Designing a Software Environment for Visual Learning in Introductory Chemical Engineering Classes

The material and energy balance class is frequently the "gateway" class in chemical engineering. Statistics over the past 23 years at this school show that 35% of the students who enroll in the material/energy balance class either fail, withdraw, or receive a grade lower than a "C". A large majority of these (66%) never complete their chemical engineering degree. The students who fail to successfully complete the material/energy balance class show a wide variety of academic abilities, as measured by SAT scores or high school GPA. However, the academic abilities of those students who fail to successfully complete the material/energy balance class and those who successfully complete the class are virtually identical. Why, then, do 35% of our students fail to complete the material and energy balance course?

Studying the Problem

In order to explore why the material and energy balance course might be such a stumbling block, we decided to study in detail the problem solving activities of introductory chemical engineering students. To do this, we ran an exploratory study in the Fall of 2006. In this study, four pairs of students used a SmartBoard™ electronic whiteboard to (a) draw chemical process diagrams of a given material and energy balance problem, (b) develop accompanying systems of equations, and (c) solve for the unknowns.

Students were told that we were interested in how they approached the solution to the problem rather than the solution itself. They were encouraged to discuss their approach so that we could follow their logic as the solution was developed. The students were allowed to work for 45 minutes before a 15 minute debriefing period.

Observations

Our review of the recordings made it clear that there was one area in which all of the groups had difficulties: translating the problem statement into a chemical process diagram and set of mathematical expressions. None of the groups was able to put together a correct process flow diagram. Without a correct process flow diagram, the derivation of the appropriate material balances was impossible. Common errors included omission of critical components, symbolizing material streams as processing units, and adding components beyond those that were described in the problem statement. We viewed students' inability to translate a problem statement into a proper process flow diagram as the fundamental problem to be addressed.

Solution for the Observed Difficulty

Based on our observations, we felt that we needed to develop some type of tool or procedure to help students make the transition from written material to visual material. Aside from being an important skill in its own right, the ability to map a written problem to a visual diagram allows students to continue learning using their preferred learning style. As Felder and Silverman[1] have found, the majority of learners at the college level are visual learners. As shown in Figure 1, the students in our material and energy balance are no different, showing a strong preference for a visual learning style (average score = - 5 on the Felder-Silverman scale). By creating a tool to aid in transforming written information into visual images, we believed that we could help students develop an essential skill that they will need not only in the material and energy balance class, but throughout their careers as chemical engineers.

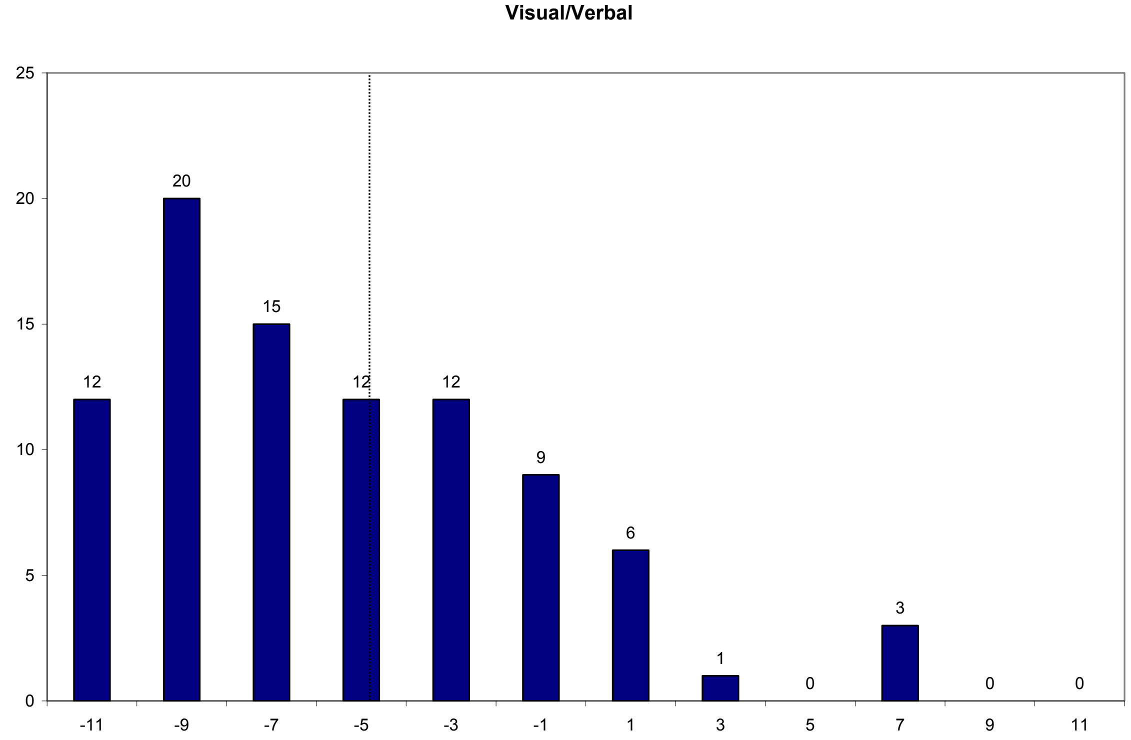

Figure 1. Scoring on Felder/Silverman Inventory of Learning Styles (Visual/Verbal)

Designing a software tool that scaffolds the transition from written to visual material faces a fundamental challenge: how to provide students with enough guidance that they can master the skill, without giving them so much guidance that they cannot perform the transition without the use of the tool? A tool similar to what we were aiming for comes with virtually all process simulation software (ASPEN, HYSYS, PRO/II). In these software packages, the user is presented with a palette of unit operations. These can be dragged and dropped into a worksheet, and then connected with material and/or energy streams to construct a process flow diagram.

In our experience, for a student attempting to learn the basics of chemical engineering, these software packages fail for a number of reasons. First, and foremost, the skills that we seek to build—the ability to develop material and energy balances—are done in the background in these packages. Thus a student using these software packages never develops the necessary problem solving skills. In addition, these packages are intended for use by professionals, and thus contain far more details than can be managed by a student at the time of their first introduction to the discipline.

Tool Development

To build a software tool to address the fundamental problem of mapping a written problem description to a visual representation of that problem, we employed a user-centered design process.[2] Our design process started with the observation that to learn the basics of material and energy balances, one needs to understand only a few generic unit operations. We started with only two: a mixer and a separator. Both of these should have ports on them that would serve as clues to the user that a material stream can be docked to them. In addition, we wanted to make it easy for students to build equations based on the chemical flow diagrams that they created. To that end, we decided to include an equations editor in the software, and to allow users to drag-and-drop elements of chemical flow diagrams into the equation editor.

Following the user-centered design process, we iteratively developed two low fidelity paper prototypes of the software before beginning the implementation of a computer-based tool. Our low fidelity prototypes were constructed as a series of screens that could be manually displayed on the Smartboard™. In these "wizard of oz" studies, introductory chemical engineering students were asked to use the prototype to help them solve the problem presented below. As the students interacted with the prototype, we were able both to observe students' difficulties in translating the written problem into process flow diagrams, and to refine and alter the design of the prototype in response to users' missteps, points of confusion, and comments.

> *Liquid extraction is an operation used to separate the components of a liquid mixture of two or more species. In the simplest case, the mixture contains two components: a solute (A) and a liquid solvent (B). The mixture is contacted in an agitated vessel with a second liquid solvent (C) that has two key properties: A dissolves in it, and B is immiscible or nearly immiscible with it. (For example, B may be water, C a hydrocarbon oil, and A a species that dissolves in both water and oil.) Some of the A transfers from B to C and then the B-rich phase (raffinate) and the C-rich phase (the extract) separate from each other in a settling tank. If the raffinate is then contacted with fresh C in another stage, more A will be transferred from it. This process can be repeated until essentially all of the A has been extracted from the B.*
>
> *Draw a process flow diagram in which acetic acid (A) is extracted from a mixture of acetic acid and water (B) into 1-hexanol (C), a liquid immiscible with water in a single stage. Label each stream with enough values to fully characterize that stream (flow rate, composition, etc.). Provide a numerical value if possible or a symbol for an unknown value (e.g., $\dot{m}$ for a flow rate).*
>
> *The following facts are given:*

a) The acetic acid/water solution enters at a rate of 400 gm/min. The acetic acid compromises 11.5 % of the solution by weight.
b) The extract phase leaving the process contains 9.6 % acetic acid by weight.
c) The raffinate phase leaving the process contains 0.5% acetic acid by weight.

Problem 4.7a, Elementary Principles of Chemical Processes, 3rd Edition, R. M. Felder and R. W. Rousseau, John Wiley and Sons, Inc., 2005

After a total of five pairs of students completed our wizard of oz studies, the design of our software stabilized, and we began implementation of a computer-based version of the environment in the summer of 2007. In order to refine the software further, we conducted a series of usability studies in the fall of 2007. These studies proved to be instrumental in helping us identify and remedy usability problems with the software. Among the important issues identified in our usability studies were the following:

- the need to provide clear visual feedback when certain operations take place (e.g., docking of a stream to a unit operation),
- the need to identify and warn users of problems with incompatible units in equations and chemical streams.
- the need to let users know when they have constructed enough equations to solve for all of the unknowns
- the need to check whether equations are correct with respect to the chemical process diagram that has been drawn, warning users of any inconsistencies.

Current Development of the Software Tool

By the end of the Fall Semester of 2007, our software environment, called ChemProV (Chemical Process Visualizer), was close to being fully developed. Figure 2 shows the computer screen that a student would see immediately after starting ChemProV. Notice that the palette contains just a few basic tools: two process units, a separator and a mixer, a chemical stream tool, and tools for splitting/joining a stream and identifying a subprocess. As currently constructed, the separator tool allows only one inlet while the mixer allows only one outlet. These software constraints prevent students from building invalid diagrams. While this selection of tools and limitations may be too severe for experienced students, we have found them to be appropriate for novices. Indeed, using these operations, one can construct the flow diagrams for many elementary material balance problems commonly encountered in a first semester chemical engineering course.

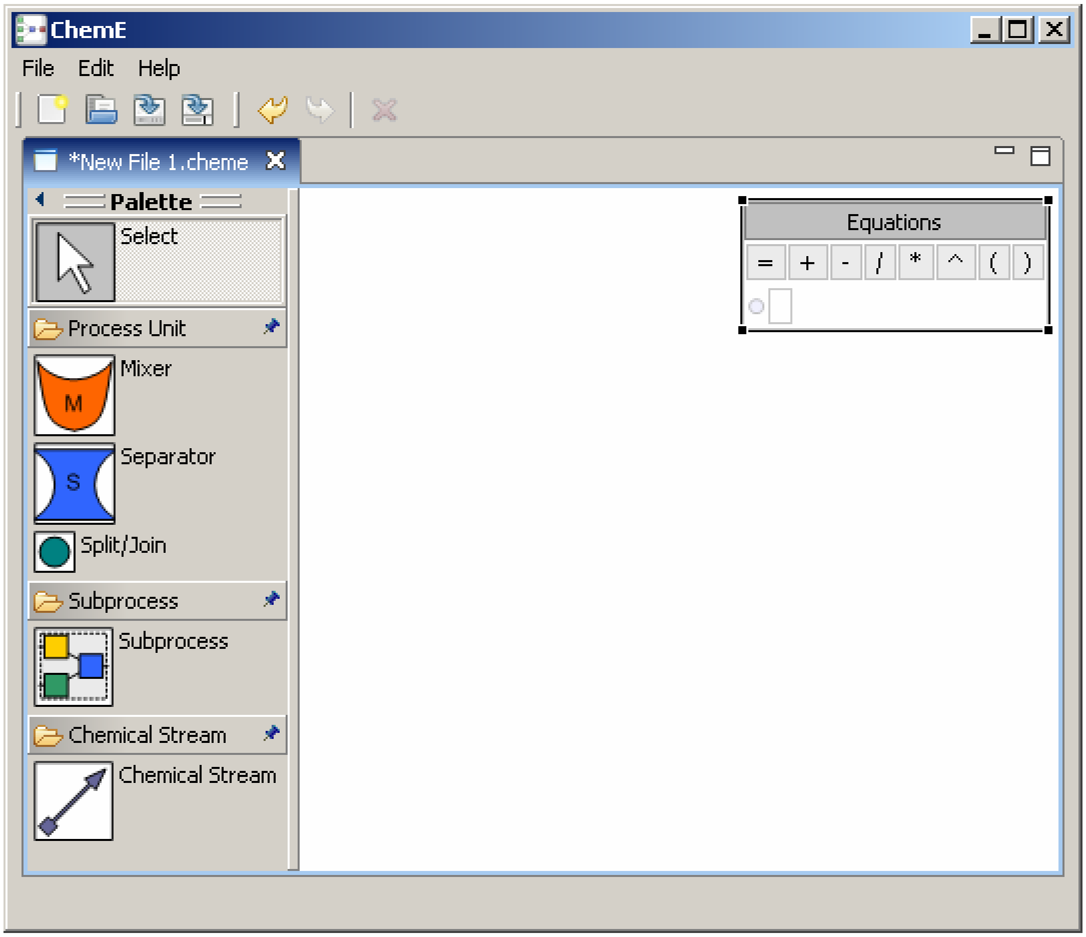

Figure 2. Screenshot of the ChemProV Software

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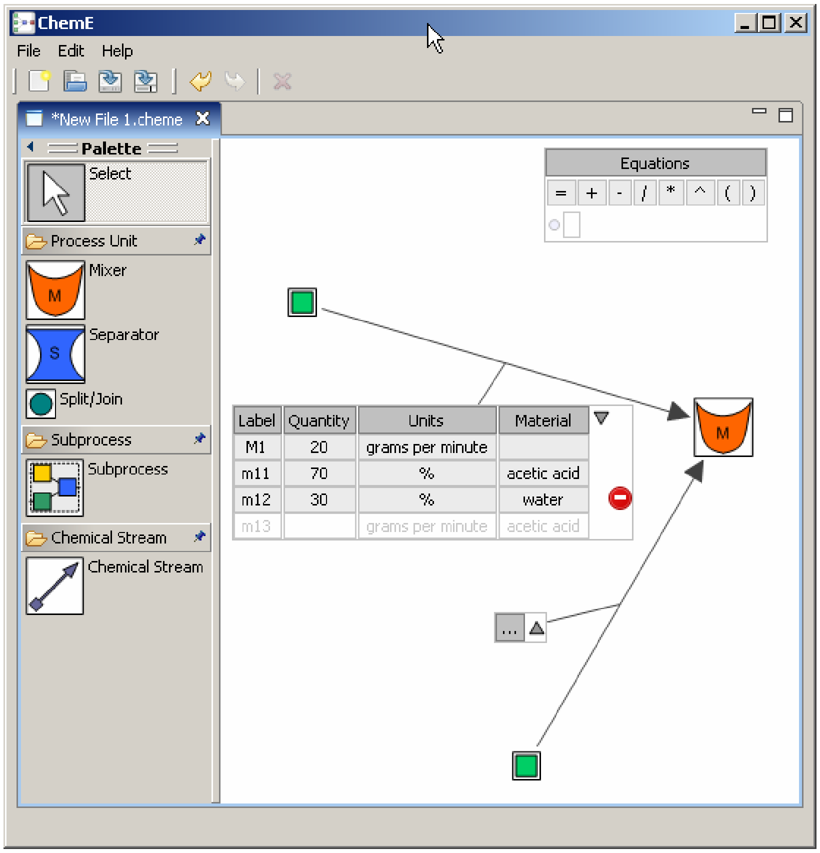
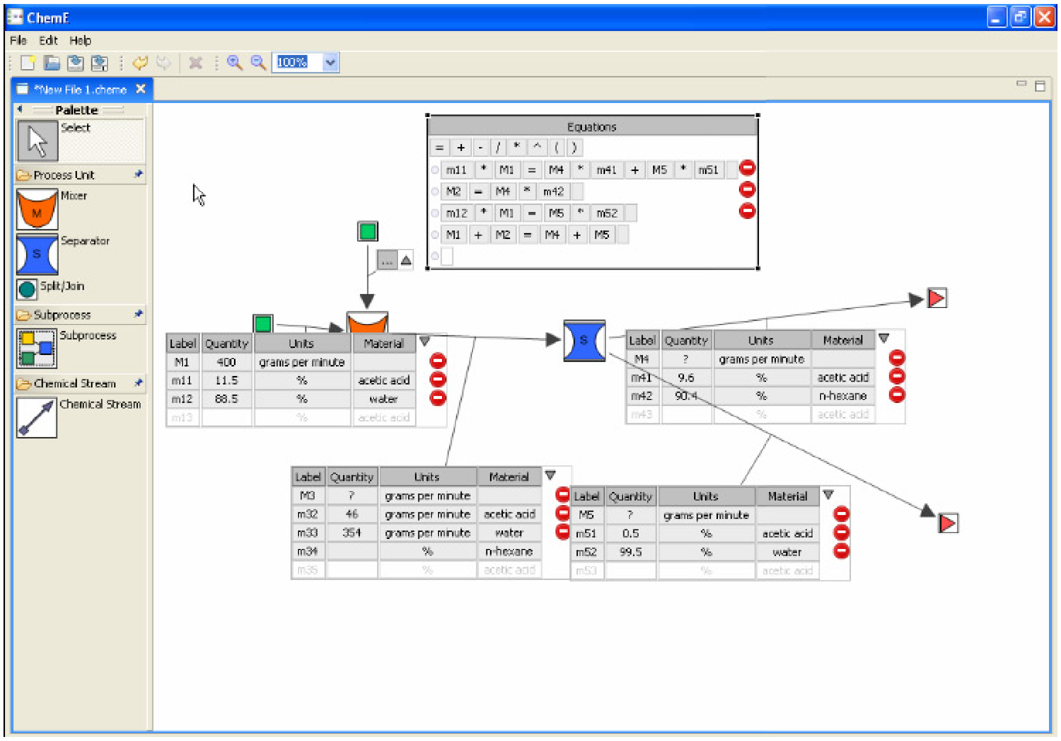
Once a flow diagram has been constructed, the user can expand the "stream tag" associated with each chemical stream to specify the details of the stream (see Figure 3). In a separate equation editor (see top right-hand corner of Figure 2), the user can build equations by dragging-and-dropping elements in the stream tags. This drag-and-drop functionality not only constrains the elements that can appear in equations; it also reinforces the relationships between the chemical flow diagram and the equations. The result of one participant's use of ChemProV to solve the example problem given above is shown in Figure 4.

In sum, there is a major difference between the software we have developed and commercially available simulation packages. In the commercially available packages, the development of the needed balances is done in the background, with no input from the user. In contrast, our ChemProV software provides a set of scaffolds to ease the process of transferring written material into mathematical expressions; however, it leaves the actual development of the balances and solving of the equations totally up to the student, thereby requiring students to practice those important skills.



Label	Quantity	Units	Material
M1	20	grams per minute	
m11	70	%	acetic acid
m12	30	%	water
m13		grams per minute	acetic acid

Figure 3. Use of 'Stream Tag" to specify details of chemical stream



m11 * M1 = M4 * m41 + M5 * m51

M2 = M4 * m42

m12 * M1 = M5 * m52

M1 + M2 = M4 + M5

Label	Quantity	Units	Material
M1	400	grams per minute	
m11	11.5	%	acetic acid
m12	88.5	%	water
m13		%	acetic acid

Label	Quantity	Units	Material
M4	?	grams per minute	
m41	9.6	%	acetic acid
m42	90.4	%	n-hexane
m43		%	acetic acid

Label	Quantity	Units	Material
M3	?	grams per minute	
m32	46	grams per minute	acetic acid
m33	354	grams per minute	water
m34		%	n-hexane
m35		%	acetic acid

Label	Quantity	Units	Material
M5	?	grams per minute	
m51	0.5	%	acetic acid
m52	99.5	%	water
m53		%	acetic acid

Figure 4. Using ChemProV to Solve the Sample Problem: One Participant’s Solution

Status and Future Work

The current version of ChemProV supports the construction of chemical flow diagrams and systems of equations, as illustrated in Figure 4. However, ChemProV in its current form does not yet support three key functionalities that we deem to be critical to its success as an educational tool:

- The ability to check for unit consistency in equations.
- The ability to check whether equations are correct with respect to the chemical flow diagram that has been created.
- The ability to check whether there are a sufficient number of equations to solve for all of the unknown equations.

Once we add the above functionalities to ChemProV and conduct a final round of usability testing, we would like to test our initial hypothesis that the ChemProV software can aid in the development of the skill of transforming written descriptions of material balance problems into graphical representations and ultimately into an appropriate mathematical representation. To that end, we plan to conduct a formal experimental study that compares the ChemProV tool to simple paper-and-pencil—the current "gold standard" medium for solving chemical balance problems. In our within-subjects study, a group of twelve to 20 students recruited from an introductory chemical engineering course will be asked to solve two chemical balance problems that are isomorphic with respect to difficulty: one using the ChemProV tool, and the other using pencil-and-paper. Task and treatment order will be fully counterbalanced in order to guard against order effects.

We will record students' problem solving activities. Their solutions will be evaluated with respect to four dependent measures: time to complete the task, accuracy of the process flow diagram, accuracy of the equations constructed, and correctness of the values obtained. In addition, we will review the recordings of students' activities in order to identify qualitatively any differences in the problem-solving processes promoted by the two media. We hope that our results will shed light on the impact that the use of the software has on the skill development in the students, ultimately providing an empirical foundation for an improved introductory chemical engineering curriculum that increases retention by addressing the problem that we have found to be most troublesome for introductory students: that of translating a written problem description into visual form.

[1] R.M. Felder and L.K. Silverman, "Learning and Teaching Styles in Engineering Education," *Engr. Education, 78*(7), 674-681 (1988).

[2] D. Norman and S. Draper, User-centered system design, Lawrence Erlbaum Assoc., Mahwah, NJ, (1986).