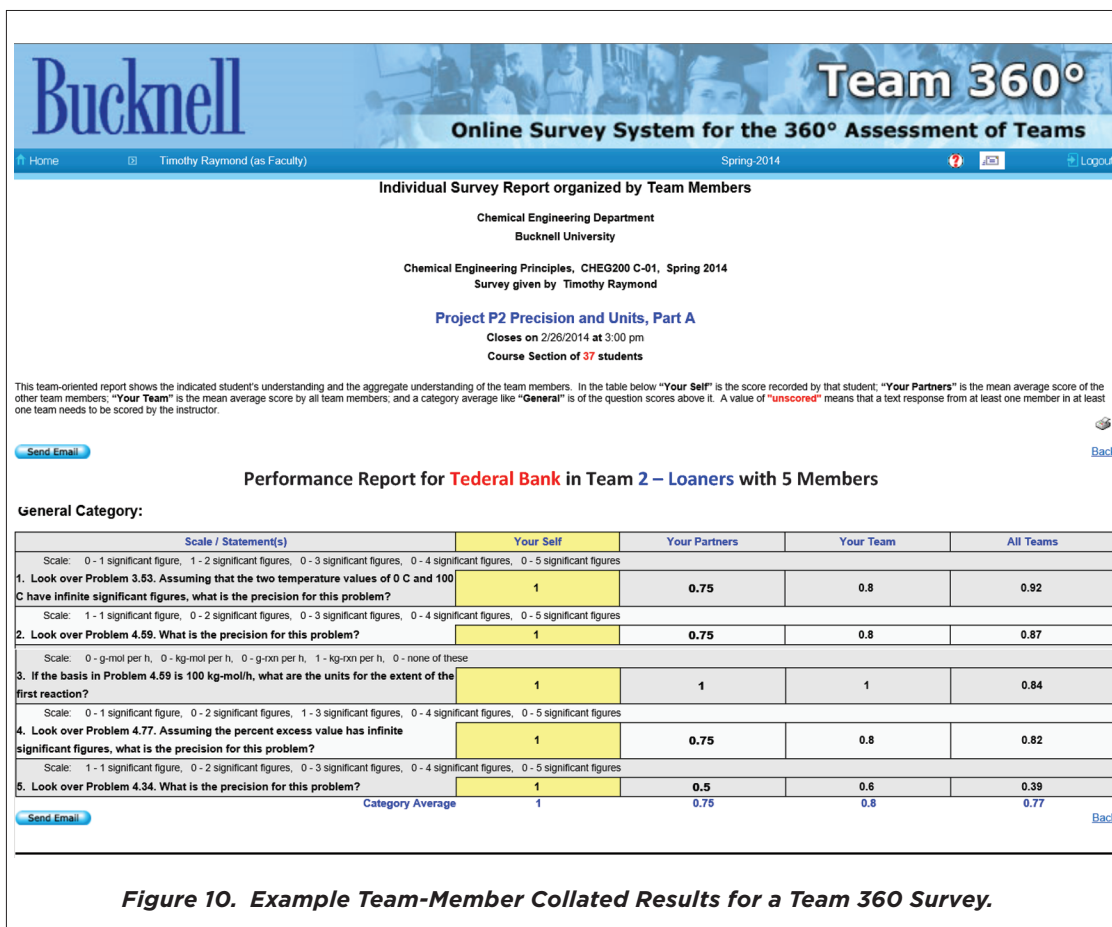
Figure 10. Example Team-Member Collated Results for a Team 360 Survey.

Team group processing, the fifth tenet of cooperative learning, is conducted during the last Friday of a two-week project. Using Team 360, team members individually answer the questions in Figure 11. These questions were developed by Michael Prince, a colleague at Bucknell University, and used by him in the junior-required heat transfer course. The students are informed that their responses to the first four questions will be shared anonymously with their teammates using Team 360. After completing the survey, the team members review the anonymous responses, discuss them as a team, and then write a team response to the four questions in a memo to the instructor, which must be submitted before they leave the co-op session.

COGNITIVE BENEFITS

Do the learning benefits of the problem-based learning (PBL) environment coupled with the holistic problem-solving methodology (PSM) described in this article concur with the findings of the

Technical Content

1) What are you proudest of in terms of your team's technical work? What did your team do particularly well?

2) Where do you think there might be errors in your technical work? Are there still technical questions that you have?

Teamwork

3) What was the most serious problem that your team had completing the assigned problems? How did your team deal with this problem?

4) What, if anything, did your team learn about problem-solving and teamwork over the course of the project assignment? What worked well for your team as a way to deal with problems or failures? Identify at least one specific area that could use improvement.

5) What was your primary role for this project?

Figure 11. Survey Questions to Facilitate the Team Group Processing Activity.

pedagogical research literature? The experience of using PBL and the holistic PSM in the introductory chemical engineering course at Bucknell University reaffirms the literature finds. Hanyak and Raymond describe in detail the course implementation and the benefits to the freshmen chemical engineering majors [17]. Their major conclusions about exam grades, alumni survey results, and concept inventory scores will be summarized here, but with some minor corrections and additional data included since the publication of their article.

Exam Grades

The introductory chemical engineering course on material balances, phase equilibria, and energy balances has been taught for over fifteen years at Bucknell University by the same instructor (Michael Hanyak) while utilizing the same course and exam content. The instructor began teaching the course as a traditional (pre-PBL) course and then transitioned to a PBL-based course starting in 1998. Consequently, student exam grades exist for the last four years of the pre-PBL course ('93, '95, '96, '97) and the first four years of the fully-implemented PBL course ('03, '05, '06, '07). The period of 1998 to 2002 represents the transition from the lecture-based format to the PBL format. A summary of the exam averages and standard deviations for the pre-PBL and PBL courses is given in Table 4. The data in Table 4 show that the PBL version of the course has led to student grades on the exams which are either the same or better (within 1 standard deviation) than the course taught

Category	Sophomore Majors		Freshmen Majors
	pre-PBL	PBL	co-taught PBL
Exam #1 Average:	71%	81%	79%
Std. Dev.:	4	1	10
Exam #2 Average:	75%	72%	74%
Std. Dev.:	10	5	6
Final Exam Average:	75%	81%	82%
Std. Dev.:	7	3	3
Years Taught:	'93, '95, '96, '97	'03, '05, '06, '07	'08, '09, '10, '11, '12, '13, '14
Total Students:	97	129	218
Exam Average:	74%	78%	78%
Std. Dev.:	2	5	4

Table 4. Cognitive Benefit to Bucknell University's ChE Majors based on the Exam Grades.

traditionally, a similar result as reported by Woods [2]. Only the courses taught by the same instructor and with the same (or very similar) exams were included in the data for the four pre-PBL years ('93, '95, '96, '97) and the four PBL years ('03, '05, '06, '07). For these eight years, the students were first-semester sophomore chemical engineering majors.

In 2008, the course (CHEG 200) was moved to the second-semester freshman year, and it was co-taught by the previous instructor (Michael Hanyak) and a new instructor (Timothy Raymond, who also taught the course in 2004). They co-taught the course for three years from 2008 through 2010. After Michael Hanyak's retirement in 2010, Timothy Raymond and Katsuyuki Wakabayashi have co-taught the course from 2011 through 2014. The data for the co-taught courses are also included for comparison in Table 4. The instructors were originally concerned that moving the course to the second semester of the freshman year might affect student performance leading to lower course grades. The exam data and the instructors' experiences interacting with the students have shown this concern was not to be the case. The seven freshman classes performed identically, within standard deviations, to the four prior PBL sophomore classes.

Alumni Survey

Beyond developing problem-solving skills, the PBL version of the CHEG 200 course has value-added components to develop career skills in teamwork, communication, and life-long learning. From a departmental survey of Bucknell chemical engineering alumni who graduated between 2007 and 2011, an open-ended question was asked: "Please provide an example (or more) of a skill developed

at Bucknell that particularly contributed to your post-graduate success." Forty-seven percent of the 132 alumni responded to the survey. While the majority of responses referred to skills which were first introduced in the CHEG 200 course such as problem-solving, teamwork, communication, and independent learning, two representative respondents specifically mentioned the course with the following quotes: "Communication is extremely important in a plant environment. Problem solving and working with a group are my main daily activities, both are skills I developed and honed at Bucknell through the group based courses like CHEG200, Heat and Mass, and Senior Design" and "An efficient and effective approach to solving problems (as taught in CHEG200)." Other responses were analyzed and matched against departmental learning outcomes. The top four commonly identified areas included communication (30% of respondents), problem solving (23%), teamwork (22%), and independent learning (7%) – all areas of focus for CHEG 200. These survey data indicate that the practicing engineers who have graduated from our department strongly value and rely on the skills originally introduced in this course. About 60% of the respondents attribute at least part of their post-graduate success to their skills in communication, teamwork, or independent learning. Since this survey was an open-ended question providing no prompts for answers, the percentages given represent minimums.

Concept Inventory

An in-house concept inventory (CI) was developed largely by the primary course instructor (Michael Hanyak) to evaluate students' understanding of key concepts from the course. The 30-question, multiple-choice concept inventory was administered at the beginning of the course and at the conclusion of the course from 2007 through 2014. Although this inventory has not been validated, its use pre-course, post-course, and nine-months later exhibits some useful trends. In Table 5, the student averaged results are shown for the indicated sophomore and freshmen class years. On average, the students scored around 40% on the pre-course and 61% on the post-course concept inventory. Nine months later, the same 30-question concept inventory was also administered at the beginning of the fluid mechanics course in the fourth semester to the chemical engineering majors who were freshmen in 2008 to 2011. No other required chemical engineering course was taken in the nine-month period after CHEG 200. For the four-year period in Table 5, the average score was around 57% nine months later. Compared to the post-course average of 61%, the students essentially retained the concepts that they learned earlier. The nine-month-later administration of the concept inventory was discontinued, since the average scores from 2008 to 2011 did not vary much and since valuable class time was being used in the first week of the ENGR 233 course to complete the concept inventory.

While the average score in Table 5 may seem low, the more important factor for a concept inventory is the gain [39]. Hake defines the gain, $<g>$, as (%post-test - %pre-test)/(100 - %pre-test). Hake's

CHEG 200 Course	No. of Students	Pre-Course CI		Post-Course CI		Hake's Gain	9-Months Later CI	
		Average	St. Dev.	Average	St. Dev.		Average	St. Dev.
Sophomores in 2007:	29	0.40	0.07	0.58	0.09	0.31	–	–
Freshmen in 2008:	25	0.38	0.08	0.60	0.09	0.35	0.62	0.10
Freshmen in 2009:	29	0.43	0.08	0.63	0.14	0.35	0.58	0.13
Freshmen in 2010:	26	0.41	0.08	0.62	0.12	0.35	0.55	0.10
Freshmen in 2011:	32	0.40	0.07	0.58	0.12	0.29	0.54	0.11
Freshmen in 2012:	26	0.40	0.09	0.59	0.14	0.31	–	–
Freshmen in 2013:	26	0.38	0.09	0.53	0.12	0.24	–	–
Freshmen in 2014:	37	0.36	0.09	0.54	0.12	0.29	–	–
Total Students:	230							
Overall Average:		0.40	0.02	0.61	0.02	0.31	0.57	0.04

Table 5. Cognitive Benefit to Bucknell University's ChE Majors based on the Concept Inventory (CI).

study focused on 62 introductory physics courses taught at high schools, colleges, and universities and enrolling a total of 6542 students. His gain data are derived from pre-test and post-test scores of the Mechanics Diagnostic and Force Concept Inventory tests, acknowledged to be of high validity and consistent reliability. Hake hoped his study would further improve the instruction in introductory mechanics and serve as a model for promoting educational reform in other disciplines [39]. Hake's data showed an average $<g> = 0.23 \pm 0.04$ for traditionally-taught (lecture-based) courses, and an average $<g> = 0.48 \pm 0.14$ for interactive engagement (active learning) courses. In these introductory courses, the ones that used interactive engagement produced learning gains on average that were over twice the gains of the ones that used traditional lecturing. Thus, students participating in the interactive engagement courses had better retention of the basic concepts. Although gain data does not exist for CHEG 200 when it was taught as a traditional lecture course, Hake's data suggest that its average gain will be lower than that for interactive engagement and closer to an average gain of 0.23. For the eight years of the pre- and post-course data in Table 5, the overall average gain was 0.31 ± 0.04. When the CHEG 200 course was co-taught by Hanyak and Raymond from 2008 to 2010, the average gain was 0.35. Applying the trends of Hake's data, the results in Table 5 from 2008 to 2010 are within about one standard deviation of Hake's interactive engagement course average, and they exceed the traditionally-taught course average by two to three standard deviations. Based on the gain results in Table 5, the concept inventory for this introductory course on chemical engineering demonstrates a gain in student conceptual knowledge similar to that reported by Hake for those introductory physics courses that used interactive engagement.
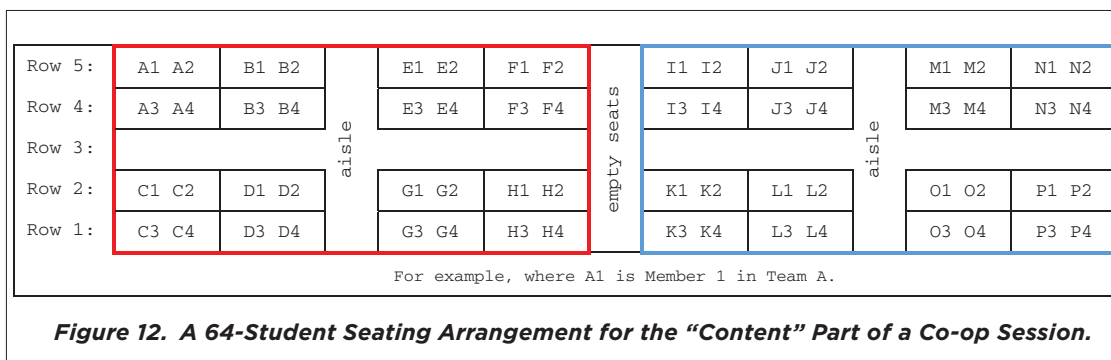
What should an instructor do to improve the gain on the concept inventory in CHEG 200, so that it is closer in value to Hake's average gain of 0.48 or Hake's largest gain of 0.69 for interactive engagement? For a pre-course score of 40%, a post-course score of 60% leads to a gain of 0.33, of 70% leads to a gain of 0.50, and of 80% leads to a gain of 0.67. A 40% score means 12 out of 30 questions were answered correctly. For 60%, 70%, and 80%, 18, 21, and 24 questions must be answered correctly, respectively. The instructor should address two areas—misconceptions and heuristic observations—to promote better long-term retention and transfer, which is needed to enhance the performance on the post-course concept inventory. Overcoming students' misconceptions is critical to having the long-term retention of material stored as proper schemata in one's long-term memory. Having students take seriously the development of heuristic observations leads to better abstraction and decontextualization of the material, which are necessary for potential transfer.

SCALABILITY

The CHEG 200 course is designed for a maximum of forty students in two-hour co-op sessions meeting three times per week, and it is conducted in a twenty-table electronic classroom that has access to forty Windows-based notebook computers. Two faculty instructors co-teach the course, where one is primarily responsible for the coordination and coaching on the analysis problems, while the other is primarily responsible for the coordination and coaching on the laboratory preparation and execution. How might the CHEG 200 course design be applied to a 50-minute class session without a laboratory component and for a class size greater than forty students? A possible answer to this question is addressed next.

As an example, a class of 64 students meeting in a traditional lecture hall might have the seating arrangement as shown in Figure 12 for the "Content" part of a co-op session. Each team has four members, and they sit in a contiguous block of seats. Note that each of the two sections (left and right) contains 32 students divided into eight teams. This section size would be similar to a CHEG 200 course without a laboratory that has only 32 students in eight four-member teams. The arrangement in Figure 12 supports team-based cooperative activities that could include the use of formative surveys conducted through personal smart phones with web browsers and/or personal iPad-type computers. During these activities, the faculty instructor would coach teams in a section by accessing them through the empty row and aisle that separate teams. A trained teaching assistant (undergraduate or graduate) is needed to coach (or tutor) the second section when doing the cooperative activities [2]. The pattern in Figure 12 can be repeated for a class size of 128 and 192 students in a traditional lecture hall, but another teaching assistant would be needed to coach each

Row 5:	A1 A2	B1 B2		E1 E2	F1 F2		I1 I2	J1 J2		M1 M2	N1 N2
Row 4:	A3 A4	B3 B4	aisle	E3 E4	F3 F4	empty seats	I3 I4	J3 J4	aisle	M3 M4	N3 N4
Row 3:											
Row 2:	C1 C2	D1 D2		G1 G2	H1 H2		K1 K2	L1 L2		O1 O2	P1 P2
Row 1:	C3 C4	D3 D4		G3 G4	H3 H4		K3 K4	L3 L4		O3 O4	P3 P4

For example, where A1 is Member 1 in Team A.

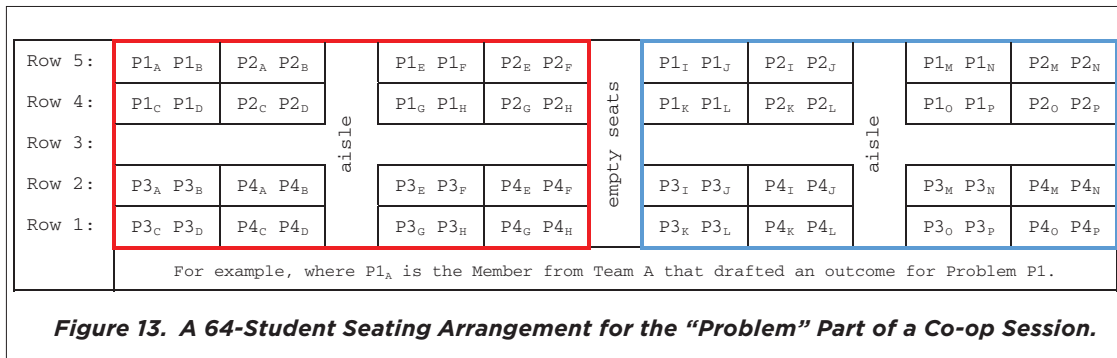**Figure 12. A 64-Student Seating Arrangement for the "Content" Part of a Co-op Session.**

new section. The coaches could rotate their positions in the next co-op session from one section to another, in order to have all students experience some interaction from the instructor and trained teaching assistants over a two-week project. Another possibly is to replace the instructor with a teaching assistant and have the instructor float and coach throughout the lecture hall. If the lecture hall is not big enough to accommodate the seating arrangement for whatever class size, then two sections of the class can be offered.

The teams in Figure 12 are assigned four analysis problems for a two-week project. For example, a two-week project on material balances might contain four problems, one for each of the four types of systems—continuous, batch, semi-batch, and semi-continuous. These same four problems could be used in the next offering of the course. When the "problem" part of co-op session is reached, students in each section would reseat themselves according to the arrangement given in Figure 13. Basically, four student members from four teams who prepared the same problem draft of the assigned outcome for that co-op session (e.g., mathematical model for Problem P1) would gather, review their draft solutions, and learn from each other's mistakes. In the first half of the "Problem" part, the coach in each section would first ascertain if each of the 32 students had prepared an initial draft that is about 75% complete and second would address any questions from the eight, four-student groups. In the second half of the "Problem" part, the coach could provide instructor-completed drafts of the four problems for review by the appropriate four-member groups and then answer any questions. Note that two copies of the instructor's draft for each problem would be needed to cover a section. All instructor's drafts would be collected at the end of the "Problem" part to be used again next year. The goal for the team members in Figure 13 is to understand their outcome and have a correct draft of it that they would give to another member on their team, so that member can prepare a draft for the next outcome at the next co-op session (e.g., passing a correct mathematical model for a problem that then would be used to draft its mathematical algorithm). As instructors experiment with the arrangements in Figures 12 and 13

Row 5:	P1$_A$ P1$_B$	P2$_A$ P2$_B$		P1$_E$ P1$_F$	P2$_E$ P2$_F$		P1$_I$ P1$_J$	P2$_I$ P2$_J$		P1$_M$ P1$_N$	P2$_M$ P2$_N$
Row 4:	P1$_C$ P1$_D$	P2$_C$ P2$_D$	aisle	P1$_G$ P1$_H$	P2$_G$ P2$_H$	empty seats	P1$_K$ P1$_L$	P2$_K$ P2$_L$	aisle	P1$_O$ P1$_P$	P2$_O$ P2$_P$
Row 3:											
Row 2:	P3$_A$ P3$_B$	P4$_A$ P4$_B$		P3$_E$ P3$_F$	P4$_E$ P4$_F$		P3$_I$ P3$_J$	P4$_I$ P4$_J$		P3$_M$ P3$_N$	P4$_M$ P4$_N$
Row 1:	P3$_C$ P3$_D$	P4$_C$ P4$_D$		P3$_G$ P3$_H$	P4$_G$ P4$_H$		P3$_K$ P3$_L$	P4$_K$ P4$_L$		P3$_O$ P3$_P$	P4$_O$ P4$_P$

For example, where P1$_A$ is the Member from Team A that drafted an outcome for Problem P1.

Figure 13. A 64-Student Seating Arrangement for the "Problem" Part of a Co-op Session.

they could adjust the format of a co-op session, like having a 20-minute "Content" part followed by a 30-minute "Problem" part.

Although the classroom structure as presented in Figures 12 and 13 provides the opportunity for active learning to happen in the "content" and "problem" parts of the co-op sessions, the instructor must design the problems and provide the resources to help drive the learning done by the students. A two-week project would address certain subject matters as illustrated in Table 2. For each project, the instructor would develop well-defined learning objectives based on Bloom's cognitive taxonomy, create contextualized problems to meet those objectives, and design exams to measure the attainment of those objectives [3]. As Figure 13 indicates, four contextualized problems are needed per two-week project to accomplish the learning in the "problem" part of the co-op sessions using the rotation schedule given in Table 3. For the "content" part of a co-op session, the instructor would initially identify troublesome topics associated with a two-week project and design active learning activities to help students strengthen their knowledge structures using the reciprocal teaching technique described under "Schemata Construction" in the "Best Practices" section of this article. As instructors monitor students having difficulty with the material from year to year, they can define new or refine old active learning activities for the "content" part. Note that the application of the holistic PSM as presented in Table 3 already incorporates the learning benefits to be gained from Bloom's cognitive taxonomy, the Kolb's Cycle, and the five tenets of cooperative learning. Since significant organization and coordination by the instructor is required, a "To Do" list for the whole semester can help manage the course. Once this list and its supporting resources are prepared, the instructor can re-use them from year to year. At Bucknell University, the "To Do" document prepared by Michael Hanyak has web links to all of the course resources like learning objectives, project assignments, handout materials, various manuals, instructor co-op scripts, and in-class exercises. A copy of this document can be accessed here. The summary section below presents some additional guidelines to be considered when implementing the holistic PSM in a PBL environment.

SUMMARY

In the introductory chemical engineering course, the students learn the fundamental principles for material balances, phase equilibria, and energy balances. Knowledge of these principles serves as the foundation for later courses in the curriculum. In a lecture-based environment, students work mostly at the lower levels of Bloom's cognitive taxonomy which leads to short-term memorization or surface learning of the material. In a problem-based learning environment, students utilize higher levels of Bloom's cognitive taxonomy which leads to deep learning of the material for the purposes of long-term retention and potential transfer. The major pedagogical elements used to create a PBL environment in the introductory chemical engineering course at Bucknell University are as follows:

- Material Coverage. Compared to a traditional lecture course, less material will be covered in a PBL course, because students are required to work at the higher levels of Bloom's cognitive taxonomy, while they process that material during class time under the guidance of the instructor. Although the students must learn the basic principles, the course learning objectives are to have the students understand those principles deeply and to develop those skills that can help them learn on their own. "Less can be more" with the value-added benefit of developing important lifelong learning skills.

- Problem-Solving Methodology. A unique conceptual framework for a holistic approach to problem solving was used for well-defined problems, since it requires the students to work at all levels of Bloom's cognitive taxonomy. Applying this framework, students can begin to cultivate abstract thinking habits and engage the cognitive processes that promote long-term retention and potential transfer of the material. Also, this framework supports the Kolb Learning Cycle and allows the students to develop their cognitive skills in each of the four quadrants of that cycle. By addressing the "Why," "What," "How," and "Why" questions in the cycle, students become better problem solvers.

- Team Projects. As an active learning technique, PBL is more effective when problems are embedded in realistic situations. To provide that realism, the students worked in teams on assigned projects as chemical engineers in a consultant company. In this scenario, the instructor is the company's project supervisor that assigns contextualized problems and provides guidance and not answers. The students were given a company handbook [22] that describes problem solving, company organization and communication, engineering projects, technical activities, communication activities, teamwork activities, professionalism, technical journal, project assessment, and documentation standards. This fictitious company and its handbook are designed to foster and encourage a professional working environment, in which students can learn to become effective technical problem solvers, communicators, and team players.

As a semester-long or capstone project, team members conducted a self-study, using an instructor-prepared manual on the process flowsheet simulation to manufacture a product from some raw materials using Aspen HYSYS [25]. In addition, teams completed five two-week projects during the semester to solve manually process unit analysis problems that require the application of the principles of material balances, phase equilibria, and energy balances. These analysis problems are intended to help the students get a better understanding of the subject matter, as well as how HYSYS does its calculations for individual process units.

- Flipped Classroom. When instructors are accustomed to mostly a lecture format, they will have to change their mind set in a PBL format, in order to move from being a "sage on the stage" to a "guide on the side." By inverting the "presentation/processing" of the material usually done in a lecture-based course, students become responsible to do the assigned reading and/or exercises outside the classroom by using resources (articles, textbooks, handouts, and online materials) made available by the instructor and then come prepared to process that material inside the classroom under the guidance of the instructor using team-based cooperative activities. For the team-based processing in the classroom to be successful, students are held accountable to complete their external assignments by using short quizzes or exercises at the start of class sessions.

  At Bucknell University, a classroom was selected that easily facilitated team-based cooperative activities and provided access to computer resources for a maximum class size of forty students. In the four-credit course with a laboratory, a 110-minute class met three times per week with a 30-minute "content" part, a 60-minute "problem" part, and a 20-minute "content part". The 60-minute "problem" part was divided into two 30-minute subparts. In the first 30-minute sub-part, half of the teams spent time on the analysis problems, while the other half spent time on laboratory preparation. In the second 30-minute sub-part, the teams switched their duties.

  For a three-credit course without a laboratory at another university, a 50-minute class could become a co-op session divided into three parts: a 15-minute "content" part, a 20-minute "problem" part, and a 15-minute "content" part. The "content" parts are team-based cooperative activities that process material from external assignments (readings or exercises), cover new or difficult conceptions, and/or address misconceptions. The "problem" part is dedicated to student peer review of the four or five process unit analysis problems with the instructor acting as a consultant when needed. A rotation schedule like that in Table 3 is used, in order to have the team members experience solving all of the analysis problems in each two-week project.

- Project Teams. The instructor formulates a diverse membership for the teams at the beginning of the course using various criteria like academic performance (GPA) and gender [24,40]. The number of team members should be equal to or greater than four students, although four is probably best. In the first week of the semester, the teams draft and sign a team contract

that states the rules of conduct, the roles of responsibilities, and the policies to handle detrimental issues. When preparing this draft, they consult a website on teamwork provided by the instructor [29]. After about three weeks, the teams are asked to read articles on learning and teaching styles, the Kolb learning cycle, and the Tuckman model on team dynamics. They then update their team contracts based on those readings. When instructors encounter dysfunctional teams, they can use the team contract to help the team members identify and correct their interpersonal problems.

- Cooperative Learning. The pedagogical framework of "cooperative learning" [7] is used to foster teamwork, because it helps students to develop and gain confidence in their interpersonal skills. Its five tenets are positive interdependence, individual accountability, face-to-face promotive interaction, appropriate use of teamwork skills, and regular self-assessment of team functioning. The two-week projects as described in this article maximize students' interdependence and interaction. Not only are exams used for individual accountability, but quizzes or surveys at the beginning of a co-op session force students to complete their external assignments before coming to that session. Teamwork skills are fostered by completing the two assignments on the team contract. At the end of a two-week project, teams must reflect on how well they are functioning and develop a written plan to take corrective actions for the next project.

- Course Management. In a PBL environment with the holistic PSM, the instructors become coaches and consultants, because they "cannot give anything to students except an opportunity for them to create their own knowledge structures [3]." Since this learning format may be foreign to the new chemical engineering majors, the instructor needs to provide structure early in the introductory course to help the students get started in the new learning environment. As the students build their confidence, the structure can be relaxed to give them more control over their own learning process. To relieve students' anxiety, they need to know what the instructor is doing and why at the beginning of the course with respect to PBL and the holistic PSM. The instructor also needs to have available the necessary resources for the students in a PBL environment, like directions, deadlines, reminders, assignments, articles, web links, surveys, etc. Course management systems like Moodle or Blackboard allow for the timely release of these resources and the use of emails to inform students. To encourage interdependence and interaction, the Team 360 survey system was used, since it displays collated results based on the team membership for their consideration. As an individual accountability mechanism, students kept a technical journal of all materials related to the introductory chemical engineering course. Teaching assistants were used to check periodically the technical journals as a formative assessment of the students' commitment. The instructor continually monitored students' progress. When they were having difficulties, the instructor designed and administered cooperative learning activities to help the students overcome those difficulties.

After incorporating these pedagogical elements into the introductory chemical engineering course at Bucknell University, the problem-based learning (PBL) approach with the holistic problem-solving methodology (PSM) has been shown to create a learning environment that nurtures deep learning rather than surface learning. Based on exam scores, student grades are either the same or better than the course taught using a lecture-based format. Based on pre- and post-course scores for an in-house concept inventory, average learning gains were within one standard deviation of the average gain reported by Hake for interactive engagement. After nine months, chemical engineering majors essentially retained their knowledge of the concepts. Finally, the problem-based learning format contributed to the development of important career skills in problem solving, teamwork, communication, and independent learning, as reported by our department's alumni.

ACKNOWLEDGMENTS

REFERENCES

1. Jonassen, D., J. Strobel, and C. B. Lee. "Everyday Problem Solving in Engineering: Lessons for Engineering Educators." *Journal of Engineering Education*, **2006**, Vol. 95, No. 2, pp. 139–151.

2. D.R. Woods. "PBL: An Evaluation of the Effectiveness of authentic Problem-Based Learning (aPBL)." *Chemical Engineering Education*, **2012**, Vol. 46, No. 2, pp. 135–144.

3. Mastascusa, E. J., W. J. Snyder, and B. S. Hoyt. *Effective Instruction for STEM Disciplines—From Learning Theory to College Teaching*. Jossey-Bass, San Francisco, CA, **2011**.

4. Bloom B. S. *Taxonomy of Educational Objectives, Handbook I: The Cognitive Domain*. David McKay, New York, **1956**. Accessed June 16, 2014 at http://www.nwlink.com/~donclark/hrd/bloom.html .

5. Prince, M. "Does Active Learning Work? A Review of the Research," *Journal of Engineering Education*, **2004**, Vol. 93, No. 3, pp. 223–231.

6. Prince, M. and R. M. Felder. "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases," *Journal of Engineering Education*, **2006**, Vol. 95, No. 2, pp. 123–138.

7. Johnson, David. W., Roger. T. Johnson, and Karl. A. Smith. *Active Learning: Cooperation in the College Classroom*. Interaction Book Co., Edina, Minnesota, **1998**.

8. School of Medicine. "Techniques of Active Learning." Virginia Commonwealth University, Richmond, VA, **2013**. Accessed February 18, 2015 at http://www.medschool.vcu.edu/curriculum/resources/.

9. Felder, R. M. and R. W. Rousseau. *Elementary Principles of Chemical Processes*, 2005 Edition. John Wiley and Sons, Hoboken, NJ, **2005**.

10. Himmelblau, D. M. and J. B. Riggs. *Basic Principles and Calculations in Chemical Engineering*, Seven Ed. Prentice Hall, Upper Saddle River, NJ, **2004**.

11. Murphy, R. M. *Introduction to Chemical Processes: Principles, Analysis, Synthesis*. McGraw-Hill, New York, NY, **2007**.

12. Polya, G. *How to Solve It: A New Aspect of Mathematical Method*, Second Edition. Doubleday, Garden City, NY, **1957**.

13. Halpern, D. F. *Thought and Knowledge: An Introduction to Critical Thinking*, Second Edition. Lawrence Erlbaum Associates, Inc., Hillsdale, NJ, **1989**.

14. Harb, J. N., Terry, R. E., Hutt, P. K., and Williamson, K. J. *Teaching Through the Cycle*. Brigham Young University Press, Provo, UT, **1995**.

15. Nason, J. A., B. J. Brooks, and M. Koretsky. "A Material Balances Course with Integrated Concept-Based Active Learning Pedagogy—Comparison of Student Perception and Performance with Their Attitudes and Approaches to Learning". *ASEE Annual Conference and Exposition*, Conference Proceedings, Vancouver, BC, Canada, **2011**.

16. Florman, S. C. *The Civilized Engineer*. St. Martin's Press, New York, NY, **1987**.

17. Hanyak, M. E. and T. M. Raymond. "Teaching Material and Energy Balances to First-Year Students Using Cooperative Team-Based Projects and Labs." *ASEE Annual Conference and Exposition*, Austin, TX, **2009**.

18. Miller, G. "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information", *Psychological Review*, **1956**, Vol. 63, pp. 81–97.

19. Hanyak, M. E. *Companion in Chemical Engineering: An Instructional Supplement*. Self-Published by Michael E. Hanyak, Chemical Engineering Department, Bucknell University, Lewisburg, PA, **2011**. Textbook distributed via On-Demand Publishing, LLC, Scotts Valley, CA thru https://www.createspace.com/3574827.

20. Steward, D. V. "Partitioning and Tearing Systems of Equations." *J. of SIAM: Series B, Numerical Analysis*, **1965**, Vol. 2, No. 2, pp. 345–365.

21. Felder, R. M. and L. K. Silverman. "Learning and Teaching Styles in Engineering Education." *Engineering Education*, **1988**, Vol. 78, No. 7, pp. 674–681.

22. Hanyak, Michael E. *Development of an Engineering Project: A Handbook for Provisional Engineers*. Chemical Engineering Department, Bucknell University, Lewisburg, PA, **2008**.

23. Oakley, B. A, D. M. Hanna, Z. Kuzmyn, and R. M. Felder. "Best Practices Involving Teamwork in the Classroom: Results From a Survey of 6435 Engineering Student Respondents." *IEEE Transaction on Education*, **2007**, Vol. 50, No. 3, pp. 266–272.

24. Oakley, B. A., R. M. Felder, R. Brent, and I. Elhajj. "Turning Student Groups into Effective Teams." *J. Student Centered Learning*, **2004**, Vol. 2, No. 1, pp. 9–34.

25. Hanyak, M. E. *Chemical Process Simulation and the Aspen HYSYS v8.3 Software*, Second Edition. Self-Published by Michael E. Hanyak, Chemical Engineering Department, Bucknell University, Lewisburg, **2013**. Textbook distributed via On-Demand Publishing, LLC, Scotts Valley, CA thru https://www.createspace.com/4529692.

26. Woods, D. R. *Rules of Thumb in Engineering Practice*. Wiley-VCH Verlag GmbH & Co., KGaA, Weinheim, **2007**.

27. Soloman, B. A. and R. M. Felder. "Index of Learning Styles Questionnaire." North Carolina State University, Raleigh, NC, **2014**. Accessed May 20, 2014 at http://www.engr.ncsu.edu/learningstyles/ilsweb.html.

28. Phillips, P. "So, You're Going to be a Member of a Team." *Chemical Engineering Progress*, **1997**, Vol. 93, No. 1, pp. 141–144.

29. TLT - Teaching and Learning with Technology. "Building Blocks for Teams." The Pennsylvania State University, State College, PA, **2012**. Accessed May 20, 2014 at http://archive.tlt.psu.edu/suggestions/teams/index.html.

30. Hanyak, M. E., D. Duggirala, C. S. Main, and J. M. Dreese. "Interactive Simulation for a Simple Manufacturing Process: Styrene Monomer from Methanol and Toluene." Chemical Engineering Department, Bucknell University, Lewisburg, PA, **2011**. Accessed June 14, 2014 at http://www.departments.bucknell.edu/chem_eng/cheg200/CinChE_Manual/Ch02/examples/web_app/styrene/.

31. Brown, A. M. and M. E. Hanyak. "Volume Change of Mixing: An Investigation." Chemical Engineering Dept., Bucknell University, Lewisburg, PA, **2007**. Accessed June 16, 2014 at http://www.departments.bucknell.edu/chem_eng/eLEAPS/cheg200/DVofMixing/DVmix.pdf.

32. Oguzie, D. N. "e-LEAPS - An Interactive Web Application to Support Learning Engineering and Problem Solving," M.S. Thesis supervised by Michael E. Hanyak. Chemical Engineering Department, Bucknell University, Lewisburg, PA, **2007**.

33. Felder, R. M. and R. Brent. "Random Thoughts: Learning by Doing." *Chemical Engineering Education*, **2003**, Vol. 37, No. 4, pp. 282–283.

34. Koretsky, M. D., J. L. Falcone, B. J. Brooks, D. L. Silverstein, C. Smith, and M. Miletic. "The AIChE Concept Warehouse: A Web-Based Tool to Promote Concept-Based Instruction." *Advances in Engineering Education*, **2014**, Vol. 4, No. 1. Accessed May 26, 2014 at http://advances.asee.org/?publication=the-aiche-concept-warehouse-a-web-based-tool-to-promote-concept-based-instruction.

35. Ngothai, Y. and M. C. Davis. "Implementation and Analysis of a Chemical Engineering Fundamentals Concept Inventory (CEFCI)." *Education for Chemical Engineers*, **2014**, Vol. 7, No. 1, pp. e32-e40.

36. Palincsar, A. S. and A. L. Brown. "Reciprocal Teaching of Comprehension: Fostering and Comprehension-Monitoring Activities." *Cognition and Instruction*, **1984**, Vol. 1, No. 2, pp. 117–175.

37. Mazur, E. *Peer Instruction: A User's Manual.* Prentice-Hall, Upper Saddle River, NJ, **1996**.

38. Narayan, Vikram. *The Team 360 Assessment System.* Ascendus Technologies, Pittsburgh, PA, **2009**. Accessed May 29, 2014 at http://www.ascendus.com.

39. Hake, R. R. "Lessons from the Physics Education Reform Effort." *Conservation Ecology* **2002**, Vol. 5, No. 2, Art. 28. Accessed June 2, 2014 at http://www.consecol.org/vol5/iss2/art28/.

40. CATME Team. *CATME SMARTER Teamwork.* Purdue University, West Lafayette, IN, **2012**. Accessed August 2, 2014 at http://info.catme.org.

AUTHOR

Michael Hanyak is Professor Emeritus of Chemical Engineering at Bucknell University in Lewisburg, PA. He received his B.S. from The Pennsylvania State University in 1966, M.S. from Carnegie Mellon University in 1968, and his Ph.D. in Chemical Engineering from the University of Pennsylvania in 1976. From 1967–1970, he worked as a senior chemical engineer at Air Products, Inc. in Allentown, PA, where he developed process simulation software for cryogenic systems. He served at Bucknell University as Professor of Chemical Engineering from 1974 to 2010 and department chairman from 1998–2002. His teaching and research interests included computer-aided engineering and design, instructional design, pedagogical software tools, and the electronic classroom. He is the recipient of the 2011 CACHE Award given by the Chemical Engineering Division of ASEE for significant contributions in the development of computer aids for chemical engineering education.