A Chemical Engineering Course for Liberal Arts Students
INDIGO: A WORLD OF BLUES

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Dip white fabric in the muddy-colored indigo dye vat, and the cloth emerges green, then slowly turns azure, cobalt, or sapphire before your eyes. The chemistry behind this reaction will be revealed—and practiced—in this course. This mysterious dye has an intriguing history, and we will study its societal and environmental impact from antiquity to the present. We will explore the use of indigo by different cultures, and each student will have the opportunity to replicate one of the techniques used to dye fabric with indigo. We will learn about the equipment used in producing indigo dye, and the three sources of indigo: synthetic, natural, and biosynthetic. The course will culminate with the design of a new indigo production facility. Students will need to determine what type of indigo to produce, the location of the facility (i.e., rural or populated area? how will it impact the population?), what environmental concerns to consider, and other aspects of a new facility.

This course description was provided to all sophomore students at Lafayette College and 19 students chose to enroll in the course. Several of the students had not taken any laboratory science courses in college and over a quarter had not had a mathematics course since high school. About half were chemical engineering majors. How does one teach process engineering to such a diverse group?

BACKGROUND INFORMATION

As the National Academy of Engineering and others have written, our society is driven by technology, and everyone should understand something about engineering.[1,2] "Everyone" includes liberal arts students. The liberal arts education was created to provide general knowledge, and to help students develop rational thought and intellectual capabilities. It included courses in literature, languages, philosophy, history, mathematics, and science. As society has become more dependent on technology, it is more important that citizens have some understanding of this technology in order to make wise decisions.[1] A well-educated citizen should not only have a background in the traditional liberal arts courses, but should also have some technical literacy. In fact, the president of Smith College stated that "the study of science and engineering should enrich and deepen the education of historians and poets."[3]

This is the logic behind the Values and Science/Technology (VaST) requirement at Lafayette College. Every sophomore is required to take a VaST course, chosen from a list of about 25 options. Each VaST course covers a different topic, but all present some aspect of science and/or technology interacting with a variety of other disciplines. The courses also address ethical or values-oriented concerns and include processed writing.[4] The VaST course has been required for many years, and is considered to be a fundamental component of the Lafayette students' education.

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Other institutions agree that engineering should be a component of the liberal arts education. Union College has embraced the ideas with its Converging Technologies curriculum, which integrates the arts, humanities, and sciences with engineering.[5] A review of technical literacy courses for non-engineering students found that courses are offered at many institutions, with a variety of names.[6] Many individuals have developed these courses and obtained encouraging results. Common course goals include providing an understanding of what engineering is, describing the engineering process, and helping students develop the ability to make informed decisions about technological issues facing society.

The challenge to engineers is to encourage students to enroll in the courses, and to make the information accessible to the students. Therefore, the courses for non-engineers are often developed around a theme or concept already familiar to students, such as robotics,[7] "How Things Work" dissection projects,[8] simple building projects,[9] or biological systems.[10] Some hands-on projects reach out to the community along with discussion questions for technical, ethical, and societal issues.[11] While these courses are interesting and exciting, chemical engineering examples are rare.

In his review of engineering for non-engineers courses, Krupczak[12] classified the courses into four types:

- *The Technology Survey Course*
- *The Technology Focus or Topics Course*
- *The Technology Creation Course (Design)*
- *The Technology Critique, Assess, Reflect, or Connect Course*

The paper also provides a framework for evaluating new courses. The VaST course described in this paper meets the requirements for a "Technology Focus or Topics Course." It focuses on one area of technology, it includes a laboratory, and social and historical aspects are considered.

CHEMICAL ENGINEERING FOR NON-ENGINEERS

This VaST course, open to all sophomores, needed to be accessible to those with a background that included little chemistry and no calculus. The course would expose the students to some broad concepts and principles that would help them have a better understanding of what engineering is, but not prepare them to practice engineering.

For example, after completing the course, I wanted students to realize that pumps have limitations, to know the purpose of filtration, and to learn that some chemical reactions result in colored substances. They would understand why blue jeans fade, but other fabrics don't. They would not be able to mathematically model a process, but they would be able to put unit operations into a useful order to produce a product. By learning this, the students might change their view of chemical plants, and have a better understanding of environmental and safety concerns.

Thus, in developing the course, I began with the following learning objectives:

By the end of the semester, students will be able to:

1. *Use multiple perspectives to answer important questions about a complicated problem*
2. *Explain the chemical differences between dyeing with indigo and dyeing with other natural dyes*
3. *Create a process flow diagram, identify major process equipment, and explain briefly how it works*
4. *Write a technically competent laboratory report on the processes studied*
5. *Show an understanding of what a professional is and the ethical responsibilities of a professional*

Experiential learning was an important part of the course concept, so I developed many active learning and laboratory exercises for the class. This paper presents descriptions, an assessment of the results, and lessons learned from teaching engineering to students who are not engineers.

COURSE ORGANIZATION

The course had two 1-hour lecture times and one 2-hour laboratory each week. The lecture meetings were seldom lectures, but most often included active learning exercises or short presentations by the students. I divided the semester into four sections, with a short quiz after each section. The first topic was the history of indigo, followed by the processing of indigo (including material balances, unit operations, and plant design), and the chemistry of indigo synthesis. The third topic was a unit on ethics (required for all VaST courses) and the final topic was cultural and artistic uses of indigo. Students purchased a book for the course,[13] were directed to resources available in the library,[14, 15] and were given several journal articles we discussed in class.[16–21]

The group of students was diverse, including 10 chemical engineering majors and nine liberal arts students (majoring in economics, psychology, history, and art). Many of the students had taken a semester of calculus, however I limited the mathematical content of the course to basic algebra, and provided extra help outside of class for those who needed it. We met once in a computer classroom where I introduced all of the students to Visio (to draw a simple Process Flow Diagram) and Excel (for creating graphs). Two of the students were especially concerned about their lack of chemistry background. I provided multiple explanations (using the chalkboard, manipulatives, and animations) for the chemical reactions they needed to learn, and, more importantly, personally helped them perform the synthesis laboratory experiments.

ACTIVE LEARNING EXERCISES

Most information was presented to the students during the one-hour time period, and I used active learning exercises extensively. Four are described below, and Table 1 shows the objectives of each activity and how they map to the overall course objectives.

• **Timeline activity:** The first weeks of the class covered the history of indigo, starting at about 3000 BC. I wanted the students to be able to mark the events in indigo history with events they were familiar with, so their first assignment was to come to class with six events that took place between 3000 BC and 500 BC: three that they had learned in high school, and three that had something to do with indigo. At the beginning of class, I drew a timeline on the blackboards around the classroom, and each student wrote his/her events on the timeline (along with their initials). As we marched through time, I illustrated important events in indigo history, and we discussed how the events the students contributed might have influenced society and the developments I provided. We had an interesting history lesson and got to know each other.

• ***New York Times* articles:** From 1874 to about 1918, the *New York Times* published more than 30 articles about the synthesis of indigo by the Germans, the commerce of indigo, and how artificial indigo would change the world. These articles are available online, so I printed copies of the original articles, pasted them to cardstock, and arranged them around the classroom. The students were divided into groups, and given questions to discuss after reading the articles. For example, they learned that as early as 1904, the discovery of "artificial indigo" was predicted to ruin villages in India and affect local textile mills. They discussed whether this happened then—as well as the lingering effects. Other articles predicted the dominance of the Germans in the dye industry, and the potential repercussions in the United States. Students were asked to consider the effect of indigo dye during World War I (for example, the articles reported the lack of dye for uniforms). A competition developed as the groups tried to find the answers and discuss their importance. The students found the activity more interesting than just reading the articles on their own. They also learned how journalism and vocabulary have changed in the last 100 years or so.

• **Unit Operations examples:** I brought samples of different schedule pipes and tubing to class, and different types of propellers and turbine mixers, so the students could hold and examine them. We discussed the differences, and how they would affect a process. In addition, I took apart old pumps and valves, so the students could examine how they worked while I explained it on the board. We took a tour of the Unit Operations laboratory to show the students the larger pieces of equipment. This was likely the first time most of the students had been in a facility with this type of equipment. The students knew something about distillation, filtration, and other processes, but most had not seen the equipment used in plants.

TABLE 1
Mapping of the in-class active learning activities goals to the course learning objectives

	Use multiple perspectives to answer important questions about a complicated problem	Explain the chemical differences between dyeing with indigo and dyeing with other natural dyes	Create a process flow diagram, identify major process equipment and explain briefly how they work	Write a technically competent laboratory report on the processes studied	Show an understanding of what a professional is and the ethical responsibilities of a professional		
Timeline: Connect events in the history of indigo with events they already know; show history of indigo in the social context.	✓						
New York Times articles: Discuss historical events in the synthesis of indigo; Interpret how synthesis of a new chemical affected world events.	✓				✓		
Unit Operations Examples: Explain how a pump or rotameter works; Illustrate meaning of pipe schedule.			✓				
Plant Design Game: Create a logical PFD; Perform economic analysis based on given information.			✓		✓		

• **Plant Design Game:** I wanted students to realize that when designing a plant, decisions must be made, and the decisions had economic and other consequences. With one week devoted to the topic, we didn't have time to cover how the decisions were made (although we did discuss synthesis trees). Instead, I devised a game where the students made their decisions (primarily choosing extraction, filtration, and drying equipment) by pulling slips of paper out of a hat and rolling dice. For example, they might choose to dry the final product with a spray dryer (expensive capital cost, but low labor cost) or with the sun (minimal capital cost, but higher labor cost). This gave them the information needed to construct a basic economic statement for their plant, and determine their profit (or loss). It was a lively competition—with a candy bar for the student with the largest profit—and the role of decisions became clear to the students.

In addition to these activities, videos on YouTube were used to demonstrate dye making and printing techniques, a DVD gave us a tour of the indigo harvest process,[22] and students gave several presentations on various topics. We were also fortunate to be invited to tour a nearby pigment plant, where the students saw the safety measures we had discussed and full-size examples of the unit operations.

LABORATORIES

The students met weekly in the laboratory for two hours for different activities. About half the activities were done individually, and half done in a group of two or three (with each group including at least one engineer). Table 2 maps the goals of the laboratory exercises to the course learning objectives. The exercises are described below.

1. Natural dyes and the necessity of mordants: Most natural dyes will not bind permanently to a fabric without the aid of a mordant. The mordant, typically a metal ion, is fixed to the fabric, and then reacts with the dye to produce color. The different metal ions produce different shades of color. Each student was given a bundle of fabric: three pieces each of linen, wool, cotton, and silk, mordanted with either chrome, tin, or alum. Each piece of fabric was cut into four pieces so each combination could be dyed in each of the four natural dyes (logwood, fusticwood, Brazilwood, or cochineal, purchased online[23]). Each student thus had 48 pieces of fabric. The assignment was to dye the fabrics, organize them creatively, and then draw conclusions on the effect of fabric, mordant, and dye on color.

2. Beginning and maintaining a vat of natural indigo: A fermentation process is used to maintain an indigo vat. The

TABLE 2
Mapping of the laboratory exercise goals to the course learning objectives

	Use multiple perspectives to answer important questions about a complicated problem	Explain the chemical differences between dyeing with indigo and dyeing with other natural dyes	Create a process flow diagram, identify major process equipment and explain briefly how they work	Write a technically competent laboratory report on the processes studied	Show an understanding of what a professional is and the ethical responsibilities of a professional		
Natural dyes: Descrbe how fabric type and mordant affect color; Explain how a mordant works.		✓					
Beginning and maintaining natural vat of indigo: Explain the fermentation process.		✓					
Indigo dyeing: Discuss how indigo dyes fabric; Compare/Contrast vat and other natural dyes.		✓					
Unit Operation experiments: Prepare a plot in Excel; Fit regression line; Explain variable area rotameter.			✓	✓			
Indigo synthesis: Use chemical laboratory equipment safely; dispose of waste properly; Calculate yield.		✓	✓	✓	✓		
Projects: Develop and use a procedure to reproduce an artform from another culture.	✓						

fermentation has nothing to do with the indigo, but it is a natural (vs. a chemical) method to remove oxygen from the liquid. Natural indigo and the necessary additives to maintain a vat can be purchased online.[24] The students observed as I added the ingredients [solid indigo, madder root (for deeper color), soda ash (to adjust pH) and wheat bran (to feed the bacteria)]. We discussed how the fermentation process removes oxygen, and related it to fermentation processes familiar to them. I explained how in the absence of oxygen, indigo changes from an insoluble form to a soluble form. Each week, when we entered the laboratory, we "fed" the vat (to maintain the bacteria responsible for the fermentation) and the students learned to recognize the strong scent of an indigo vat.

3. Indigo dyeing: Indigo is a vat dye, insoluble in water, and cannot be applied directly to fabric. The reduced form of the dye is soluble in water, and will bind to cloth (see Figure 1). As the cloth is exposed to oxygen, the dye structure changes and the dye becomes physically embedded in the cloth. Each student was given pieces of cotton, silk, wool, and linen to dye with natural indigo. They learned the importance of physically working the dye into the fabric and saw it turn from green to blue as oxygen reached the cloth as it was pulled out of the vat.

4. Unit Operations experiments: Using a pump designed for a small outdoor fountain and different sizes of tubing, the students collected data for a pump curve, which they created in Excel. They calibrated a variable area rotameter and wrote a page describing how it works. Last, using a Girder and Panel hydrodynamic building set,[25] they constructed a continuous process (with water circulating) and observed the response of the system when various valves were closed, and described how a siphon in the process worked.

5. Synthesis of indigo: Using o-nitrobenzaldeyde, acetone, and NaOH, each student synthesized indigo (see the Appendix, page 272 for the procedure used). Before beginning the laboratory, they had to find and summarize the MSDS for each component. I demonstrated the use of a graduated cylinder, analytical balance, and Buchner funnel for the nonengineering students, preweighed 0.5 g of o-nitrobenzaledhyde for each student, and instructed all students on yield calculations and waste disposal. The students practiced operations of chemical engineering (mixing, filtration, and drying) at a small scale, which gave them a basis for understanding the larger scales we discussed in class.

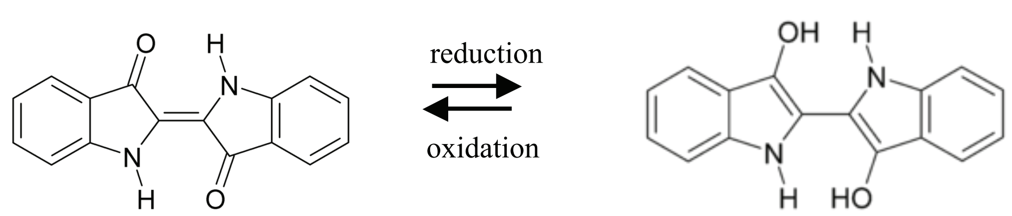

***Figure 1**. Indigo dye in its soluble and insoluble forms.*

6. Project weeks: The students were given a white cotton dish towel, access to the dyes and other materials, and encouraged to create something using the artistic techniques we had learned about in class (batik, shibori,[26] and stamping). They also created an advertisement that detailed how their creation was made.

The students enjoyed the time in the laboratory, asked insightful questions, and produced well-written and technically accurate memos. One student (a chemical engineer) created a magnificent display from the first project that made it easy for an observer to draw conclusions on the effect of mordant and fabric. We used her display to note how fabric type (animal protein or plant cellulose) affected the dye color. For example, wool was dyed a darker color than the other fabrics for all dyes, and mordanting with alum also resulted in darker colors than chrome or tin. Surprisingly, cochineal dyed the fabrics pink with tin and alum mordants, but purple with chrome. These observations could not be explained in this course, but the students learned to observe and draw conclusions.

We spent two weeks dyeing with indigo to get deeper colors. The first week, many students discovered that rinsing the fabric before it was dry removed most of the indigo. They were able to correct this the second week. In class, when we discussed the different modes of dye attachment, they understood why this had happened with the indigo and not the other dyes. Indigo is not chemically bound to the fabric, but is physically trapped between fibers. The more the fabric is kneaded in the vat, the more indigo gets trapped between fibers instead of on the outside surface. Dye on the outside surface washes or rubs off.

Most engineers and all non-engineers were surprised that the pump could only lift the water to a certain height, practical information that may be useful to them someday. I was impressed by their explanations of how a rotameter works. Both engineering and liberal arts students were able to use the resources I provided[27, 28] to describe how the variable area influences the measurement. The engineering students used equations, the liberal arts students used words, but both communicated effectively.

The engineers had no trouble synthesizing indigo (they had completed organic chemistry laboratory), and most of the nonengineers were able to do the laboratory with little help. One student, however, never was able to quite follow the steps. Eventually, after class I walked her through the procedure step-by-step and she was able to produce a small amount of indigo. She was pleased with her success.

During the project weeks, the students created works of art. In order

TABLE 3

Final plant design paper assessment. Sample data from two students, showing the notes taken from their work. This was used to assign point values for their final papers.

Student (type of indigo)	**Safety & Environment** (10 pts)	**Chemistry** (10 points)	Unit Operations		
			Agitation (10 points)	**Extraction** (10 points)	**Filtration** (10 points)
1 (natural)	Educate and train workers. Pay well for good workers. Use leaves as fertilizer. Keep seeds for the next crop. 10	Rotate crops (rice and indigo) to avoid nitrogen depletion. Oxygen dissolves indoxyl producing indigotan. 10	Incorporates oxygen to cause reaction of indoxyl to indigotan. 10	Leaching—takes the indoxyl out of the leaves and dissolves it in the water. 10	Uses cloth to catch indigotan precipitate 9
2 (natural)	Leaves make rich compost. Crop rotation. Production will be ethical and fair to farmers. 10	"No harmful chemicals are allowed to be used that would take nutrients away from the soil." "By avoiding pesticides, microorganisms are killed off." Indigo plants are nitrogen hungry. 6	Agitate with paddles until water is oxidized. 10	Will extract dye – no leaf fragments in product – but no other description 6	To remove plant leaves 8

to apply the first learning objective—to answer an important question—each student researched a dyeing technique from Africa or India. They discovered what natural materials the artists use to create the patterns in the cloth, what symbolism is present in the design, and how the cloths are used. The students then used a variation of the engineering design process to develop a process to create their own cloths, either using the cultural symbols or choosing their own symbols. I was pleased with the different techniques they were willing to try, their use of chemistry and the engineering process to create them, and how their efforts turned out.

ASSESSMENT

The main assessment (to measure knowledge of engineering gained) was performed on the final paper of the class, where the students had to design a plant to produce either natural, synthetic, or biosynthetic indigo. I analyzed the papers according to the following questions:

1. *Were unit operations described correctly and placed in a logical order (focusing on agitation, extraction, and filtration)?*
2. *Did the student exhibit an understanding of the chemistry behind the process?*
3. *Were safety and environmental concerns addressed?*

I read the papers multiple times, compiled notes on how they addressed the questions above in a master sheet, and gave a grade on each aspect (see Table 3 for the analysis of two liberal arts students' papers). A summary of the results is shown in Table 4, along with the type of indigo they planned to produce. Interestingly, the majority of the engineering students chose to produce synthetic indigo while most liberal arts students chose natural indigo. The liberal arts students were able to describe the chemistry and unit operations adequately—and nearly as well as the engineering students, although one liberal arts student included some misstatements about the chemistry of nitrogen. The four liberal arts students who attempted to describe the fermentation process did so correctly. All students excelled on describing the measures they would take to protect workers and the environment. For example, an economics student wrote "Blue Earth [her company name] uses 19th century methods but treats workers and uses farming techniques with a 21st century outlook," and an engineering studies student wrote "This industrial factory will create blue but stay 'Green'." This student was creative and described how his factory would meet LEED certification, and chose his equipment so the factory could be changed from producing natural indigo to biosynthetic indigo once the biosynthetic method became more reproducible. Another student (psychology major) created a contract between her company and Genocor to share the biosynthetic technology between them. As I read the papers, I could often discern the student's interests and major. For example, a history major wrote "A plant [indigo] that has such an interesting history deserves to continue making history." After reading and grading these papers, I was convinced that the liberal arts students had met the objectives of the course. They could create a process flow diagram and explain how the major unit operations worked, and address the plant design from multiple perspectives.

Other assessments included other writing assignments (some more creative than technical, and not considered in this paper) and four quizzes. The first quiz covered the history of indigo production, and the last quiz covered ethics and moral theory. Table 5

TABLE 4
Final plant design paper assessment.
Summary data for nine liberal arts students and the 10 engineering students.

Student (type of indigo)	**Safety & Environment** (10 pts)	**Chemistry** (10 points)	**Unit Operations**		
			Agitation (10 points)	**Extraction** (10 points)	**Filtration** (10 points)
Liberal Arts Students Natural: 5 Synthetic: 2 Biosynthetic: 2	10/10	8.6/10	9.7/10	8.9/10	8.8/10
Engineering Students Natural: 2 Synthetic: 7 Biosynthetic: 1	10/10	9.7/10	9.8/10	9.7/10	9.7/10

TABLE 5
Summary of quiz performance. There was no significant difference in quiz performance between the liberal arts and engineering students on quizzes covering history, unit operations, or chemistry (two sample t-test, $p < 0.05$). The engineers did perform slightly better on the ethics quiz, which primarily covered professional ethics.

	Liberal Arts Students	**Engineering Students**	t statistic
	(n=9)	(n=10)	
History Quiz			
average	81	80	-0.36
median	78	80	
Unit Operations Quiz			
average	93	95	0.73
median	98	96	
Chemistry Quiz			
average	88	88	0.36
median	90	93	
Ethics quiz			
average	86	90	1.39
median	86	90	

contains a summary of student performance on the four quizzes.

Quiz 2 covered pumps, pipes, valves, and the unit operations we had discussed (filtration, leaching, drying, and pumping). Most of the questions required qualitative answers, but a few required algebraic equations to find the answers, including some simple material balances. While the sample size is small, the liberal arts students performed as well as the engineering students (see Table 5). The t-statistic was calculated assuming equal variance for the two sets of students. Quiz 3 had fill-in-the-blank questions about the chemistry of color and dyeing, fermentation and synthesis of indigo, and chemistry of natural fibers. The students were quizzed about the history of the synthesis of indigo and its effect on society. They also needed to know what type of information was contained in an MSDS sheet. Again, the engineers and liberal arts students performed similarly (see Table 5). One liberal arts student always performed worse than all the other students on Quizzes 2 and 3, which resulted in the difference between the average and median in Table 5.

The students wrote other papers, including a creative exercise where they described life as an African indigo dyer. These papers were analyzed for evidence of three elements of critical thinking (indentifying problems, considering cultural and social assumptions, and identifying conclusions and implications).[29] No significant difference in critical thinking skills was noted between the engineering and liberal arts students.

The last form of assessment came from the anonymous student evaluations of the course, completed by 18 of the 19 students. A summary of the evaluations is shown in Table 6 (next page), beginning with a content analysis of the written comments. Overall, the students liked the experiential aspects of the course. The numerical evaluations indicate that the students liked the course, but placed less value on the specific topic. A rating of 4.0 is still "very good," however. One student commented that he liked "linking the somewhat eclectic and esoteric topic back to relevant topics such as safety and morality," and a second student wrote that "the mix of science, engineering, writing, and art was something different and interesting"—comments that show the students understand the purpose of the VaST course.

FUTURE WORK

Recently, a chemical engineering senior who took the course as a sophomore helped develop a simple dyeing kinetics experiment. We have developed the procedure and the basic analysis, and expect to include the experiment in the next course offering. Drying is a major unit operation in the processing of indigo, but is difficult to analyze due to the simultaneous heat and mass transfer. A chemical engineering student has designed and built a simple evaporator to demonstrate a part of the drying process. Students will collect mass data as a portion of the water is evaporated and complete a mass balance on the process. This experiment will also be included in the next course offering. Burrows[30] describes other experiments using natural dyes, and some will be included in the next course offering.

CONCLUSIONS

I developed this course to present some basic chemical engineering concepts to liberal arts students, using hands-on activities in the classroom and laboratory. By the end of the course, the students were comfortable in an engineering laboratory and wrote technically competent reports. They could explain the chemistry of indigo dyeing. The students' final plant design papers incorporated their laboratory experiences, contained a reasonable process flow diagram and description of several unit operations, and demonstrated that they could look at indigo production from multiple perspectives. The papers showed that students realized the importance of economics, safety, and the environment in everyday processes. These liberal arts students had gained a new perspective on engineering.

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See* "Indigo," *continued on page 272

TABLE 6
Analysis of Student Evaluations of the Course

Written Comment	Number of Students
Labs put into reality what we were learning	3
Hands-on dyeing of cloth was particularly useful	3
Liked creative assignments	2
Include more ethics	2
Numerical Evaluation (Rated 1 to 5, 5 = Excellent)	
Three Highest Characteristics	**Three Lowest Characteristics**
Instructor's enthusiasm (4.9)	Relevance & usefulness of course content (4.0)
Interest in students' learning (4.8)	Organization (4.1)
Examples and illustrations (4.8)	Use of class time (4.3)