Perspective: 2015 AIChE Institute Lecture Award

The Future of the Lecture

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Introduction

About a year ago, I went to a film festival. This in itself is unusual: I do not like movies much, but my wife was away, and friends graciously offered to take me. The film which we saw, *The Ivory Tower,* was a documentary concluding that college is not worth the cost. The film was especially critical of large state universities like mine. It asserted that these institutions permit students to have 4 years of excessive partying, in return for which they assume personal debt which their education does not help them repay. The professors at these universities are depicted as lazy, selfish, and interested only in narrow, unimportant research. The professors are not interested in education. The administrators of state and private universities are shown as interested only in their balance sheets and astonishingly ignorant of classroom education.

I was angry and offended. I decided that the few students depicted positively in the film must all be engineers. But at the same time, I knew that the film did have some real truth, and that I and all of us in education needed to think about the issues that the film explores. I did not know many answers to these questions, but I did want to start talking about them. At almost the same time, I was chosen as the 2014 AIChE lecturer, an unexpected honor. I decided to use that lecture not to review a research area, like diffusion or product design, but instead to talk about the future of undergraduate teaching and especially how the electronic revolution will affect this teaching. My focus on undergraduate education reflects where I think most about how students learn. My conclusion, detailed below, is that electronics would not change the lecture format that much, but it does provide opportunities to enrich education.

I want to stress that my conclusions are not a prescription for anyone except me. That is why I have adopted such an informal tone in writing this perspective. Your ideas and opinions and experiences are more valuable to you than mine are, and you should respect them as such. Please do not believe what I say without reflection; but please do reflect.

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Lecture Content

The lecture has three characteristics: its content, format, and evaluation. Its content depends on the discipline in which the lecture is offered. Developing this content requires a consensus among those working in this area. One way to think about this content is to idealize it as having two parts, "poetry" and "grammar." In this sense, it is the same as the requirements for a country, which also need both poetry and grammar.[1] For example, Germany began to be defined as a country after the epics of Goethe, which were literally poetry describing the folklore of the German speaking peoples. In the same sense, Germany became a country only after the first German grammar book appeared. This book was authored by Jacob Grimm, the older of the Grimm brothers who collected the standard childhood fairy tales. Ironically, Grimm was not a native German speaker, but spoke the Swabian dialect.

In the same way, we can idealize chemical engineering as having a core of poetry and grammar. The poetry comes from the periodic table, which requires that all matter be made up of a small number of elements. As everyone remembers, Dmitri Mendeleev, born in Siberia and the youngest of 14 children, suggested the periodic table in 1869 at the age of 33. Because my teaching is often focused on petrochemical mixtures, which are described by continuous functions, I tend to forget that chemical sciences are at their core dominated by this periodic table. In physics, we can get any wavelength; in mechanical engineering, we can get any rpm; but in chemistry, we only have that small number of elements, so we cannot have any band gap that we want. When I talk about this to lay audiences, I remind them that all matter is made up of this small number of molecular LEGO® bricks, and we cannot have any size and shape that we want.

If the poetry of chemical engineering comes from the periodic table, the grammar comes from the organizing idea of unit operations. While chemical engineering began with the 1887 lectures by George E. Davis at the University of Manchester, the real structure of the profession dates from the

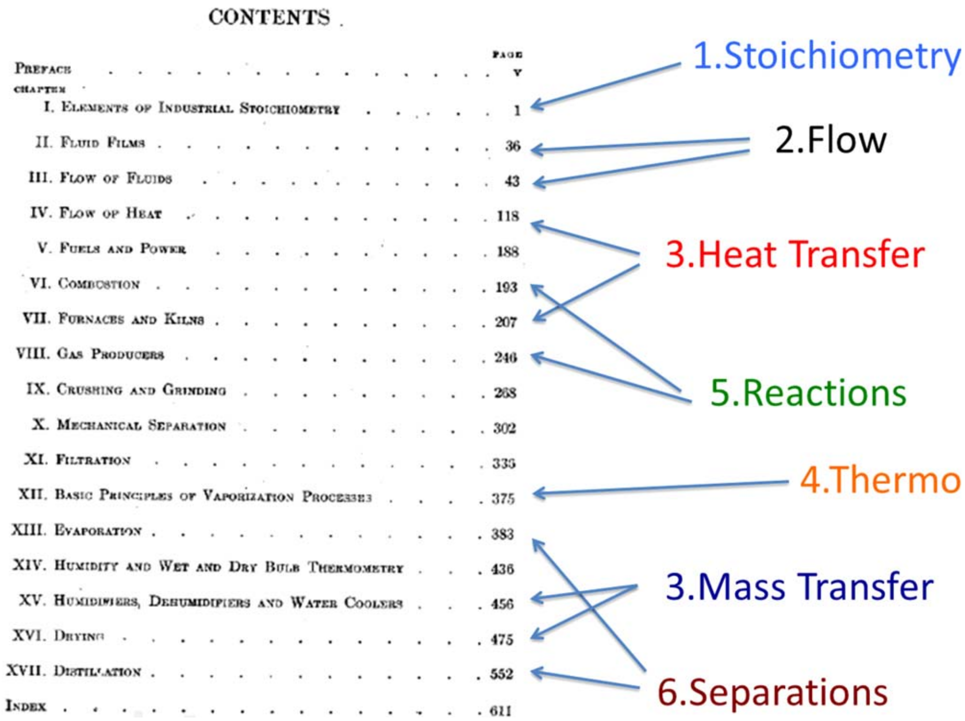
CONTENTS

Figure 1. Chemical engineering gets its structure from unit operations.

The table of contents in the 1923 Waker, Lewis and McAdams text closely parallels the current curriculum. However, there are now two additions: biology and materials science.

1916 report by Arthur D. Little, suggesting that the profession would best be organized by function rather than by industry.[2] In other words, distillation should be treated in the same way, whether the materials being distilled were ethanol, crude oil, or silanes. This suggestion was codified in the book *Principles of Chemical Engineering*, published in 1923 by Walker, Lewis, and McAdams.[3] This book defined the curriculum as generally taught today. To illustrate this, please look at the table of contents, shown in Figure 1. The chapters correspond remarkably to modern courses, as the arrows show. Of course, the content of the chapters is very different today: the one on reactions was largely concerned with coal and makes little mention of catalysis. Still, this book provided the grammar of our profession.

Chemical engineering is unusual among the different branches of engineering in the homogeneity of this curriculum at different institutions.[4] In contrast, civil engineering essentially offers four different programs in each department: structures, transportation, environmental, and systems. Mechanical engineering is so heterogeneous that some of its practitioners joke that "ME" stands for "miscellaneous engineering." But chemical engineering continues to respect the grammar of unit operations, embellished only by tentative additions in biology and materials science.[5,6]

Lecture Format

Traditional

Remarkably, the format of the lecture has changed very little over the last 1000 years, as the picture in Figure 2 of a lecture in 1233 suggests. The students sit in rows, often with a book or writing materials in front of them. The professor stands in front of the group, or, if he sits, is usually on an elevated platform. Some students are attentive, others gossip, and some are soundly asleep. Each of us who teaches finds similar behavior in almost every class, on almost every day.

In the same sense, just as we can idealize the structure of a discipline as poetry and grammar, so we can organize lecture formats around three teachers: Calvin, Socrates, and Lape. John Calvin (1509–1564), the theologian who drove much of the Protestant Revolution, was supremely confident.[7] He was sure that he understood the mind of God, and he was equally sure that those who disagreed did not. The Spanish physician Michael Servetus is a good example.

Figure 2. Henry of Germany delivering a lecture to university students in Bologna in 1233.

The behavior of students is very much the same today. Laurentius de Voltolina - The Yorck Project: 10.000 Meisterwerke der Malerei" DVD-ROM, 2002. ISBN 3936122202. Distributed by DIRECTMEDIA Publishing GmbH.

When Servetus publically disagreed with Calvin, Calvin had Servetus burned at the stake. This seems to me not much different than the attitude of some of the professors who taught me. When I disagreed, they were not amused. Fortunately, I found they were usually right. Still, extensive academic research shows that Calvin's method of the one way transfer of knowledge is not the best way of teaching.[8]

Interestingly, Calvin's traditional lecture format is implicit in the so-called MOOCs, the massive open online courses. In many of these courses, well-known professors at prestigious universities show taped lectures viewed by students from around the world. The poster child for these courses is Harvard's introductory computer science course, CS 50, which is used by Dartmouth and Yale, among others. Enrollments in the 100,000s are sometimes claimed for the MOOCs, and elite university presidents dream of turning these courses into a major revenue stream. As Wills has suggested,[9] this is "higher education discovering the mega-church."

I urge everyone in education to take at least part of one of these MOOCs. The lecturers are superb, and laboratory demonstrations are often effective. At the same time, I have found the courses frustrating. For example, one of the advantages claimed is that if I do not understand a point that the professor is making, I can run the tape back a minute or so and listen to it again. This is true: the professor says the same thing again. But darn it, I did not get it the first time, and he says exactly the same thing again. A live lecturer would never do that: he would use different words or different examples. Knowing that I was having trouble, a live lecturer would seek an explanation that I had a better chance of understanding.

Perhaps because of this, as MOOCs have matured, their appeal has dramatically lessened. Moreover, students taking the course online do much less well than those on campus. In one highly publicized case at San Jose State, fewer than a quarter of the students working online passed an introductory math course.[10] This does not mean that all distance learning is doomed: the Open University in the United Kingdom has convincingly demonstrated effective teaching at a distance for over 50 years.[11] It does mean that some of those trying MOOCs do not yet know how to be successful. It is not enough to teach the way John Calvin taught, even if you are omniscient.

Active

One alternative format for the "traditional lecture" is the "active lecture" exemplified by the teaching of Socrates (469–399 BC).[12] Socrates taught by asking students leading questions, by forcing them to take an intellectually active role in the development of ideas. The painting by Raphael, *School of Athens*, which is too complex to reprint here, illustrates what happens. At first glance, this form of teaching produces chaos; but with more careful examination, we realize that almost all shown in the painting are learning. Some are reading, some talking, and some just pondering quietly. Such an "active lecture" is broadly felt to produce more learning than imitations of Calvin.[13–15]

Of course, the challenge is to facilitate this type of learning when we both expect students to master basic skills and when we have enrollments well above 100 students. To do so, we need some time devoted to one-way knowledge transfer and some to active learning. To meet both objectives, we often have classes with large traditional lectures and small "active" recitations. At Minnesota, the large lectures are the responsibility of one lead professor and meet three times a week; and the smaller recitations meet two times per week, with an enrollment limited to 25 students. Moreover—and this is important—the recitations are covered by tenure-track faculty who also attend the lectures. Knowing my colleagues will be in the audience makes me work just that much harder. Those colleagues help explain when I was confusing and suggest alternative ways to make a presentation. Doing this gives us professors a sense of common purpose.

At this point, I should stress that these opinions are personal, what I conclude from watching my own classes. While I think these are a reasonable start for me, I recognize that many have studied engineering education in much more controlled environments, and have hence can have a stronger scientific basis for their conclusions.[8,16] They are reasonably irritated when their ideas are ignored.[17] As you consider my own ideas, please temper them with what others have found in reaching your own conclusions.

Flipped

There is a third format of lecture, often called a "flipped classroom." To understand this, remember your high school Shakespeare class. In that class, your teacher did not read *Hamlet* to you; instead, you read the play on your own, and the teacher led a discussion of the play in class. A flipped classroom is similar: the standard lectures that the professor normally gives are recorded and made available to the students as a resource. The classroom hours then become a discussion or a tutorial on the subject.

I was suspicious of the flipped classroom. I was sure that the difficult and abstract material of, say, chemical thermodynamics, could never be farmed out to recorded lectures. I admitted that the tutorials could be useful, but I did not see how we could deliver these for over 100 students in an effective way. Professor Nancy Lape, teaching thermodynamics at Harvey Mudd College, one of the Claremont Colleges in Los Angeles, challenged my skepticism by splitting her class and assigning half her students to an active learning classroom (like Socrates) and half to a flipped classroom (taped lectures and classroom discussions). She then tested the students to see who learned more.

The results, shown in Figure 3, show that both groups learn the same.[18] The two settings produce the same amount of learning. I must emphasize that the amounts learned using the active and the flipped formats are what is about equal; both of these have been shown in extensive studies to be superior methods of teaching compared with the traditional, Calvin-like lecture.[8] While the data in Figure 3 do not have the precision we expect in the measures of thermodynamic properties, they are similar to results for flipped classrooms for differential equations, studied in parallel by Professor Lape's colleagues.[19] Active learning, fostered either by active lectures or flipped classrooms, is a better format for the lecture.

Evaluation

We should also mention how we will judge which students have learned enough to pass the course, a major

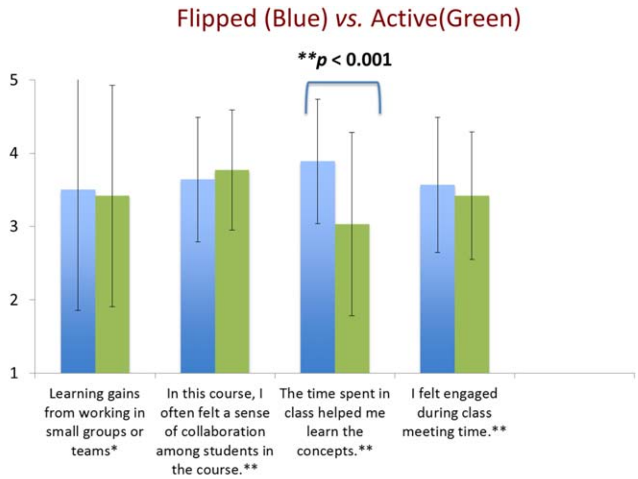

Figure 3. Active lectures produce the same learning as flipped lectures.

The left hand bars, for flipped, are the same as the right hand bars, for active. Both these are superior to the traditional lecture.

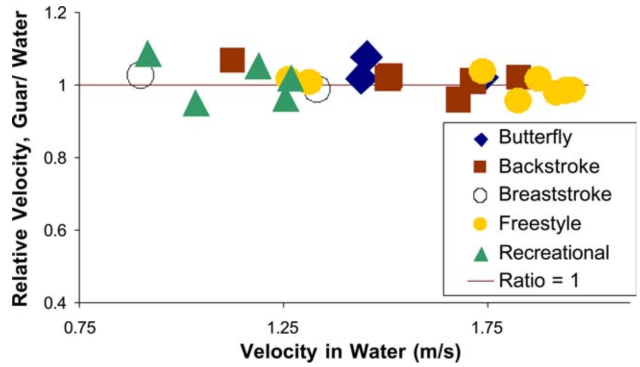

Figure 4. Swimming in syrup.

These data give the speed of humans swimming in a Guar gum solution relative to that in water. The guar solution has twice the viscosity of water. The results can spur discussion of different types of flow.

concern throughout education. These judgments depend on whether you want to distinguish carefully among the brightest students or whether you are trying to establish a minimum level of competence for the less gifted students. The first is more controversial and probably more difficult. In the United States, the most common metric has been the SATs, formerly known as the Scholastic Aptitude Tests.[20] After years of analysis, most agree that these show only who can take the test better; the correlation of the performance of the elite group in college is not well predicted by the SAT scores. At the other extreme is the requirement for graduation for the first 500 years at Cambridge University: a student had to live for 3 years within sight of Great St Mary's Church and pass an exam set by the university. Because I believe that all students who pass 4 years of chemical engineering courses are well trained, I do not think establishing the minimum qualification should be that difficult.

What will the Future Lectures Look Like?

I conclude that those of us in chemical engineering education will in the future almost certainly still be teaching mostly with lectures where we stand in front of students and talk, though not all the time. Our students' grandparents will still recognize our classes as being superficially similar to what those grandparents remember. Our goal will continue to be to have our students more actively engaged in listening, thinking about what we are saying. We will want to use electronic media any time that it efficiently facilitates this active learning goal. Such use may include electronic clickers, where we poll students while the class is running to determine whether we are getting through. It may include votes, where the students hold up flashcards to report on the results of a specific problem. It may include short videos, illustrating a specific idea, like viscosity.

Again, my goal in this article is to spur discussion among you readers on what specifically to do. I am going to suggest specific targets to make you think about how to improve. These are not necessarily targets I recommend for you, but where I myself want to do more for my students. If you do not find my suggestions sensible for you, others give good alternatives.[8,16]

I have five current targets. This list is not a proscription, but five ideas where I myself plan to try to enhance learning. I want to use some taped lectures for material I know is tricky or boring, where each student has to work through the ideas individually. For example, whenever I have taught mass transfer across interfaces, my students wind up either number plugging or confused. I must make them work the arithmetic themselves several times, in slightly different ways, before they begin to have a feeling for what they are doing. To make these taped lectures, I am learning from MOOCs. When I take a MOOC, I am always struck that the length of the lectures is not 50 min, but typically 20, and some segments are as short as 5 min. When these mini-lectures are combined with sample problems, they should be a strong supplement to my conventional active lectures.

Second, I continue to seek ways to encourage active listening. I want students to estimate numerical values of key parameters, and I often ask them to graph two variables vs. each other. After each has done so, I ask them to compare with the student sitting in the neighboring seat and to decide who is correct; then I collect opinions from the entire class.

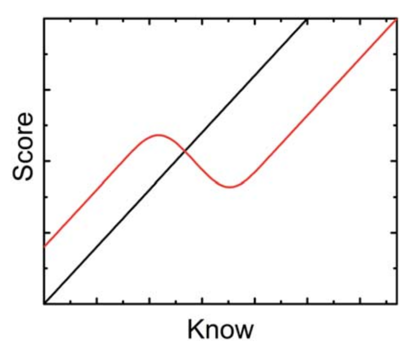

Figure 5. A schematic of exam scores vs. knowledge.

Helping students who reach the minimum, which often produces one form of "teachable moment," can give them huge gains.

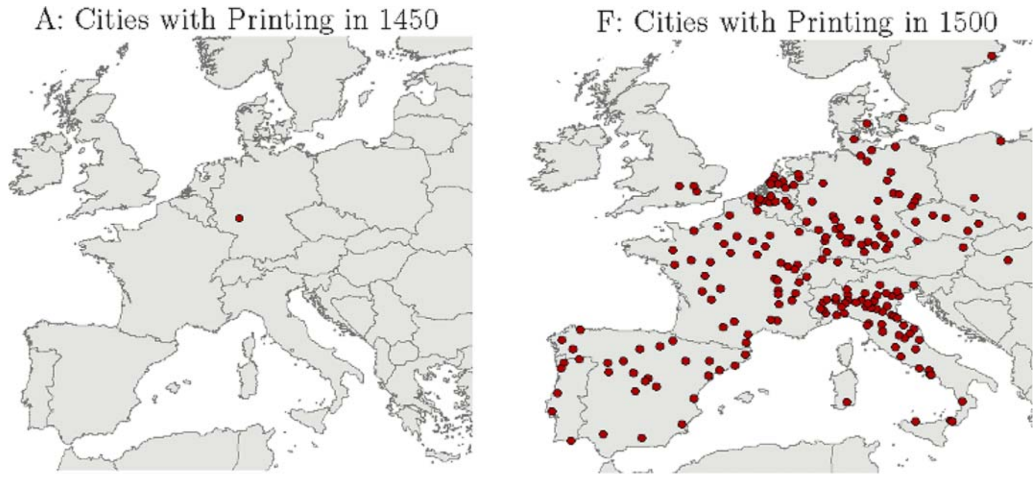

Figure 6. The expansion of printing.

This expansion was the first information revolution, made books widely available. It eliminated the wandering scholar, but it did not eliminate the lecture. Information technology and economic change: The impact of the printing press" Jeremiah Dittmar 11 February 2011. http://www.voxeu.org/article/information-technology-and-economic-change-impact-printing-press

In elementary education, this is sometimes described with the mantra "Think; Pair; Share."[21] I keep trying to foster these opinions with questions for discussion. Whenever possible, I want to supplement these questions with experimental data, just to remind them all of the uncertainty in what we are concluding. For example, the results for humans swimming in syrup, shown in Figure 4, can illustrate the differences between laminar and turbulent flow.

Examples of these questions for discussion follow:

- *Graph flow vs. pressure drop*. This involves Cartesian and logarithmic coordinates, and laminar vs. turbulent flow.
- *Which is bigger, a mass transfer coefficient in a liquid or in a gas?* This raises questions of units and of flux as the product of this coefficient and the concentration.
- *Fish populations are described with a second-order equation, but can be chaotic. Why?* This hinges on differential vs. difference equations.

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Third, I want to use more demonstrations showing the effects involved. Because these are hard to supply quickly in class, they are a natural for electronic presentation. Fourth, I want to encourage my students to form peer groups for studying, because I find these more effective than recitations and office hours. Please understand that I still want recitations and office hours, but I think peer groups are one of the most effective ways of learning.

Finally, I want to talk about teachable moments by referring to a plot of exam score vs. knowledge, qualitatively sketched in Figure 5. 1 suspect most of us assume that the more our students know, the better they will do on exams. But this clearly is not true: if they know absolutely nothing at all, they will still score a few points on our exams just for showing up and spelling their own names correctly. Then, for small amounts of learning, I believe that they will score better, just as the figure suggests.

However, as they master more, they may score less because their knowledge is superficial, and they do not understand the nuances of what we are trying to teach. I find this is especially true of wannabe "B" students, who may be working to near capacity. Moreover, because there is no easy way to unlearn what is confusing them, more work may mean that their scores drop still further as their confusion worsens. This frustrates both them and me.

But just when they are desperate, we teachers often have a chance to make a real difference. We can make one small correction, and all of a sudden, confusion lessens, their hard work pays off, and they quickly move to a much greater understanding. If we teachers can take advantage of these "teachable moments," we can lift our students to much greater understanding. All of us teachers live for these moments.

Conclusions

I believe the electronics revolution will not dramatically change the basic structure of the lecture. We will want to use either active or flipped format, whatever works better for the material we are teaching. While we will occasionally use completely electronic presentation, we expect that most of our effort will go into making students listen actively to our summary of the material. We will regularly use electronic media to supplement and enrich what we say, but we want to maximize the human contact with our students, for this is the best catalyst for learning. However, while I expect this future, I understand that others can disagree.[22]

In our current teaching, we need to remember the current information revolution is the second one in learning, not the first. To support this memory, look at Figure 6. The left-hand one shows the printing presses in 1450; the right-hand one shows the presses 50 years later. At this time, the roads between the small cities were muddy, and the chief method of moving among these cities was walking. Yet the need to move information created a huge support system, driven by the universities. In the future, we will be able to more easily command the resources to help learning, but we will still be limited by the time it takes our minds to absorb new information. In this brave new world, we will still depend on the lecture.

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