

AN INDUCTIVE APPROACH TO TEACHING HEAT AND MASS TRANSFER

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Abstract

This paper presents a method to teach heat and mass transfer courses that will appeal to the inductive learner. A deductive learner prefers to proceed from general to specific, while an inductive learner prefers to proceed from specific to general. Studies have shown that induction promotes deeper learning and results in longer retention of the information to students. Induction, in many cases, is also the method in which the original material was discovered! This style of teaching is relatively rare in engineering courses and is almost non-existent in textbooks.

Instructors can teach inductively by presenting familiar phenomena, practical issues, or experimental observations before presenting a general principle. Surprisingly, most textbooks still use an exclusively deductive approach, proceeding from first principles and governing equations to specific applications. Since there are relatively few textbooks that are written using an inductive approach; this makes implementation of the inductive method a challenge. Another challenge is that students typically will not have a wide range of experience or intuition needed to begin the inductive process. A simple laboratory experiment or demonstration will provide the foundation (observations or data) from which the inductive process is initiated.

We have integrated inductive learning into our coverage of heat transfer and mass transfer. In heat transfer, for example, simple heat exchanger design is the first topic addressed in the course. Discussion of the significance of the overall heat transfer coefficient provides a meaningful framework for introduction of topics such as conduction and convection, which are introduced later in the course.

In mass transfer, presented in the context of a transport phenomena course, students start with the design of a gas absorption tower. They are shown both laboratory equipment and pictures of industrial towers used to remove an impurity from a gas stream. If possible, they perform experiments on a laboratory gas absorption tower and observe the gas and liquid flowing

over the packing material and measure inlet and outlet gas concentrations. Next, they use a simple model of the tower with a constant overall transfer unit height. The students then proceed to learn about the overall mass transfer coefficients, individual phase coefficients, and the film theory of mass transfer. This portion of the material ends with an experiment in diffusion, Fick's law of diffusion and the measurement and prediction of a diffusion coefficient.

We believe that presenting course material in this order establishes the industrial importance of the equipment and gives a reason for why the student needs to learn the material. The student starts with simple concepts that are easily grasped; a liquid stream is heated from a second stream and a sulfur dioxide in a gas stream is removed by using a liquid stream. The learning then examines how the process works by *looking* inside the equipment and seeing why heat and mass are transported. The learning culminates with the presentation of fundamental continuum concepts of convection, conduction and diffusion.

Inductive Learning and Teaching Styles

Deductive teaching begins with rules or principles and then proceeds to deduce consequences or resulting phenomena. This is the natural teaching style in higher education, particularly in mathematics and engineering courses. Using a deductive teaching style, a professor can cover a large quantity of material in a short amount of time simply by lecturing and presenting derivations. Most topics in engineering courses are approached deductively; most courses are arranged in a deductive structure, and most curricula are organized to utilize a deductive order of courses.

Induction is the more natural *learning* style in which the learners explore observations and then infer the governing principles from them^[1]. Children learn by observation, not by deriving outcomes by beginning with first principles. Once familiar with an outcome or phenomenon, a child's natural curiosity will lead him or her to ask for an explanation. The Scientific method also begins with induction when a scientist formulates generalizations that explain experimental observations. Those generalizations can then be extended and applied to other situations to deduce outcomes or describe phenomena. The concepts of inductive learning and deductive learning are illustrated in Figure 1.

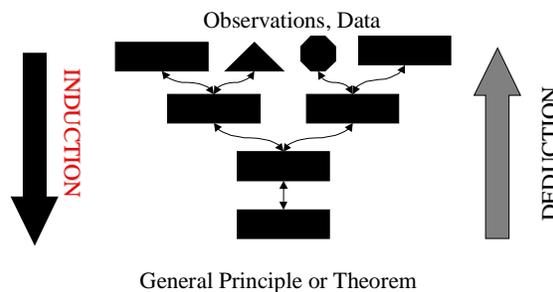


Figure 1. Deductive learning is begins with principles, and inductive learning begins with observations (Adapted from Felder et al. ^[2]).

Felder makes several observations about inductive and deductive learning ^[1, 2]:

- Students who prefer inductive learning (inductive learners) need motivation for theoretical material.
- Purely deductive teaching makes the students think that the material was straightforward for the instructor to develop (i.e., obvious)
- Purely deductive teaching leaves the student thinking that he or she could never come up with the derivation by him/herself.
- Deductive teaching may be more efficient for short-term retention.
- Inductive teaching is better for long-term retention and transfer of concepts.
- Everyone learns deductively and inductively. Preference for one may be mild or strong.

In order to address both inductive and deductive learning styles, Felder and Silverman suggest approaching topics much as scientific method is used: first by induction and then by deduction^[1]. An in-class presentation of observable phenomena creates a framework for inferring general principles. These governing principles can then be used to deduce other implications and consequences. The authors then present an interesting approach to a fluid mechanics topic that addresses a variety of learning styles, including inductive learning.

In this paper, we present examples of inductive teaching of heat transfer and mass transfer topics. This paper is unique in that we have also implemented an inductive approach to the overall course structure, beginning with applications and design to establish a framework for all the topics covered throughout the course. We also describe the inductive approach to individual topics in heat transfer and mass transfer. We have found that this inductive approach to heat and mass transfer has naturally created opportunities for active learning via laboratory experiments and in-class discussions of experimental observations, thus contributing further to students' understanding and retention of new material as shown in Figure 2.

Textbooks, in general, are written using a highly organized deductive approach. The authors of this paper are not aware of the existence of a chemical engineering textbook with topics written with an inductive approach. The typical heat transfer or mass transfer text starts with an introductory chapter on diffusion or conduction and then develops applications using these coefficients. The classic example of one of the most popular chemical engineering textbooks is that of Bird, Stewart and Lightfoot³. This text starts with an introductory chapter on viscosity and momentum transport, followed by chapters on the derivation of the momentum balance. These authors do start their derivations with an examination of the principles using shell balances, which are excellent tools to show students the action of each of the contributing terms.

The authors are not aware of any textbooks that present this material in an inductive topic order and that use inductive methods to introduce new material. It is recognized by the authors of this paper that an inductive textbook may at first be very unpopular with the chemical engineering community.

There are several texts that start with an example of a chemical process to illustrate the importance of the material to be covered in subsequent chapters. These introductory examples are important for global learners to see the whole picture and are useful for inductive learners to see why they need to learn the material in the following chapters. Good examples of this practice can be found in textbooks such Middleman^[4], Cussler^[5], Russell and Denn^[6] and Fogler^[7].

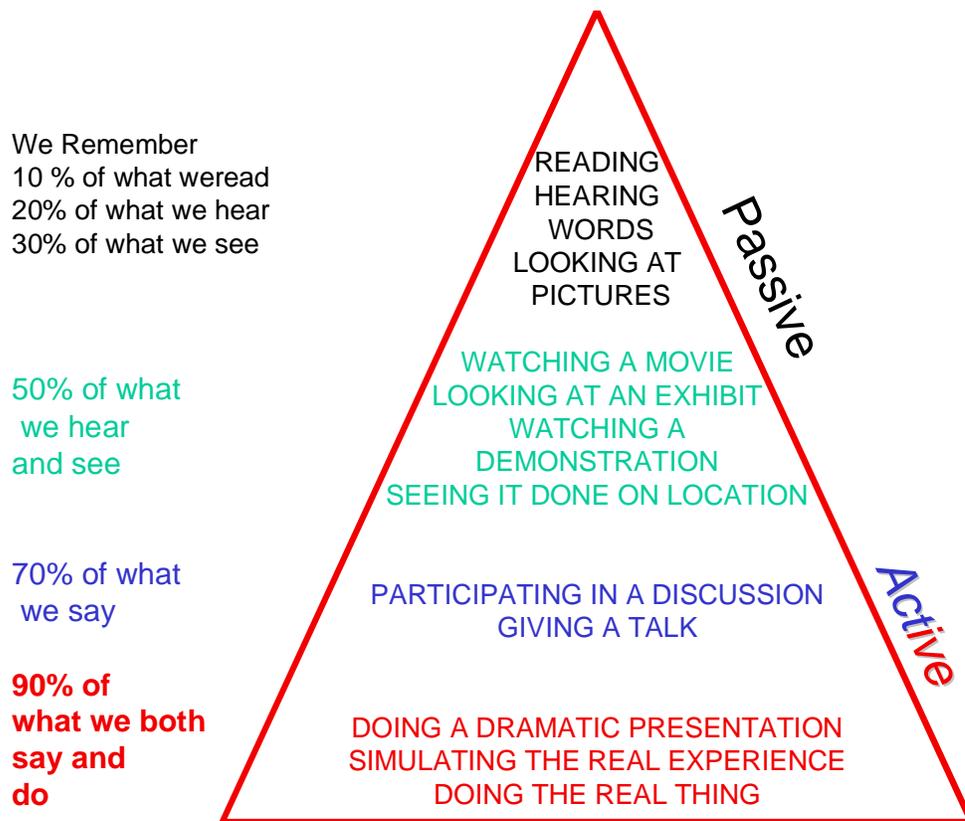


Figure 2. Active learning contributes to student understanding and retention of new material.

Heat Transfer

In order to introduce an inductive approach to the structure of the heat transfer course that is offered in the fall of the junior year, the class begins with a discussion about heat exchangers. On the first day of class, students visit the laboratory where they observe the operation of a shell and tube heat exchanger. Returning to the classroom, students explore the application of the performance equation for single pass heat exchangers:

$$q = UA\Delta T_{LM}$$

Equipped with this simple equation, students investigate the effect of each variable: How does the heat exchanger area (A) affect the rate of heat transfer (q) or one of the outlet temperatures? What is the effect of the value of the overall heat transfer coefficient, U? Students are also introduced to the units of the heat transfer rate and the overall heat transfer coefficient, and they are familiarized with representative values of the overall heat transfer coefficient as presented their textbook by Incropera and DeWitt^[8]. Students work modified example and homework problems from Chapter 11 of their textbook in which they choose typical values of the overall heat transfer coefficient instead of calculating it by traditional methods (as they will later in the course).

Once they are comfortable with the application of the performance equation and the effects of the different variables, the mechanisms of heat transfer occurring inside the heat exchanger are introduced. In this introductory heat transfer course, these include only conduction and convection. Students have a basic qualitative understanding of conduction and convection, and are able relate this to the relatively new application of heat exchangers. Students are presented that both mechanisms of heat transfer, conduction and convection, have an impact on the overall heat transfer coefficient. This establishes a framework for the remainder of the course, and provides motivation for the exploration of the individual mechanisms of heat transfer.

As conduction and convection are explored in depth throughout the course, these topics are always introduced by their relevance to the now familiar heat exchanger.

As suggested by Felder and Silverman^[1] individual topics can be addressed first by induction and then by deduction. Conduction is introduced first by a class discussion of their experiences with conduction: cooking with a metal spoon and grabbing a handle that is too hot (this would not happen with a wooden spoon), adding new insulation to a house to lower energy costs of heating and cooling. The relevance to conduction of heat through the wall of a pipe in a heat exchanger is emphasized. Following this discussion of conduction, the students proceed to the laboratory where they rediscover Fourier's Law by performing an experiment. The experiment is performed on an Armfield HT11 Linear Heat Conduction apparatus. The apparatus consists of an electrical heat source (students can set the voltage, measure the current, and calculate the power input), a material sample (brass, aluminum, stainless steel, cork, or paper), and a heat sink. The samples are insulated to ensure one-dimensional heat transfer from the heat source toward the heat sink. Students measure steady-state temperature profiles through the samples, and discover that these temperature profiles are linear. They discover that, for a given material sample, the temperature gradient is proportional to the heat input. They learn that the same heat input will result in different temperature gradients in different samples. They compare the different temperature gradients that result from using different samples. For homework, they graph their temperature profiles (Temperature vs. distance from heat source) and calculate the slope $\frac{\Delta T}{\Delta x}$. In the next class they are supplied with tabulated values of thermal conductivity (k), and discover that these values represent the proportionality constant that relates the value of heat input to the resulting temperature gradient for a given material. In short, they have rediscovered Fourier's Law.

The topic of natural and forced convective heat transfer begins with a discussion of familiar examples of convection. How long does it take to cook a potato in boiling water (100°C)? How long does it take to cook a potato in an oven at 200°C? Do you feel colder standing outside on a cold windy day, or on a cold day without wind? Why do children blow on a hot spoonful of soup before eating it? Following this discussion, students investigate convective cooling by performing an experiment in which they investigate the cooling of a hot cup of coffee^[9]. They discover that the rate of cooling is faster initially, when the coffee is hotter, and slows down as the coffee cools. This provides the framework for the presentation of Newton's Law of Cooling and the quantitative treatment of natural and forced convection systems.

Mass Transport Example

In the senior level transport phenomena course the subject of mass transport is introduced using the example of gas absorption tower. They are shown both laboratory equipment and pictures of industrial towers used to remove an impurity from a gas stream. In future classes, the students will perform experiments on a laboratory gas absorption tower and observe the gas and liquid flowing over the packing material and measure inlet and outlet gas concentrations. This is followed by a simple model of the tower with a constant overall transfer unit height.

$$\frac{d(Gy)}{dz} = -K_{oy} a A_c (y - y^*)$$

$$\frac{d(Lx)}{dz} = -K_{oy} a A_c (y - y^*)$$

The students then proceed to learn how to predict overall mass transfer coefficients, from the individual phase coefficients and learn 2-phase mass transfer $\frac{1}{K_{oy}} = \frac{H}{k_x} + \frac{1}{k_y}$.

Next the idea that diffusion is a random process is introduced using two bags of different colored balls. Volunteers are selected, and students exchange a fixed number of balls between the bags. This style of lecture introduces the students to diffusion without showing any mathematics and proves to the student that it is a very simple observation. Next, following chapter one of Cussler⁵, diffusion of two gases through a long tube is introduced by asking the students what will effect the rate of diffusion - tube length, diameter etc. This example introduces the student to the driving force concept that is fundamental to all mass transfer. Now the students have a word equation for the two mass transfer models labeled by Cussler as Fick's Law and the mass transfer coefficient model. Examples of these two models are shown for the cases of metal embrittlement by H₂ and dissolving a solid in a liquid. In this manner the students are not scared away from the basic principles describing the random process of diffusion.

Following this introduction to diffusion is an example of diffusion of molecules through a slab geometry (Stefan or Arnold cell). This derivation shows the origination of the use of a mass transfer coefficient for a single phase and also illustrates the concept of the log mean

concentration difference given by: $(1-y)_{lm} = \frac{(1-y_i)-(1-y)}{\ln\left(\frac{1-y_i}{1-y}\right)}$ from unimolecular diffusion

model. This log mean concentration difference is related back to the gas absorption column in relating UMD mass transfer coefficients to UMD coefficients. This adds another level of complexity to the gas absorption column, in that most of the individual phase coefficients are measured from dilute systems and require this type of conversion factor. A gas absorption tower using this type of conversion is now given to the students as a homework problem. The final problem using the mass transfer coefficient method is convective diffusion within from a pipe wall to the fluid.

Next the diffusion method is employed to show examples of vapor deposition on a solid surface, multicomponent char combustion, the shrinking core model, diffusion with reaction in packed beds and within a catalyst. The mass transport section ends with unsteady-state reaction and diffusion.

Heat Transfer in Transport Phenomena

The second major topic in the senior level transport phenomena course is heat transfer and it is introduced using a double pipe heat exchanger. This is similar to the method employed in the Junior level heat transfer course and the previous application of discussed for the gas absorption tower. Lectures with this material starts with the student discussing the use of a double pipe heat exchanger; drawing temperature profiles for various flow patterns, conducting overall energy balances, followed by deriving the differential equations describing heat transfer using an overall heat transfer coefficient, U_0 . For counter-current flow:

$$\frac{dT'}{dz} = \frac{U_0}{m'C'_p}(T - T')2\pi R_0$$

$$\frac{dT}{dz} = \frac{U_0}{mC_p}(T - T')2\pi R_0$$

The analogy between the gas absorption tower and the double pipe heat exchanger is illustrated by the similarity in equations shown in this paper. From these differential equations the origin of the log mean temperature difference is illustrated and the assumptions in its use are shown to the students. Problems are solved using a constant value for the overall heat transfer coefficient.

The next topic is to discuss the terms composing the overall heat transfer coefficient: $\frac{1}{U_0} = \frac{1}{h_0} + \frac{(R_0 - R_i)A_i}{kA_{lm}} + \frac{A_i}{A_0 h_0}$. Since these students are already familiar to each of these terms, the focus of the lecture moves to describing conduction. Unlike the previous example in mass transfer, we have not developed an in-class demonstration similar to the balls in a bag example given above. But, the students perform a heat conduction experiment using metal samples to obtain temperature profiles and the linear relationship between heat flux and a temperature

gradient. Now the students can analyze conduction through various geometries using practical applications such as a double paneled window, electrical wire with insulation etc. The convective boundary condition is added in the next set of problems to show the classic heat conduction problems of heat loss from insulation and fins and other extended surfaces. The topic of heat transport ends with unsteady-state conduction.

Topic Order for Transport Phenomena

In the transport phenomena course the topic order was inverted from the traditional texts in transport such as Bird Stewart and Lightfoot³, Welty Wicks and Wilson¹⁰ and Geankoplis¹¹. In this semesters transport course, mass transport was taught first followed by heat followed by momentum. This order was put into place for both practical and pedagogical reasons.

First the senior class of students had just completed a course on separations and reaction engineering in the Spring 1999 semester. The heat transfer course was taught in the Fall of 1998 (2 semesters time lag) and fluids was taught in the Spring of 1998 (3 semester time lag). So the students were most familiar with mass transport.

Secondly, mass transport is easy to visualize using color transformations such as the coffee leaching¹² and the dissolving of a colored drug¹³ or Miracle Grow Fertilizer. Also the random nature of diffusion is easily introduced using the colored balls and bag demonstration.

Heat transport easily follows mass transport since the equations and boundary conditions are nearly identical. Students can feel hot and cold objects, but they can only see a temperature difference through the use of large digital temperature displays.

Momentum transport requires the student to derive the balances using either a force balance or a flux balance. The flux balance follows directly from mass and heat transport, but it is intuitively more difficult to visualize. The force balance is easier for a student to employ, but it does not follow naturally from the flux balances used in mass and heat.

Momentum transport is the only subject that has a multitude of constitutive equations for non-newtonian fluids. Mass and heat transport only have one constitutive equation.

In a typical undergraduate transport course mass transport is the last subject and tends to have the shortest coverage. In some cases mass transport is not covered at all. This is unfortunate since mass transport is perhaps the most important subject for a chemical engineer.

Based on these the above rationale, the transport course was taught for the first time at Rowan using this inverse order of topics. One disadvantage of this order of topics is that the combined mass, heat and momentum transport must be covered at the end of the course. A second disadvantage is the boundary conditions for mass transfer are more complex than heat transfer. Student feedback, however, indicated that the benefits of presenting the material in the chosen order outweighed the drawbacks. No students commented negatively on what we anticipated to be potential sources of difficulty for the students.

Student Comments and Professor Evaluation

The students in the senior transport phenomena course were asked to comment on the inductive order of the topics as well as the overall order of mass, heat and momentum transport. All of these students had been introduced to transport phenomena in their fluids, heat transfer and separations courses. The heat transfer and separations courses had been taught in previous years using the traditional format of conduction/diffusion coefficients ending with the design of process equipment. So for this study the students were familiar with both styles of lecture.

In general students commented that they liked having mass transfer introduced first in the transport course. Students commented that they could, “see” mass transport happening and heat transport was more difficult to see.

All students agreed that unsteady-state transport should be covered last, since it is the most difficult subject.

Some students commented that they felt that an introduction to the equipment, followed by the diffusion/conduction theory and then equipment models would have worked best. Other students commented that they preferred the order of topics in the textbook.

Most of the students preferred starting with mass transfer. One student commented that “I think to the chemical engineer, mass and heat transport are more important than momentum,” and another “since mass and heat are the most important, so obviously they should be focussed on more. We did a lot of reviewing of heat info from the previous heat transfer class and the in-depth mass transport discussions were a good intro to the other two.”

In summary, the above analysis shows that a limited number of students prefer having an inductive order of topics. In addition, students felt that the order of topics starting with mass transfer in the transport course was the most logical and easiest to understand.

Future Teaching Plans

This paper discusses several concepts related to the inductive style of teaching and learning. The first concept is presenting material using an inductive lecture format. A professor starts with an experiment or shows results of an experiment and ends with the derivation of equations describing these results. The second concept presented in this paper is an inductive order of topics within an area of transport. For example heat transfer could be taught starting with heat exchangers and overall heat transfer coefficients followed by sections on the factors that contribute to the overall heat transfer coefficient such as conduction and convection. Finally this area of transport could end with coverage of unsteady-state heat transfer. Each of the lectures presented in this novel topical order could be done in an inductive manner; starting from experimental observations and ending with a derivation of the governing equation. Since this is the first time we have taught these courses using an inductive style we will continue to analyze this style of teaching and make improvements on this method.

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Robert Hesketh is Associate Professor of Chemical Engineering at Rowan University. He received his B.S. in 1982 from the University of Illinois and his Ph.D. from the University of Delaware in 1987. After his Ph.D. he conducted research at the University of Cambridge, England. Prior to joining the faculty at Rowan in 1996 he was a faculty member of the University of Tulsa. Robert's research is in the chemistry of gaseous pollutant formation and destruction related to combustion processes. Nitrogen compounds are of particular environmental concern because they are the principal source of NOX in exhaust gases from many combustion devices. This research is focused on first deriving reaction pathways for combustion of nitrogen contained in fuel and second to use these pathways to reduce NOX production. Robert employs cooperative learning techniques in his classes. His teaching experience ranges from graduate level courses to 9th grade students in an Engineering Summer Camp funded by the NSF. Robert's dedication to teaching has been rewarded by receiving several educational awards including the 1999 Ray W. Fahien Award, 1998 Dow Outstanding New Faculty Award, the 1999 and 1998 Joseph J. Martin Award, and four teaching awards.