ChE classroom

A HOLISTIC APPROACH TO ChE EDUCATION

PART 2. Approach at the Introductory Level*

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The objective of this paper, the second of two parts, is to describe the introductory chemical engineering course taught since 1985 at the former University of Barcelona. It follows the professional and issue-oriented holistic or integrated approach to education described in Part 1 of this paper.[1] In this type of approach, students who have the basic background in science and mathematics begin their more formal chemical engineering education by working together in cooperative groups, investigating and trying to solve real engineering problems (open questions).

The introductory course described here deals with the preliminary design of a chemical plant, and the questions that arise are related to the elementary principles of chemical process engineering, unit operations, and transport phenomena. The integrated class work and the laboratory simulate a real working environment, with emphasis on decision making in relation to issues that are of interest to students, acting as practicing chemical engineers, and to the community in which they live. The course is organized so that students can

- *Learn how to ask relevant questions when dealing with practicing engineering and public policy issues*
- *Assume responsibility for their own learning*
- *Experience team responsibility in class*
- *Work in a challenging, creative, responsible, interdependent and enjoyable environment.*

The advantages of adopting a cooperative learning scheme with classroom activities designed to foster creativity and research (the discovery process) in education have been extensively discussed elsewhere.[2-10]

Students will also be learning the concepts and basic principles of chemical engineering that are required by professionals responsible for the analysis and design of a given chemical plant. They will be made aware of their leading role in the design and operation of a new generation of chemical processes that have to be efficient and safe, with minimal adverse environmental impact, while also being economically feasible in a global economy. The course also introduces the roles of and opportunities for chemical engineers and provides a perspective for subsequent classes.[11]

The course lasts two semesters and was originally designed for third-year chemistry or second-year chemical engineering majors who had already been exposed to basic mathematics, chemistry, physics, and thermodynamics. The teaching load is 75 hours of class work plus 45 hours of laboratory or field work per semester—about 25% larger than an equivalent major course taught in Spain with traditional teaching approaches.

During the first semester, students learn basic macroscopic balances for mass, heat, and momentum as well as their differential counterparts in one dimension. They work in groups to investigate and try to solve real engineering problems (*i.e.*, mostly open-ended problems, related to the design of a chemical plant). Students use the knowledge and techniques they learned in previous years and are self-motivated to go a step further by applying these techniques to an industrial-scale problem with larger mass flow rates and energy needs.

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In the second semester, students further investigate the transfer mechanisms and rate equations introduced during the first semester and apply them in the form of differential or microscopic balances to analyze a variety of situations of industrial and societal interest.

The course ends with a project where, in addition to the chemical engineering principles and basic economics dealt with during the course, students have to consider some aspect of environmental engineering, risk assessment, and analysis,[12,13] as an integral part of the everyday practice of chemical engineering. The course has also been taught in the past to chemistry students as two, one-semester courses, each covering macroscopic and microscopic balances, respectively, and both including a final project.

COURSE GUIDELINES

As can be seen in Table 1, the course begins with an introduction to chemical engineering and process plant de-

TABLE 1
Course Guidelines: Blocks and Activities

BLOCK 1		
Introduction	• Chemistry, Chemical Engineering, and Technology	• Manufacturing a given chemical; feasibility and plant location studies (5 hrs) • Searching for a process: from chemistry to chemical engineering (5 hrs) • *Field work:* Students visit a petrochemical site (5 hrs)
	• Chemical Processing	• Process description: Scaling up, from laboratory to industrial scale; unit operations and transport mechanisms; choosing the best proposal (5 hrs)
BLOCK 2		
Macroscopic Balances	• Conservation principles, equilibrium, and rate equations	• Overall and partial material balances for the plant and relevant process equipment (10 hrs) • *Laboratory work:* Unsteady state mass balances in stirred tanks (3 hrs) • Analysis of plant energy requirements; identifying donors and receptors of energy in the plant (5 hrs) • Outlet temperature in a continuous adiabatic reactor (10 hrs) • Identification of sources of momentum; momentum balances in bends and other accessories (5 hrs)
	• Unit Operations	• *Laboratory work:* Batch distillation of ideal and non-ideal mixutres; design and applications (3 hrs) • Continuous distillation or alternative mass transfer operations; design hypothesis/applications (10 hrs) • Design of a tubular heat exchanger (5 hrs) • Chemical reactors; types and applications; design of the process reactor(s) (10 hrs) • *Laboratory work:* Mass and energy balances in a batch reactor with 1st-order kinetics (6 hrs) • *Laboratory work:* Mechanical energy balance; applications to flow in conduits (6 hrs) • Design of pumps and/or compressors (5 hrs) • *Free laboratory and field work (22 hrs)*
BLOCK 3		
Microscopic balances	• Introduction	• From unit operations to transport phenomena; identification of transport mechanisms in different equipment of the plant (5 hrs)
	• Steady-state heat conduction	• Formulation of Fourier's Law from one-dimensional heat conduction data; application to furnace design; boundary conditions (5 hrs) • Design of a furnace from real data (5 hrs) • Saving energy; application of Fourier's Law and heat transfer coefficients to pipe insulation (5 hrs) • *Laboratory (computer experiments):* Steady heat conduction through composite materials (3 hrs)
	• Steady-state mass diffusion	• Mass fluxes, diffusion and convection of mass; formulation of Fick's Law (5 hrs) • *Laboratory work:* Mass diffusion with chemical reaction (3 hrs) • *Laboratory (computer experiments):* Measurement of mass diffusivities in gases (Arnold's cell) and in liquids (3 hrs)
	• Diffusion of momentum in steady state	• Formulation of Newton's Law of viscosity from one-dimensional data; vector and tensor analysis; stress and deformation tensors (5 hrs) • Microscopic momentum balances to determine the velocity profiles in simple one-dimensional flows of industrial or environmental interest (5 hrs)
	• Unsteady transport phenomena	• *Laboratory:* Unsteady heat conduction in solid bodies; formulation of Fourier's 2nd Law (3 hrs) • *Laboratory:* Numerical solutions of PDEs; time evolution of the velocity profiles between a fixed and a suddenly sliding wall (9 hrs)
	• Transport equations	• Lagrangian and eulerian representations; substantial derivative; formulation of generalized transport equations (5 hrs) • Determination of velocity, temperature, and concentration profiles in industrial and environmental flow of interest; exact, approximate, and numerical solutions (15 hrs) • *Free laboratory and field work (24 hrs)*
BLOCK 4		
Project	• Design of a chemical plant	• Preliminary design of a chemical plant; economical feasibility, plot plan, general flowsheet, equipment design, and environmental issues (20 hrs)

sign (block 1), continues with macroscopic (block 2) and microscopic balances (block 3), and ends with a project (block 4) as mentioned above. Each block is developed through a set of activities that are carried out in the classroom or in the laboratory or field. The Table includes a list of tentative activities with their duration. Those corresponding to the first semester (blocks 1 and 2) are more professionally oriented, while those of the second semester (mainly block 3) emphasize societal issues. Activities change each year because student interests and the chosen chemical process vary. The guidelines presented here correspond to the course outline given in Table 1, which represents a syntheses of the course content over the last eight years.

Activities generally last for 5 or 10 hours of class work, distributed in 3 hours plus 2 hours per week. The objectives and content of the activities are decided by the class when relevant questions are asked at the end of the previous activity. Groups of four to five students work in the class or in the laboratory to attain the objectives initially set for that activity, under the coordination of a group leader—a role that is assumed in a rotary fashion by all students. Each leader also has the responsibility of evaluating group members, preparing the group's report to the instructors, and making oral presentations to the class. The role of the instructors, professors, and TAs is one of facilitators of learning—helping students learn by asking pertinent questions. When the need arises, the instructors or invited experts in the specific field being analyzed may also dispense knowledge to the class. A detailed description of the organization and procedures adopted in and applied to the present course is given in reference 1.

BLOCK 1
Introduction to Chemical Engineering

The first block is of an introductory nature and is designed to help students who have only a basic scientific background to become acquainted with the chemical industry.[14,15] It also illustrates the differences between laboratory processes and operations (which students know so well) and those carried out on an industrial scale in a chemical plant. In the process, the students come to appreciate the differences in the professional profiles of a chemist and a chemical engineer and become aware of the role played by science (chemistry), engineering (chemical), and technology.[16] It may be convenient at this point to provide the class with reports such as the US National Research Council's report of "Critical Technologies: The Role of Chemistry and Chemical Engineering," or some equivalent publication. Since one of the objectives of chemical engineering is the design and operation of chemical plants, the introductory block deals with what is needed to accomplish this objective.

The introductory block and the course usually begins with a story concerning the interest of a group of business people willing to invest money and resources for the purpose of producing a given chemical(s) in the geographical area where the course takes place. The story may be summarized and explained with a simulated letter from the investors addressed to a chemical engineering consultant firm (the class) requesting an evaluation of the feasibility and costs of the chemical plant suited to produce such chemical(s). If, for example, the chemical were nitric acid, the case-study approach of Ray and Johnston[17] could be an answer to that request and the book by Sinnott[18] would be a helpful reference for the preliminary process design.

The **first activity** then becomes writing a proposal, including all the basic and preliminary items and questions that the class thinks should be addressed during this consulting job (*e.g.,* during at least the first semester of the course). The proposal is in fact the preliminary description of the course contents. The following questions are generally addressed:

- *What are the local, regional, and world-wide needs for the chemical, and what is its total annual production rate?*
- *Who are the leading producers, and how will the actual price and possible profit margins be affected when the new plant becomes operational?*
- *Which of the existing chemical processes is the best for a given plant location?*
- *Is there room for improving any of the existing chemical processes?*
- *Would new regulatory actions concerning the environment, raw materials, etc., provide room for competitive advantages in relation to current producers?*

If the plant is not local, students also address the question

- *Which is the best region or country in which to locate the new plant?*

In addition to considering manufacturing an existing product or material, students become aware of other situations that a chemical manufacturer may face, such as how to create and produce a new material, the convenience of integrating a product purchased elsewhere, how to convert a by-product into a valuable product, environmental issues, etc. Other questions about incorporating new technologies and new materials or construction may also be addressed.[19]

To answer the above questions, which are strongly business and economically oriented and less related to technology and chemistry, it is necessary to carry out a preliminary analysis and design of the chemical plant.[19-21] Therefore, the content of the course follows from, and is justified by, the criteria applied by the investors in deciding the design, construction, and operation of the plant. The initial set of questions could be followed by more specific questions concerning factors that might affect the decision of where to

locate the plant. If there is a chemical industrial site located nearby, it could be useful if the investor's letter mentions a chemical produced in that area. This will not only give the students a sense of reality, but it will also help facilitate the necessary collaboration between the university and industry.

In the **second activity** of the introductory block, students begin searching for the best chemical process (*e.g.,* treatment and separation of materials and chemical reaction paths) that could be licensed to obtain the desired chemical. In the process of answering this question, students continue to act as chemists or first-year chemical engineering students, searching the literature for chemical reaction information as well as chemical, physical, and hazardous information about all chemicals involved. They also search for techniques to separate and purify the products of reaction and for information on maximum yields and energy requirements. They should be able to propose a laboratory setup to carry out the process at a scale familiar to them, and they should ask themselves, "What can possibly be the differences in design and operation between the laboratory scale and the industrial plant?" and "How can the laboratory operations be carried out on an industrial scale?"

The **third activity** of the introductory block includes preparing a proposal for implementing the process on an industrial scale. The students should identify the differences between the laboratory and an industrial scale, including a comparison of the type of equipment (or unit operations), the mode of operation (discontinuous or continuous), and the operating conditions (isothermal, adiabatic, variable temperature, isobaric, etc.). The comparisons will bring attention to the difficulties involved when large amounts of chemicals have to be processed at possibly high temperatures and pressures and—thus, demonstrating the need for control strategies, providing for safety, and meeting environmental standards. The basic content and principles of chemical engineering will be made clear to the students.

The third activity continues with the classification of all operations and the identification of the underlying transport mechanisms. This, in turn, helps students identify the need for basic macroscopic balances for mass, energy, and momentum as a necessary part of the design. The next subject in the activities constituting the second block of the course is thus defined. Finally, the activity and the introductory block may conclude with an extended closing presentation, a discussion of the results, and a decision concerning the chemical process best suited to the problem—which is the process that will be studied by the class during the rest of the course.

The first block is also used to acquaint students with the course methodology and procedures.[1] This is the reason why it has also been so extensively described here. Group work and class discussion are favored from the beginning, and the initial leading role played by the professor is progressively decreased. It should be noted that the content of the introductory activities is well established in the course regardless of the active role played by the students in deciding the topics to be considered on a yearly basis. What has been presented above roughly reflects the content of these activities during the past eight years.

BLOCK 2
Macroscopic Conservation Principles and Balances

The second block covers mainly macroscopic balances for mass, energy, and momentum, for the whole or parts of the process,[22] and some unit operations. It also may include microscopic or differential balances in one direction if needed. This is the case when dealing with plug-flow situations in preliminary heat exchanger and tubular chemical reactor designs. Transient operations are incorporated either when batch operations take place in the process or as a generalization of steady balances. Also, examples of loading and unloading tanks or equipment, and simulations of start-up situations help illustrate time dependence. Students learn how to extend their experience on closed systems to open systems. Whenever transfer rates occur across interfaces bounding one-dimensional flows within a given piece of equipment, calculations are performed using mass/heat transfer coefficients or using efficiencies provided by the professor or found in the literature. Students generally work with a variety of books published in English or in Spanish on chemical engineering principles, process plant design, unit operations, and transport processes.

Some activities in the second block require knowledge not yet acquired by the students and which is difficult for them to learn on their own in a short period of time. In these cases, the professor may use part of the activity time to present and discuss these new concepts or subjects. Table 1 shows that the chemical plant under study will probably include heat exchangers, continuous separation equipment, pumps and compressors, etc. Other equipment not present in the chemical plant may be introduced and studied, for example, as possible alternatives. Also, the need to recover valuable unreacted chemicals may lead to the study of recycled material balances.

The design of any piece of equipment can be carried out in a set of separate activities if the instructors introduce the necessary additional material to students in seminars or lectures. For example, students understand intermittent (batch) distillation from their chemistry experience in the laboratories, but they may need help in learning continuous separation processes and in formulating hypotheses to simplify the calculation equations necessary to design the plant. These seminars allow students to discuss specific topics with specialists in the field, other professors, or staff from industry, and they are organized like a continuing education program for industry or a graduate seminar in a university. After finishing the presentations, the specialists become engaged in group discussions or mini-lectures at the students' re-

quests.[3] Coordinating classwork and outside contributions is complex because students' interests determine the topics of concern, but after some experience with the course, planning these related activities becomes an easier task.

BLOCK 3
Microscopic Balances

The second semester (the third block) begins by focusing on the use of microscopic balances to characterize transport phenomena situations of interest in the chemical plant already designed and around the site. The conservation principles are applied in differential form to further study some of the activities carried out during the first semester and to provide information for decision-making in relation to societal issues that may arise. This procedure for linking the first and second semesters of the course not only reinforces the learning process but also shows students how to increase their depth of analysis by asking pertinent questions.

For example, the first activity of this third block examines how the plant under study can be further analyzed and how equipment design and operation can be improved. One answer to these questions is to better understand and characterize the transport processes occurring in the plant and, thus, moving from unit operations to transport phenomena, as shown in Table 1. The objectives of this activity involve finding the relationship between unit operations and transport phenomena and identifying the different types of balances, their characteristics and applications. The actions undertaken by students to attain these objectives include:

- Analysis of the process flow sheet of the previously designed plant
- Identification of the physical, chemical, and mechanical operations in that process
- Determination of the type of transport present in each operation and its classification according to the phenomena involved
- Phenomenological description of possible relationships between the size of equipment and the rate of transport phenomena present
- Identification of factors affecting transfer rates at a given location in a piece of equipment,
- Phenomenological formulation of the microscopic balances for heat, mass, and momentum, with a preliminary analysis of the need for different boundary conditions.

The rest of the activities are organized so that differential energy balances are studied first, followed by mass and momentum. This structure was chosen because temperature and concentration are scalars and the corresponding balances are more easily deduced and understood by students initially. The differential mass balances are more difficult to introduce because of the need to define and use different velocities to characterize the diffusion of all the species present. Students work with different transport phenomena textbooks.[23-25]

The initial activities of the third block deal with steady and unsteady pure conduction and mass diffusion situations so that the basic transport mechanisms for energy and mass through different media are well understood first—before convection is introduced. These activities are supported by computer-simulated experiments to help students who are not familiar with differential balances to deal with non-uniform spatial distribution of variables and fluxes within a given domain. All computer experiments show screen images which are replicas of real equipment, forcing the students to act as if they were in the laboratory. They may change media, or initial and boundary conditions, and get results in a real or compressed time scale with the same accuracy and precision as in real experiments. This scientific, analytical approach forces students to gather evidence (information) and to use it to deduce general relationships or laws that can be readily applied to many different problems of engineering and related societal concerns.

The societal and business competitive issues that most commonly interest students are related to: the minimization of energy losses in the plant; estimation and reduction of emissions; characterization of the movement or dispersion of contaminants through different media, or through underground water beds, after accidental leaking from the plant; and the compliance with quality standards by obtaining a given product distribution in a chemical reactor. In some cases, the last issue has allowed inclusion of an activity at the end of this third block for comparing the performance of different types of chemical reactors. If time allows, numerical two-dimensional calculations are carried out in a tubular reactor, and predictions are compared with the one-dimensional results obtained during the first semester.

It should be noted that issue-oriented engineering education means, in this course, that students learn how to apply the science and available technology to provide quantitative information (estimates) for decision making. Also, these issues encourage them to investigate and propose new alternatives for better understanding of the scientific phenomena involved. Students discuss the issues in order to comprehend the limitations involved in setting public policies, but *learning engineering* is the primary goal of the course. For example, if students become involved with the issue of volatile organic compounds (VOCs) emissions, they will have to identify the sources and assess the limitations of the measurement techniques. They will need to focus their efforts on setting up and solving the pertinent differential balances (see, for example, references 13 and 26).

BLOCK 4
Project

The purpose of the final project is to make students aware that the concepts and techniques studied in this and in previ-

ous courses are very relevant for the design of economically feasible chemical processes. The plant they design should operate safely and with minimal adverse environmental impact. The project also makes clear the need for further knowledge in the different areas that make up the chemical engineering profession and provides an opportunity to evaluate the overall student performances from a professional point of view. Students have access to all the information and documentation from previous years.

The organization of this last block, summarizing all past activities and forcing students to make decisions, varies depending on the number of students enrolled in the course. Projects are chosen by each group from a list made available by the professor and are not generally repeated for several years. When several groups choose the same project, a random draw is conducted. In some instances students are allowed to work on a project not included on the original list but which can be defined within the conceptual framework of the course. In the present course, different group configurations have been successfully tried, ranging from two to four students per group. That decision depends on enrollment.

The duration and objectives of the project may also vary slightly from year to year depending on how the course develops (*i.e.,* number of activities carried out by students). The usual length is one month, and the class work during this period may also include complementary seminars on principles and applications of process control to answer student questions on how to operate a given plant. In this respect the project is a convenient way to end this introductory course because it justifies not only the above mentioned methodology, organization, and guidelines, but also the overall curricula of chemical engineering. When the course has been offered as two separate parts, a project of shorter duration (*e.g.,* two weeks) has been included at the end of each semester.

EVALUATION AND RESULTS

Student Assessment • Students have been assessed according only to their performance when solving individually or as group members real engineering problems in the classroom and in the laboratory. An external and more global assessment of the course using different techniques (see, for example, reference 27) is currently being developed.

The overall grade that each individual student obtains at the end of the term is based on the following aspects:

- *Quality of work carried out individually, as part of a group effort, or when leading a group—both in the classroom and in the laboratory. This work has been reviewed by the professor both as oral presentations and as the reports handed in at the end of each activity. The quality of both results and presentation is considered. Each individual group member has also been evaluated by the group leader in each activity. The weight of all these items is 35%.*
- *Ability to solve unknown problems, similar to those considered in the activities, in several test sessions of limited duration carried out during part of several class periods. These tests are individual, but books and notes are allowed—again, to reproduce a real working environment. In some cases, students are asked to propose test questions with the understanding that the professor will incorporate the best ones, up to 50% of the total. The open-book tests, three per semester, account for 30% of the total.*
- *Performance in project development with its oral cross-examination is the final and most important element to student evaluation. The weight of this part is 35%.*

The attitude of the students during the course, their ability to write and orally communicate, and their involvement and enthusiasm are also considered in their final grading. This more subjective component, which is considered during an evaluation session with all instructors present, can modify the grade resulting from the above three aspects by ten points.

Results • On one hand, an examination of student performance during the past eight years shows that average student participation (attendance and involvement) were among the *highest* in the college of chemistry at the Tarragona campus. The lowest attendance has been 95% of enrollment—when class attendance in engineering schools in Spain may be as low as 60% of enrollment. On the other hand, failure rates are *lower* than in equivalent courses—generally of the order of 10%, with below-average students performing better than expected. It is important to realize that the number of failures may reach 60% in some science and engineering courses. Failure rates are also lower than when the same course was taught following a traditional approach nine years ago.

Different surveys given by external organizations indicate that a large majority (more than 90%) of the students had a very favorable opinion of the course. They valued the opportunity to explore and learn on their own and suggested that other courses be organized in a similar fashion. They stated, however, that their initial reaction was not completely favorable, due to several factors: because of the extra effort the course would require in terms of participation; because it did not use a reference textbook; and because the students would have to assume responsibility for their own learning (later on, this factor became highly valued). Students also expressed some sense of initial frustration because of the difficulties they encountered in handling real-life problems after their years of studying passively.

Students mentioned that this course affected their overall performance because they tended to spend more time on it

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SUMMARY

Process systems engineering is the cornerstone of a modern chemical engineering curriculum. Since the systems approach is fast becoming a fact of life in the worlds of business and commerce, it is imperative that our students and faculty become familiar with it. In addition, the use of PSE technology will allow us to effectively incorporate more material into the curriculum through computer-aided learning and simulation. By viewing processes as systems, students and faculty will be able to focus more clearly on the curriculum—thus streamlining the material presented.

A good understanding of PSE enhances student understanding of chemical engineering science since the PSE course material and software are based on chemical engineering fundamentals. Therefore, the PSE case studies actually reinforce the traditional course material. ❐

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than on their other courses, and they reported that their interest in the course was the main cause for spending extra time. Some students (less than 10%) said that they felt uneasy about making decisions independently. This minority also felt they could have learned more (contents) if the professor had assumed a more active and leading role. Most students were surprised by the importance that presentations have on the class' opinion about a given work, regardless of its intrinsic quality. All of the students thought that more time should be assigned to the project. Final reports exceeded expectations, however. The overall rating of the course was among the highest during its eight years of existence, with students placing great value on the instructor's efforts to bring the practicing world of the engineer into the classroom.

The opinion of other faculty and of industry about the performance of our students and graduating engineers after taking this course is favorable, as reported in the first part of this paper.[1] Also, the implementation of this introductory course increased enrollment in chemical engineering, particularly that of women.

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