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Promoting Metacognition through Writing Exercises in Chemical Engineering

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Abstract

A high-level goal of all disciplines is for students to develop the capacity for lifelong learning. To develop the capacity of lifelong learning, the overall educative environment should not only include guidance through specific material or actions/experiences to own the material, but additionally students should immerse into self-knowledge. Metacognition has been described as reflection about actions[1]. It has also been defined by connection prior knowledge with the learning of a new task and what are the skills required to do so[2]. Reflection exercises include introspection on your own knowledge, ability, motivation by answering specific questions[3]. The idea of "writing to learn" has been investigated in education courses[4], and preliminary findings suggest that there may be no change in student success in the course in which it is implemented, but that students develop an appreciation for self-reflective writing on top of the usual course goals. In this paper we will present the effects of reflective writing in a technical setting. This study includes two chemical engineering core courses. The first is chemical engineering thermodynamics, that includes material perceived as seemingly unintuitive, making it a challenge for novices to understand. At UMBC, student feedback for the past several years included complaints about having to "know" too many equations, the existence of an apparent disconnect between theory and real world examples, and a textbook they do not enjoy using. This led us to introduce reflective writing in thermodynamics (fall of 2012) through weekly reflection paragraphs were students wrote a 200 word reflection paragraph based on questions that prompted them to think about: what they thought they learned, how they learned, what was their inspiration to learn, and how reflective writing helped them through the process. We then evaluated the quality of reflection paragraphs and looked into any relationships with course grades. We found a statistically significant correlation between this quality and final course grades[5]. For the spring of 2013, we continued the promotion of metacognition in chemical process control and safety, another undergraduate chemical engineering core course using a modified assignment. Students were given one technical problem and then assigned the following four activities each week: a) solve the problem, b) personalize the problem, c) integrate problem with other chemical engineering courses, and d) think of a related problem. In this paper we will present the analysis of this valuable data set of student reflections as we seek to more deeply analyze students reflective writing in terms of (1) the specific technical content discussed and (2) the way the student engaged with the content, its connections to other ideas, and their own understanding ("thinking about thinking," or metacognition).

Introduction

Chemical engineering thermodynamics and chemical process control and safety are two required courses taught in the fall and spring of the junior year, respectively. The prerequisites for thermodynamics include material and energy balances, organic chemistry, and multivariable calculus, while the prerequisites for controls and safety are numerical methods, differential equations, thermodynamics, and fluid mechanics. Students often criticize these two courses as being more abstract and less intuitive than the other three required courses in the junior year: fluid mechanics, heat and mass transfer, and chemical reaction kinetics. There are complaints that it is harder to connect theory and real world examples, that there is too much math involved in the courses, and in the case of thermodynamics, dislike of the textbook by Smith, Van Ness, and Abbott.

Starting in the fall of 2012 with thermodynamics and then continuing into the spring of 2013 with process control and safety, we restructured both courses with two major goals in mind: (1) actively reading textbooks and references, and (2) reflecting on learning and self-assessing learning techniques.

In previous years, thermodynamics consisted of a lecture followed by solving problems in groups. In 2012, students began class with a sort activity related to the required reading for that day, followed by a brief, not-graded "concept clarity" written assignment, then class problem solving based on the students' feedback. Instead of having 7-10 homework problems per week, students did just 3 problems plus one reflection assignment per week. In process control and safety, the course previously had three projects as the only assignments other than exams. In 2013, the projects were modified to include weekly status updates in which students were required to solve part of the project, then explain how their work related to examples outside of class.

There were 53 students in thermodynamics in 2012 and 38 students in process control and safety in 2013. There were 36 students who took both courses in these semesters. As self-reported using CATME, this set of students is 69% male and 31% female, with 50% White, 25% Asian, 19% Black, 3% Hispanic, and 3% Native American. For this population, we will compare student performance on reflection assignments versus exams and final grades within and across both courses. The students who did not take both courses in sequence are excluded from this comparison.

Methods

In thermodynamics, reflection paragraphs were worth 6% of the total course grade. Students submitted up to twelve reflections through the semester, with the first three weeks' assignments used not towards grading but instead to get students acclimated to the expectations of this style of assignments. Of the other nine weeks, the students six highest-scoring efforts counted toward the grade. Students were given the same six questions every week, and asked to apply three of them to their choice of learning activity: homework problems, reading, or exams. The six questions are

1) What did you learn? How do you know you learned it?
2) What components were easy? Why?
3) What inspired you to learn? Why?
4) Why was the experience significant? Why?
5) What there a particular piece of thinking or realization that provided a change of perspective?
6) How does reflection help your learning?

In process control and safety, the weekly status updates comprised 20% of the total course grade (but this 20% is divided between technical work, the first prompt below, and reflection work, the other three prompts). Students submitted up to fourteen weekly updates through the semester, and the ten highest-scoring efforts counted toward the course grade. Students were given the same four prompts each week and required to apply them to the project component due that week. The four prompts are to

1) Solve the project component (or otherwise appropriately address the prompt) by clearly explaining your strategy in enough detail that no "steps" are skipped.

2) Personalize the problem (or prompt) by connecting it to your own life outside the course.
3) Integrate the prompt with your understanding from other chemical engineering courses.
4) Think of a related problem that you can now solve (or if it is a prompt, think of a related prompt you can now discuss). Clearly explain the problem (prompt) and how it is different from the original problem (or prompt). Clearly explain the solution method and how it is different from the original problem (or prompt).[6]

Rubrics for the assignments are given in the appendix.

Results and Discussion

In thermodynamics, the scores on reflection activities are compared against exam performance in Figure 1, below. The R^2 value for this data is 0.0094. There is no statistically significant correlation between the reflection grade and exam grades among the 36 students considered here.

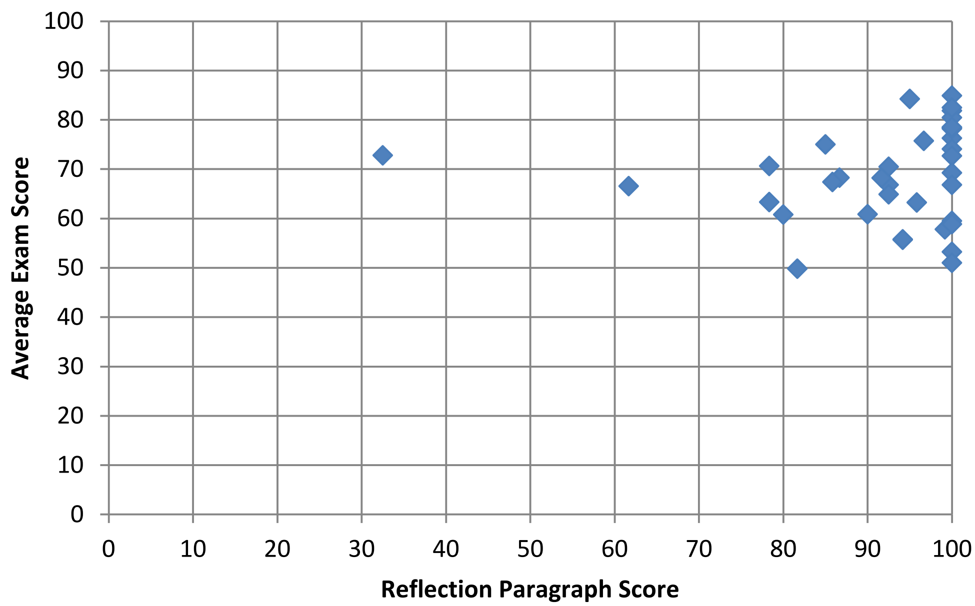

Figure 1. No Correlation between Student Reflection Grades and Exam Performance in Thermodynamics

The picture is slightly different when considering overall course grade, which includes homework and projects grades. For the 36 students presented in Figure 2, below, the R^2 value is 0.14, which is too weak to claim that reflection performance can predict course performance, but it can be claimed that there is a slight positive correlation between the data (α=0.05). This correlation is more pronounced when considering the 17 students who did not take process control the next semester; of the 53 students in thermodynamics, 16 submitted five or fewer reflection assignments; only one student from this population passed the course and took process control in the subsequent semester. A more thorough consideration of the reflection assignment in thermodynamics can be found in the literature.[5]

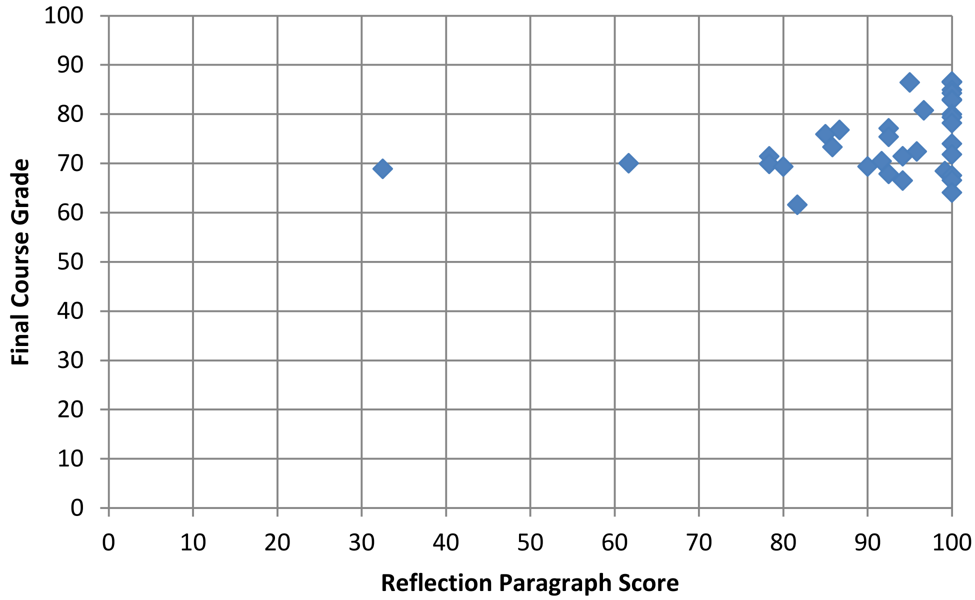

Figure 2. Weak Positive Correlation between Student Reflection Grades and Overall Performance in Thermodynamics

Figure 3 shows that there is a much stronger correlation between reflection performance and exam performance in the process control course, with an R^2 value of 0.26. While this value is too small to allow us to predict performance based on reflection assignments, there is enough evidence to refute the possibility of no correlation ($\alpha<0.01$).

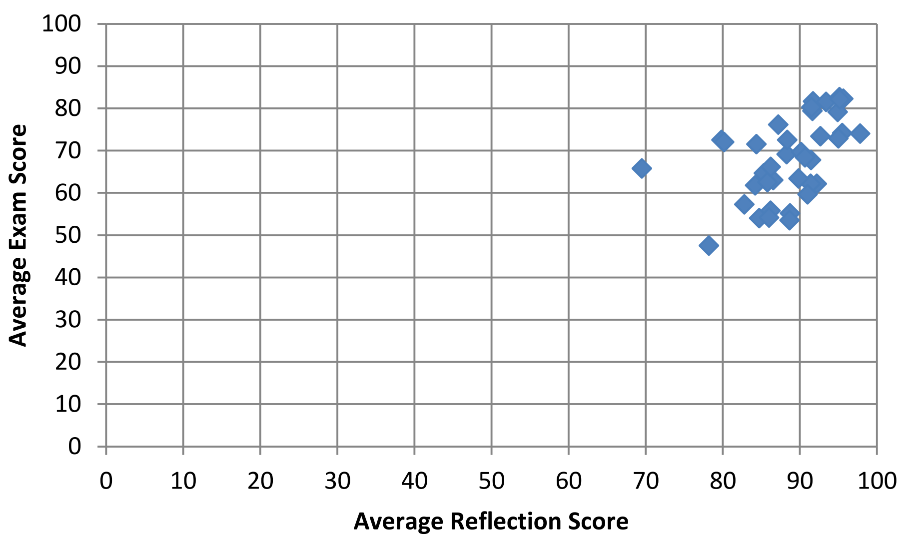

Figure 3. Weak Positive Correlation between Student Reflection Grades and Exam Performance in Process Control

Given that reflection writing and homework was worth 20% of the grade in process control, it is less surprising that there is a statistically significant positive correlation between reflection grades and final course grades, as shown in Figure 4. Here, the R^2 value of 0.41 ensures a positive correlation between the two measures ($\alpha<0.01$).

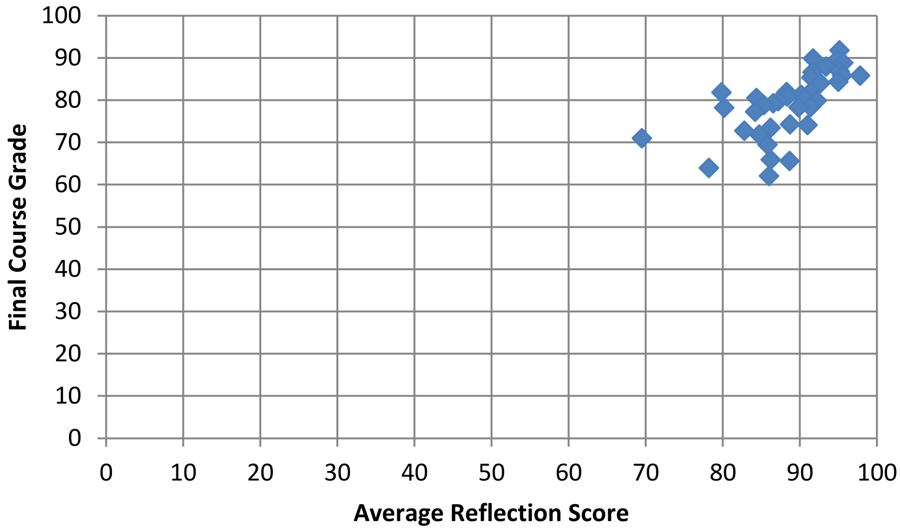

Figure 4. Positive Correlation between Student Reflection Grades and Overall Performance in Process Control

Of more interest numerically is a comparison between the two courses. Both reflection (Figure 5) and overall (Figure 6) scores in thermodynamics and process control show positive linear correlation with R^2 values of 0.37 and 0.47, respectively. The probability of a negative correlation is less than $\alpha=10^{-4}$.

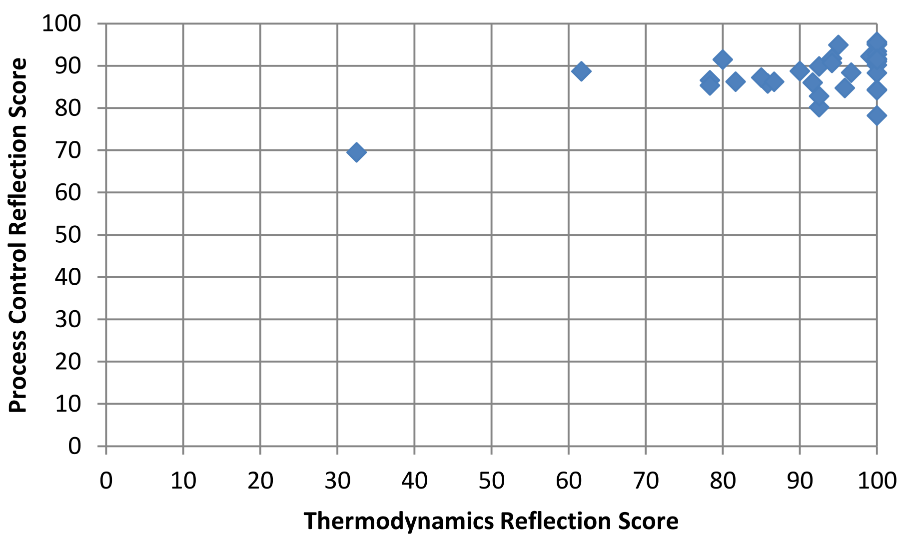

Figure 5. Positive Correlation between Student Reflection Grades in Thermodynamics and Process Control

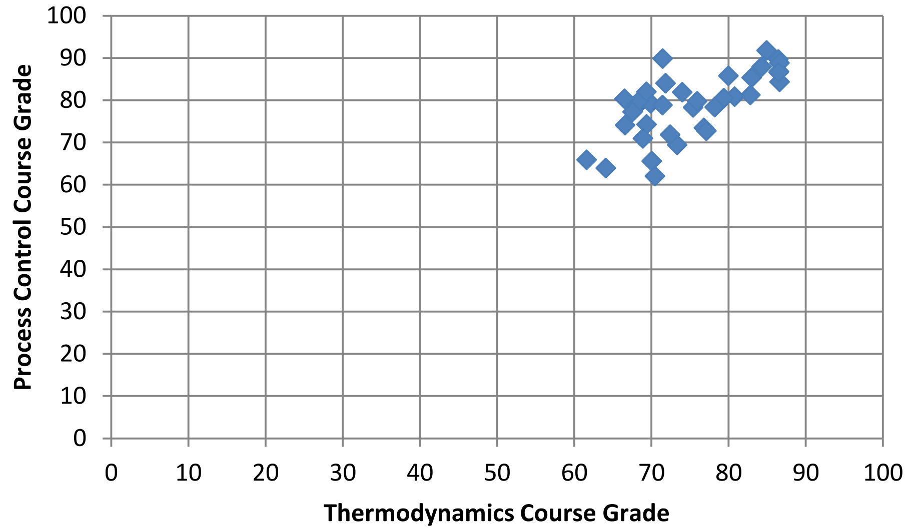

Figure 6. Positive Correlation between Overall Grades in Thermodynamics and Process Control

Summary

The objective of the study is to improve conceptual understanding of the material through writing exercises (reflection paragraphs and problems memos). As shown in the results section grades in the classes (thermodynamics and process control) are part of the measure of the expected conceptual understanding, which is complemented by self-assessment evaluations. Ultimately tracking student performance as they move through the program until graduation could provide an indirect effectiveness measure.

Our approach provides a platform for students to reflect upon their own learning, course experience, or at least a second exposure to class material. These results are the beginning of our efforts to empower students with the responsibility of their own learning by making them think and write about their practice as they gain new knowledge. Our results are yet to show a conclusive correlation between exam performance or final course grade with the ability to reflect. However, we believe that through this practice students will gain experience in self – assessing their knowledge and comprehension of fundamentals. We notice that the first exposure in thermodynamics to reflection gives us less of a correlation compared to what happened in process control, it begs the question: could one semester of reflection in Thermodynamics places student on higher ground for academic achievement when they start Process Control?

We continued our efforts in the thermodynamics in the Fall of 2013 and are currently doing the same in Process Control Spring 2014 and have ongoing student work data analysis.

Examples of Student Work

In this section we provide some illustrative examples of student work. We have chosen two examples from both courses. In both cases the first examples comes from the beginning of the semester and the second at the end of the semester. The examples are exactly taken from the documents the students submitted. These examples exemplify the type of thinking the students are doing by combining writing and engineering exercises.

Example 1 Thermodynamics

2012 ENCH 300 *Reflection*
Name:
HW: 4
Readings: 125-128 133-144
Problems, Examples: About the problem on Tuesday, I do it another way. For Q+W=ΔU,
$\Delta U=\int_{T1}^{T2} Cv dT = \int_{T1}^{T2} (Cp - R) dT = R\int_{T1}^{T2} \left(\frac{Cp}{R} - 1\right) dT$, from PV=RT and $PV^{1.55}=K$ (K is a constant), we can get $V^{0.55}=K/RT$, $V^{-0.55}=RT/K$, $P=K/V^{1.55}$;
Also since $V^{-1.55}=-\frac{1}{0.55}d(V^{-0.55})$, so $W=-\int PdV=\int KV^{-1.55}dV = \frac{1}{0.55} R(T_2-T_1)$, Q= ΔU-W

Questions: (Bold the questions you are answering)
1) What did you learn? How do you know you learned it?
2) What components were easy? Why?
3) What inspired you to learn? Why?
4) Why was the experience significant? Why?
5) What there a particular piece of thinking or realization that provided a change of perspective?
6) How does reflection help your learning?

Paragraph: (Include your paragraph – make sure it does not exceed the maximum number of words allowed, 200)

I learned how to calculate the heat (usually equals ΔH) in a chemical reaction. Because reactions usually don't occur at 298.15K and we can't use the standard heats of formation directly, we usually need to devise a path for purpose of calculation. This is possible because ΔH is a state function and don't depend on the path. We can proceed from reactants at initial temperature to 298.15K at standard state, get the ΔHR and then with heat-of-formation data from Table C.4, we can get the ΔH298. After that, we make the products go to final temperature and can also get a ΔHP. For the calculation of ΔHR and ΔHP, we can use what we learned before; just the heat capacity here refers to "mean heat capacity". It is a function of temperature; we can find relative data from Table C.1/2/3. The idea of devising a path is very important, if we can't get the result directly and maybe we will need to turn to another way and from what we already know to get the final answer. The reflection can help me summarize these steps and give me a general thought for the calculation of total heat in a reaction.

Self grade based on the rubric below, bold your selection.

Requirements	(20 pts)	(15 pts)	(10 pts)	(5 pts)	(0 pts)
Reflection Paragraph	A thoughtful narrative answering the 3 questions, relating the	**Quality narrative – mixing thoughts and facts; answering 3**	Stating facts, answering 3 questions.	Poor quality analysis and did not answer all required questions.	Not taking the exercise seriously.

	material in the week.	**questions.**			

If you believe you deserve points in between the sections ie. 12 or 9, briefly explain your reasoning (does not count as part of your 200 words allowed).

Example 2 Thermodynamics

2012 ENCH 300 ***Reflection***
Name:
HW: 12
Readings: 498-502 510-511, 514-515, 517-518
Problems, Examples:

- Develop expressions for the mole fractions of reacting species (as functions of the reaction coordinate) for the given reaction (Homework Problem, Worked Independently)
- Analyzing the formation of "synthesis gas," by discussing the effects of varying parameters (i.e. pressure & temperature) and determining the molar fractions and feed composition of the reacting species (Class Problem, Worked with Peers)
- Estimating the equilibrium of a gaseous mixture, in regards to the molar fractions/composition and the concept of fugacity (Discussion Problem, Worked with Teacher's Assistant)

Questions:

1) **What did you learn? How do you know you learned it?**
2) **What components were easy? Why?**
3) What inspired you to learn? Why?
4) Why was the experience significant? Why?
5) What there a particular piece of thinking or realization that provided a change of perspective?
6) **How does reflection help your learning?**

Paragraph:
After taking the first two exams and putting effort in improving my studying habits, I thought there was nothing to worry about. However, I soon realized that I wasn't as prepared for the third exam as I had anticipated. Regardless of my performance on the test, I felt that there were several components that were easy in this exam. While I didn't finish completing the table, I knew the steps to determining the missing values. With at least two values from the table (ex. pressure and temperature), one can use the attached pressure-enthalpy diagram to find the remaining parameters (specific entropy, physical state, etc.) at any given point of the process. Moreover, in order to complete the table, one has to have a good understanding of the assumptions that can be made for each type of equipment, such as constant pressure through a heat exchanger. Likewise, there were a few concepts that I had forgotten not only from the material I learned in this class (i.e. isentropic calculations), but also from material in the past engineering courses (i.e. mass balance application). Reflection has made me realize the importance of reviewing both old and new concepts to approach a problem.

Requirements	(20 pts)	(15 pts)	(10 pts)	(5 pts)	(0 pts)
Reflection Paragraph	A thoughtful narrative answering the 3 questions, relating the material in the week.	Quality narrative – mixing thoughts and facts; answering 3 questions.	Stating facts, answering 3 questions.	Poor quality analysis and did not answer all required questions.	Not taking the exercise seriously.

18 points: I think that my reflection paragraph goes a little beyond the requirements of the 15 pt grade. I attempted to discuss my thoughts on the recent exam.

Example 1 Process Control

Prompt: In class, we found the optimal reactor temperature for a continuous stirred tank reactor with the series reaction A→B→C. Rework this problem for the case in which the value of chemical C is actually negative – that is, -$0.20/gmol. What could a negative value represent?

Relevant parameters:

rate of reaction 1: r1=k1CAexp(-E1/RT)
rate of reaction 2: r2=k2CBexp(-E2/RT)
reaction 1 rate constant: k1=3.8604×106 Hz
reaction 2 rate constant: k2=1.8628×1013 Hz
activation energy for reaction 1: E1/R=5033 K
activation energy for reaction 2: E2/R=10065 K
volumetric feed rate (pure A): FV = 10 L/s
reactor volume: Vr=100 L
initial concentration of A in feed: CA0 = 1.0 M
value of pure A: VAF = $0.15/gmol
value of A exiting reactor: VA = $0.10/gmol
value of B exiting reactor: VB=$0.50/gmol
value of C exiting reactor: VC=-$0.20/gmol

Student submission:

Memorandum

To:
From:
Date: 8 February 2013
Subject: Optimization Problems

Solve:
First of all, the value of C could be negative because the separation process would be prohibitively expensive or the environmental process is expensive.

I used Excel Solver for this problem. I set up three mass transfer equations with the typical set-up of:
0=in-out+gen-cons. I used this for A, B, and C. For generation and consumption, I used rate equations, with the rate constant dependent on temperature, based on the Arrhenius equation. All needed constants were provided. I also set up a profit equation. This was based on the value of A, B, and C and their amounts entering and exiting the system. I wanted Solver to adjust temperature to find a maximum profit, with the constraints that the mass balances equaled zero. However, this didn't work since it also needed to change the outgoing concentrations, so it ended up being 4 equations with 4 variables, and the maximum profit was not necessarily based on an optimum temperature. Therefore (without sufficient time to redo it in Matlab), I made the assumption that it should minimize concentration of C to maximize profit. This allowed Solver to give a sensible answer, which is hopefully also the actual maximum profit. This gave:

T=	289
Ca=	0.48659283
Cb=	0.45050109
Cc=	0.06290609

And a profit of $1.11/s.

The excel sheet is included below:

A:	Ca0*Fv-CaFv-kCaV		=	1.59872E-14
B:	(-Cb*Fv+kCaFv-kCbV)		=	-4.996E-15
C:	(-CcFv+kCbV)		=	-1.07692E14
T=	289	kCaV=	5.134071709	
Ca=	0.48659283	kCbV=	0.629060851	
Cb=	0.45050109			
Cc=	0.06290609			
k1=	3860400			
k2=	1.8628E+13			
E1/R=	5033			
E2/R=	10065			
Fv=	10			
V=	100			
Ca0=	1			
Vaf=	0.15			
Va=	0.1			
Vb=	0.5			
Vc=	-0.2			
Profit=	Fv[CaVa+CbVb+CcVc]-Fv[Ca0Va]			
Profit=	1.11328609			

Personalize:
This question has application to my personal life outside the course. There are often financial considerations, in which there are multiple factors at play. For example, I have gone ice skating a

couple of times recently. The ice skating rink charges for using the rink and for skate rentals. The question is if it is cheaper for me to buy skates. This way, every time, I go I don't have to pay for skate rentals. Another idea is that I could potentially sell the used skates when I am done with them. They will obviously depreciate in value. In this way, it is similar to the original prompt, where initial A costs more. In this case, there is also a time factor- as it dependent on the frequency of the skating.

Integrate:
This prompt reminded me of several chemical engineering courses that I have taken. Most clearly, this question (or the solution to it) relied on mass flows that were clearly delineated in the Kinetics class. This was helpful, as setting up the mass balances was review and made it easier. In addition, the economic aspect was reminiscent of the economic analyses performed on chemical plants in senior design. However, this is a more microscopic view-looking at just one process and trying to optimize it. This optimization aspect reminded me of Matlab exercises in ENCH 225 and Excel Solver that was frequently used in Separations courses. I did in fact try to use Excel Solver to solve this problem, but in retrospect, it may have been a better idea to use Matlab.

Think:
A related problem would be if reactant A has two pathways leading to either B or C. Also, each reaction rate could be a different order of kinetics. This would lead to different mass balance equations with different reaction rates, now one of them could be to the first order and one to the second order. With the reaction going to either B or C, it would also simplify the problem, such that perhaps the reaction could be manipulated to give solely the more desired product. In solving this problem, I would first check if this short-cut can be utilized. If not, the I would set it up similarly to the original prompt, but with the different order reaction rates.

Example 2 Process Control

Prompt: Write a Hazards and Operability study for the case of baking a cake from scratch. Consider three "units" in your analysis: the bowl in which the batter is prepared, the pan into which the batter is poured, and the oven in which the cake is baked. You should easily be able to come up with 30 possible causes/corrections of deviations across these three units.

Student submission:

Memorandum

To:
From:
Date: 05 May 2013
Subject: SPIT #13 HazOp Study.

SOLVE:

Item	Node	Parameters	Deviation	Causes	Consequence	Action
1	Bowl	Mixing	No	Not enough time	No batter, pieces stuck to	Re-mix the starting

					the bowl	components
2			Low	Do not have appropriate mixer	Inconsistent batter	Re-mix the starting materials for longer period of time
3			High	Mixing too long	Cake does not rise	Create new batter mixture
4		Ingredients	No	Did not buy	No cake	Buy supplies
5			Low	Not enough $	Not tasty cake	Have adequate $
6			High	Worked all week	Wasting product	Make a shopping list
7			Other than	Wrong ingredients	Cake does not taste “right”	Buy correct ingredients
8		Settling	No	Not enough time	Batter is not ready	Cake does not “come up”
9			Low	Hungry	Batter barely rises	Leave the batter to rise
10			High	Forgot about it in the fridge	Batter is too cold / frozen	Uncooked Cake
1	Pan	Greasing	No	No grease oil	Cake burned on the bottom	Scrape off burned cake
2			Low	Not enough oil to fully coat the pan	Cake burned in some spots on the bottom	Gently try to pry off the cake without braking it
3			Other than	Using low smoke point grease	Smoke in the kitchen	Stop baking or air out the kitchen
4		Temperature	High	Right out of the oven	Burned hands	Use heat resistant gloves
5			Low	Did not set the oven on the correct temperature	The cake is not cooked all the way through	Try cooking for a little longer
6			Other than	Not correct temperature	The cake does not taste “right”	Scrap start all over
7		Shape	Other than	Did not have a “correct” pan	Not the “expected” shape of the cake	Cut up the cake and reshape
8			High	Pan too deep	Difficult to take out the cake	Cut up and carefully remove
9			Low	Pan with low borders	Batter overflows	Cake burns in the oven
10			No	Surface is not Teflon	Impossible to remove the cake because it got stuck to the	Scrape everything out

					bottom	
1	Oven	Power	High	Not calibrated to the correct temperatures on the display	Cake burns	Set to a lower temperature when baking
2			Low	Not calibrated to the correct temperatures on the display	Cake isn't cooked	Set to a higher temperature when baking
3			Sooner than	Power shuts off before the timer runs out during baking	Cake isn't cooked	Make few smaller cakes
4		Heating coils	No	One of the coils is broken	Cake isn't cooked all the way through	Replace the broken coil
5			High	Do not loose heat quick enough	Burned hands when getting the pan	Pull the cake out horizontally when taking out the cake
6			No	Coils are dirty	Smoke in the kitchen	Clean the Oven
7		Trays	Low	Too close to the bottom coil	Cake always burns on the bottom	Try putting on the middle tray and increasing the baking temperature
8			Other than	Trays are immovable	Cake cannot be crispy on top without burning	Try putting another pan under the baking pan
9			High	Trays are too close to the top coil	The cake is always burned and not cooked on the bottom	Set on the lowest tray and increase the temperature
10			More	Trays periodically fall of the rails	Multiple burns and cake on the floor	Be careful when putting pans on the trays

PERSONALISE: I do not bake but I do have an oven that I use extensively throughout the week. Everything that I have mentioned in this table came from the oven that I use. The temperature inside the oven is always much higher than what the display shows. The trays inside are unevenly spaced and food either burns on the top or the bottom. Coils inside the oven remain hot for a very long time and if I do not reach directly into the oven I always burn my hands. Also I have had quite a few accidents with mixing bowls. One time after I left the bowl in the freezer to settle the doe it cracked as soon as I took it. Many plastic bowls as well as having a nonstick inside surface also have a very slippery outside surface. When trying to mix something in the bowl it is very important to have a towel underneath it or some sticky rubbery surface otherwise the bowl and the doe usually end up on the floor.

INTEGRATE: During our other ENCH course we are not too involved with safety and figuring out different permutations that can happen during a process. This table gives a good starting point to brainstorm a system so as to make it as safe as possible. One of the previous' SPITS dealt with an experimental apparatus that is used in ENCH 225 laboratory. A HazOp table could have been constructed to figure out all the possible adverse events that could happen during that laboratory.

THINK: Periodically I compete in different sport events and competition is a very valuable tool to really highlight your own weaknesses. In a sense competitions are like exams and all weaknesses come out to the surface. Usually before the competition I create a map of things that I want to happen, things that can go wrong, and my "escape plan". In a way my map is very similar to the HazOp table where I try to figure out exactly what I want to happen, what can go wrong before and during the competition, and what can be done to prevent or avoid a negative event from happening. For instance it is important to not be hungry but also eating too much food can cause sluggishness. It is very advantageous to know exactly how much food you need to consume before and during the event to perform at the optimum capacity. This analogy loosely resembles the HazOp table where we take an element of a process and break it down to how things can go wrong, the consequences, and what actions can be taken to fix the undesirable results.

Next Steps

As mentioned before we continued our efforts in the Fall of 2013 in Thermodynamics and currently in Process Control this Spring. We have recently been awarded an in-house grant to begin textual analysis of student submissions for assignments in both courses. Preliminary work in coding the content of the thermodynamics reflections has been previously presented.[3] The goal of this textual analysis is to determine whether students who are most successful at reflection, exams, or overall have any trends in topics or vocabulary in their writing. Preliminary results of this analysis should be ready for the June conference.

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[7] J. Zubizarreta, The Learning Portfolio: Reflective Practice for Improving Student Learning, San Francisco, CA: Jossey-Bass, 2009.

Appendix

Process Control Rubric

Criterion	Possible Points	Characteristics of a very good response (80-100% of possible points)	Characteristics of an acceptable response (50-70% of possible points)	Characteristics of a poor response (20-40% of possible points)
Solution	10	All parts of prompt are addressed and all technical content is complete and accurate, with perhaps some minor error in transcription or computation.	Most to all parts of prompt are addressed. Up to one significant technical error.	Some to all parts of prompt are addressed. More than one significant technical errors.
Personalization	10	Connection between prompt and application to personal life outside of course is clearly considered, showing evidence of serious thought and effort.	Connection between prompt and application to personal life outside of course is mostly clearly considered or somewhat trivial.	Connection between prompt and application to personal life outside of course is unclear, not well discussed, and/or trivial.
Integration	10	Connection between prompt and application to chemical engineering knowledge is clearly considered, showing evidence of serious thought and effort.	Connection between prompt and application to chemical engineering knowledge is mostly clearly considered or somewhat trivial.	Connection between prompt and application to chemical engineering knowledge is unclear, not well discussed, and/or trivial.
Thought	10	Proposed prompt or problem is clearly related to the original prompt, includes an accurate discussion of the solution or solution method, displays further understanding of the course material.	Proposed prompt or problem is missing one of the three qualities expressed at left: clear relation to original prompt, accurate solution discussion, display of understanding.	Proposed prompt or problem is missing two of the three qualities expressed at left: clear relation to original prompt, accurate solution discussion, display of understanding.
Communication	10	Memo is properly formatted in terms of font, layout, captioning, and length, uses correct, clear, and appropriate technical English, is professional in tone and has few to no typographical errors.	Some errors in formatting, usage, and grammar – enough to be distracting while reading.	Several errors in formatting, usage, and grammar – enough to be confusing to read and understand.