Experiments With
INTEGRATION OF EARLY ENGINEERING EDUCATION

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Engineering education traditionally places initial emphasis on "exposition," followed by "application," within the domain of a specific course. Subject matter is programmed so that the general and inclusive ideas of the discipline are presented first, followed by progressive differentiation in terms of detail and specificity. Often, in the early years of engineering education, exposition and applications phases dominate the curriculum, while integration receives scant attention. With the current urgency to provide a well-rounded learning experience, skills in addition to conventional engineering abilities are being stressed at all levels in academia, including the early formative years when the science content dominates the curriculum.

A typical engineering teaching plan includes

- *Exposition of scientific principles*
- *Exposition of engineering principles*
- *Acquisition of practical and theoretical skills*
- *Application of acquired skills and knowledge to solve complex problems*

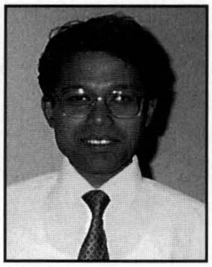
Appropriate assessment and feedback then follow. A systems analogy version of traditional education in terms of the stimulus, response, and feedback process is that the input of teaching material, the input from students, the course goals, and the outcomes all feed into the course itself (see Figure 1).

An important detail missing from this unidimensional approach relates to the multidimensional, distributed, and interactive nature of learning (drawing from the systems analogy) and consequently the complex multivariable structure of the educational process. Further, most of the relevant application phase usually occurs toward the end of the degree curriculum (in the form of design and thesis), often long after the principles have been taught. If we recognize that all aspects of learning should be interrelated, then educators need to explore appropriate integrative learning tools to avoid excessive fragmentation of curriculum and to foster interaction among the participants.[1-3]

This article highlights the dangers of excessive fragmentation in course presentation, especially in the early stages of engineering education. A lack of relationship between courses could also create rigid compartmentalization of knowledge. Our attempts to encourage cooperative learning and integrative reconciliation (systems analogy) between courses will be discussed.

A PROBLEM AREA AND POSSIBLE SOLUTION

Early engineering courses rich in scientific content attempt to introduce key principles and tools so that more detailed and differentiated material may follow and provide the scaffolding for further learning. But it is common to find that little effort has been spent in creating links between the courses. For effective problem solving, it is necessary to have an integrated cognitive structure for flexible retrieval



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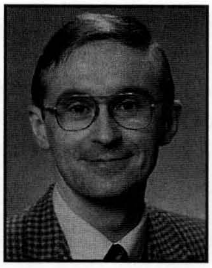

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and application of acquired tools. Thus, the convenient practice of minutely segregating a discipline into courses and sub-courses is often insufficient for deep learning. Courses offered in parallel or in sequence, served in bite-size chunks for ease of digestion, often appear confined within watertight compartments that serve their specific purpose, with little time left for forays into neighboring territories. Such methods may be responsible for eliciting student responses such as "...that was taught in fluid mechanics...are we supposed to know it for heat transfer?"

Studies[4,5] show that the early formative years in engineering education are crucial in engendering a professional attitude and weaning students away from their high school attitudes. The first- and second-year students face a range of diverse subjects, involving various faculties, with seemingly minimal connections between them. Students fail to see any relationship between the early courses and their chosen professional discipline. Ideas, concepts, and applications are commonly presented in the context of a particular course without recognition of courses taught in parallel. This practice frequently results in substantial segregation between courses without relational mapping and may foster a disposition toward rote memorizing, which in turn results in loss of associative learning in the initial stages.

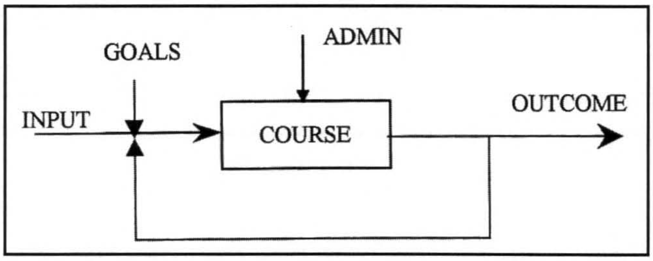


Figure 1. *Systems analogy of unidimensional curriculum experience.*

A message that needs to be emphasized early on is that as a body of knowledge, chemical engineering has structure and form, is built on fundamental laws, concepts, empirical observations, and data that we believe are self-consistent. Our discipline is not an unrelated collection of a few thousand equations put together to solve problems in a "cookbook" manner. Students must be guided to avoid missing the forest for the trees. They often do not see any relationship between concurrent courses, but view them as isolated hurdles to be overcome sequentially, and they perceive that lessons learned in a particular subject will not come under rigorous tests within the framework of a different course. This implies that the provision of a "road map" of the discipline, showing links between the different courses and how they fit in, may be advisable. This aspect is currently being explored in our department.

For efficient delivery of a large body of knowledge, minimal overlap tends to exist between syllabi of different courses. As a result, students continue to solve unidimensional, specialized problems tailored for a specific course. The postponement in training to solve multifaceted problems continues for the major part of undergraduate education. Thus, crucial connective links between different courses may remain hidden for the majority of students. The consequence is a distorted view of real-life problems that have been massaged in view of a specific course syllabus.

Meaningful learning is by definition relatable and anchorable to established ideas in the cognitive structure.[6] Thus, it is not uncommon to find that the structure of the discipline is unclear in the early stages of engineering education, sometimes resulting in lack of motivation and interest. It is often only in the final stages of a degree program that advanced students have opportunities for integrating their learning through thesis and design work involving challenging problems.

Rigid compartmentalizing implies that equations and methods memorized to solve typical problems for respective courses would not be flexibly available for solving "open-ended, real-life" problems. A review or refresher material within a course may temporarily help retrieve "lost information." Thus, integration is important not only within the confines of a course (intra-course), but also in relation to the discipline and courses conducted in parallel. Therefore, following a detailed exposition and application phase within separate courses, a mechanism for integration of the subject matter is desirable.

FIELD TRIAL

In order to encourage course integration, three years ago we started the practice of collaborating with other instructors within the department to devise a single joint project that would count for both courses. The final project is normally carried out in small groups, often with minor technical variations for each group, thus encouraging cross-fertilization within and between the groups without duplication. The presentation of results in formal reports, and often orally, provide further opportunity to improve verbal and writing skills.

At the University of Sydney, we offer Material and Energy Balances and Process Case Studies during the first year. During the second year, Chemical Engineering Computation is offered as a sophomore problem-solving course, involving nonlinear equations, interpolation, least-squares, and numerical calculus, while the parallel Fluid Mechanics and Heat and Mass Transfer courses focus on the fundamental principles of corresponding transport processes and on equipment design. The remaining courses during the first and second years involve other faculties. We decided to set joint end-of-course projects that would highlight the lessons learned in each of the engineering courses during the first and second years, and also to combine elements from each course to solve a complex engineering problem.

Our course schedule permitted setting a joint project on early process design (Flowsheet of a Bio-Refinery) for Material and Energy Balances and Process Case Studies during the first year, and on fluid flow analysis/optimization for Fluid Mechanics and Chemical Engineering Computation during the second year. Our objectives were

- ❑ *To attempt integration between two courses*
- ❑ *To solve a nontrivial problem*
- ❑ *To provide early analysis and synthesis experience*
- ❑ *To encourage team effort*

Typically, the classes were divided into four- or five-member groups composed of weak, average, and strong students (based on their grade-point average). The groups were drawn from concurrently offered courses; thus, there were often a few students (6-8) who were not part of one or the other course. These students were distributed into groups so that there were at least two members taking both courses. The management and task allocation were left for the group members to arrange. Initial instructions to help the teams function effectively were provided through preparation sessions in which professional roles and responsibilities were discussed and group responsibilities were produced in written form.

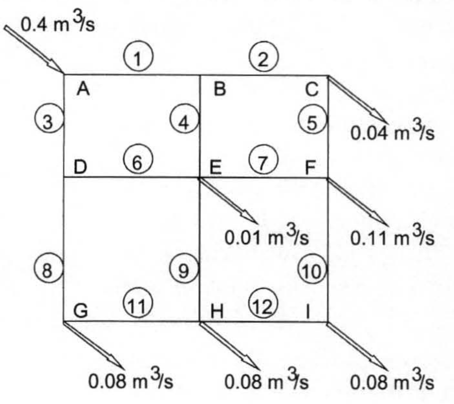
Opportunities were provided for the group members to meet during the tutorial hours and on their own. Every group member was asked to assess their peers' efforts (on a scale of 0-10) and to indicate the actual contribution of each group member in a section on "who did what" attached to the final

TABLE 1: PIPE NETWORK ANALYSIS

PROBLEM STATEMENT

In order to specify appropriately sized flowmeters for monitoring the water flowrates in the cleaning-water distribution network at the Waikikamukau Dairy Cooperative, you are required to estimate the flowrate in each pipe in the system, shown diagrammatically in the figure. You must use a systematic technique for this problem.

- The total flowrate of $0.4\ ms^{-1}$ enters the system at point A. Cleaning equipment draws off the indicated flows at points C, E, F, G, H, and I.
- Ignore the effects of differences in elevation. Water may be assumed to have a kinematic viscosity of $10^{-6} m^2 s^{-1}$, and all the pipes are made of carbon steel.
- You must use both a spreadsheet and a FORTRAN program to carry out the iterative calculations, but you must first do a hand calculation for one iteration of your method. You must then include a printout of your spreadsheet for this case and the results of the FORTRAN program to validate your computer code. Record the time that you spend on each approach (spreadsheet and program) and comment on the ease of use of each approach for this application.
- You must document the spreadsheet fully and clearly, and also include an attachment specifying the formulae used in the cells together with the order of calculation.
- For the FORTRAN program, each step in the program must be clearly documented, and you must attach an explanation of the order of calculations (a flow chart may be a useful way of doing this). The formulae used at each step of the calculation must also be specified.
- Relationships between the friction factor, the Reynolds number, and the relative roughness are given in Perry's *Chemical Engineers/ Handbook* and in Coulson and Richardson, Volume 1. It is your responsibility to use formulae appropriate for the range of Reynolds numbers and data given.
- While your submissions should be tidy, handwritten attempts will not be penalized compared with typewritten ones, provided that the material can be readily assessed.
- You must present a summary page at the front of the submission, giving your group number and a table showing the following results for each pipe:



Pipe Data

Pipe No.	Length (m)	Diameter (m)
1	100	0.3
2	100	0.3
3	125	0.4
4	125	0.2
5	125	0.3
6	100	0.3
7	100	0.2
8	250	0.25
9	250	0.3
10	250	0.2
11	100	0.3
12	100	0.2

1. Direction of flow
2. Average velocity
3. Volumetric flowrate
4. Pressure drop

- You must explain all your calculations, document your FORTRAN program and your spreadsheet, and hand in printouts of your spreadsheet, your program, and the results from the program.

Analyses and Discussion Topics

1. Why is more than one iteration necessary in order to get a converged solution, even with a problem involving only two pipes?
2. Why do problems with many pipes (and "loops" of pipes) take more iterations to converge than a two-pipe problem?
3. What would happen if all the pipe diameters were doubled? Would the flowrates be the same in all the pipes? If not, why not?
4. Is your final solution sensitive to the initial guess?
5. If all the flowrates into and out of the system were increased by 10%, would all the flowrates within the system also increase by 10%?
6. How much different would the flowrates be (for the original inlet and outlet flowrates) if the pipes were completely smooth?
7. Suggest globe valves for flow regulation and check valves for back-flow prevention at appropriate points. If a centrifugal pump is installed for supplying water from a tank and the outgoing flows are connected to specified equipment, show how these affect your calculations.

submission. The lecturers and tutors monitored the individual group members during the tutorial, and class hours were assigned for the project. At the conclusion of the project, team members were questioned on the technical aspects of the project such that team members were individually held responsible for the entirety of the project content. This input formed the basis for awarding a final mark to an individual student. The final mark was the team project grade modified by up to twenty percent according to the results of the peer-effort assessments and the interviews such that the average mark for the individuals in the group was the same as the team mark. Evidence whether the group process was working was noted during the tutorials themselves.

Apart from the initial instructions on how to function as a team, support was offered to help teams function effectively if it was needed. Otherwise the groups were encouraged to gain autonomy and to promote internal communication with a minimum of staff intervention. The students approached the problem through internal coordination, sharing of common difficulties and insights, encouraging weaker students, fostering a sense of responsibility, accountability, and creation of memorable situations. The average duration of the shared project was about four weeks before the termination of the semester and the projects were typically assessed at fifteen percent of the total course marks for each of the courses.

An example of one of our problem statements is summarized in Table 1. The problem on pipe network analysis using fluid mechanics principles, was intended to bridge the gap between two parallel courses: one based on programming and numerical methods, and the other oriented toward engineering science. The main tasks for the problem in Table 1 were

- *To formulate the design equations to be solved*
- *To determine methods for solving the sub-problems and the overall problem*
- *To plan a set of modules using a spreadsheet and a programming language*
- *To debug and execute the programs*
- *To modify the programs to test different conditions*

Table 2 provides a guideline on the approach and considerations in solving the problem posed in Table 1.

RESULTS

The exercise of "shared course projects" has now been carried out over a three-year period for the first- and second-year courses mentioned above. The problems selected, incorporating components for each course, were relatively large in order to provide a greater challenge than those from

TABLE 2. PIPE NETWORK ANALYSIS—A SOLUTION APPROACH

Solution and Programming Issues (students normally provide full programs and spreadsheets with model equations employed)

- Carry out hand calculation for a single step using the Hardy-Cross Method (*i.e.,* assign signed flow directions to the pipe segment flows and set the sum of flow rates in each loop as zero).
- Choose the guessed values of flow rates in all pipe segments by mass balances.
- Include the Colebrook (or similar) and Hagen-Poiseuille equations for calculating pipe friction losses. Check for flow-regime and use the appropriate equations.
- Include pipe expansion-contraction losses at each junction and the pipe fitting losses.
- Use a local Newton or bisection method for solving the implicit Colebrook or similar equation.
- Develop a flow chart showing the sequence of computations.
- Input the program in modules; test and debug the program at each stage.
- Use comments to make programs readable.
- Carry out one computer iteration and compare with hand calculations.
- Implement full iterative computation for all loops. Modify and test various cases.
- Print out results.

Summary of Analyses and Discussions (students normally provide numerical answers and analyses)

1. Iterative solution is necessary in order to obtain a converged solution because, even though mass is conserved for an initial guess, the sum of head loss around each circuit is non-zero. The converged solution will ensure that mass is conserved and a zero net head loss is obtained within each of the flow circuits.
2. A problem with multiple pipes requires more iterations because in a multiple-pipe circuit, some pipes participate in more than one circuit, and consequently head and flow corrections from more than one circuit need to be applied until the flow rates are balanced.
3. If all pipe diameters are doubled in size, the converged flow rates in each pipe would approximately remain the same. The small differences in converged flows are due to the fact that the head losses computed are not linear with respect to the pipe diameters.
4. The final solution should be insensitive to the initial guess. The solution should be unique.
5. If all the flow rates into and out of the system were increased by 10%, all the other flow rates in the system would increase by approximately 10%. Small discrepancies are due to the nonlinearity of the equations.
6. If the pipes were all smooth, friction factors would be less for a given Reynolds number; hence the head losses would be less. Thus, flow rates would be slightly different because the head loss dependence is nonlinear with respect to pipe roughness.
7. The connection of a supply pump and of outgoing flows will require setting up head-loss equations in an outer loop and incorporating the flow resistances of the associated piping and connected devices. After the inner-loop flow computations are balanced, calculations must be carried out for the outer loop, including the pump performance characteristics, to satisfy the constraints provided. Any flow excess or deficit must be balanced along with the inner-loop flow distributions and solved iteratively.

a single course. A side benefit of the shared project was that the combined time and effort provided by the lecturers and tutors for the two courses helped optimize the total input, and no additional time allocation was needed.

The students found the problems challenging and stimulating, but not overwhelming. The groups functioned better than satisfactory in achieving their objectives and few conflicts were noted. Conflicts related to communication were resolved through encouraging the students to make contact by phone and/or e-mail. Lack of responsibility by any individual was penalized through a lowering that individual's grade. The fact that group members needed to cooperate for a common goal engendered a sense of belonging and a degree of independence and responsibility throughout the project. Our experience indicates that the majority of the teams functioned without major complaints, knew what the other team members were doing, and displayed a satisfactory level of understanding.

The levels of difficulty were not the same for the projects. For some projects the students had to select an appropriate computing tool. In such cases, about two-thirds of the groups opted for the spreadsheet, while a third opted for FORTRAN. For the project described above, no such choice was provided, and the groups were required to set up both a spreadsheet and a program. The groups typically divided the tasks among themselves to concentrate on particular aspects of the problem and then combined efforts on the more difficult parts.

The student experiences indicated varied styles of learning and degrees of expertise in using these tools. A majority of the students were found to be competent in using one of the techniques, while only about a third was proficient in using both. The exercise also highlighted the strengths and weaknesses of the tools used. The spreadsheet was faster in presenting results and was relatively easier to debug but it provided less flexibility and was tedious for variable definition and usage. Developing a program required greater discipline and effort, but was more flexible for experimenting and when it worked, it was more satisfactory in terms of the learning experience.

A majority of the students noted that the project usually took on a life of its own. They also said that it helped them gain an understanding of how their fellow students think and work: "I not only got to know how I think and solve problems, but I also realized the false steps taken and assumptions made by my partners." The students also gained first-hand experience on how to cope with deadline pressures and peer review.

The students spent more time on the project than they anticipated, expressed satisfaction on completing the project, and considered it a memorable experience. Feedback from course evaluations showed improved satisfaction with the courses (about ten to fifteen percent greater satisfaction ratings were noted). Carry-over from the experience to subsequent years was noted in the form of better appreciation of the principles learned from computation and fluid mechanics. Apart from this improvement in carry-over to subsequent years, anecdotal evidence from written course assessments suggests that more students learned more individual course material than before and better understood the relationship between the integrated courses than previous students who experienced a more compartmentalized approach to teaching.

Traditionally, early engineering courses are taught without invoking a major project, sometimes involving only a minor project with limited time and resources. With pooled resources and more challenging projects to offer, the mechanism described has the potential of achieving better results than the traditional approach. In addition, teaching and learning tend to be more rewarding and enjoyable due to the higher degree of interaction between participants with efficient use of resources.

The exercise provided a mechanism to synergize greater curriculum integration, minimize compartmentalization, strengthen cross-disciplinary learning, and reduce student anxiety in meeting submission deadlines for two different courses. The distributed learning process also encouraged variations in approach and ways of learning, such that the students were not subjected to a single prescribed mode throughout. The format of these projects could also be derived from a larger research project to enhance the challenge and to permit the direct flow of research work into teaching.

CONCLUSIONS

Tackling challenging problems with group-based learning can foster deep learning and understanding within the discipline during the formative stages of education. The integrative learning experience can help in the following aspects:

- *It provides students with the option of being involved in structuring their own learning experience*
- *Teachers act as mentors, facilitators, and resource persons rather than as dispensers of information*
- *Teachers discipline and interrupt students less and are less constrained by a lack of time*
- *Students develop both initiative and the skills needed to work cooperatively with their peers*
- *The format assists in developing communication skills*
- *The projects encourage and enable students to critically evaluate their own and each other's work*
- *Students develop confidence in tackling challenging problems*
- *Less able students have the opportunity to reach the competency level of their peers*

Through positive intervention in encouraging reconciliation between courses, we may avoid the ill effects of compartmentalizing courses and help integrate the acquired knowledge of our discipline. Research on cooperative learning is summed up succinctly by Wells, et al.:[7] "...to achieve most effectively the educational goal of knowledge construction, schools and classrooms need to become communities of literate thinkers engaged in collaborative enquiries."

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INTEGRATING PROCESS SAFETY

Continued from page 203.

- *Best-practice databases (e.g., for an ethylene plant, what controls, procedures, and training are adequate)*
- *Methodology to determine time-concentration effects of various toxic materials and combination of these materials*
- *Computational methods for determining fire resistance of structural components in process facilities*

IDENTIFYING PROBLEMS AND MULTIDISCIPLINARY APPROACH

Universities solve problems identified by researchers or industry. For an applied engineering field such as process safety engineering, the problems are usually identified by industry. The approach is to develop effective mechanisms for getting industry input and then taking a multidisciplinary approach to solve the problem. To address the latter, the Center has assembled a highly qualified team of experts who have international reputations in fields ranging across reaction engineering, inherently safe design, numerical analysis, system and equipment reliability, applied probability, organizational structure and planning, non-destructive evaluation, experimental fracture mechanics, materials testing, risk assessment, exposure assessment, cost-benefit analysis, and other areas of expertise.

The vehicle used to identify problems is based on two factors: first, the Center actively seeks input from industry in identifying process safety engineering problems that the Center can help solve, and second, an annual symposium "Beyond Regulatory Compliance: Making Safety Second Nature" is a vehicle to generate ideas and to identify problems.

CONCLUSIONS

In response to the changing role of chemical engineering, chemical engineering departments must adjust and modify their approach to education and research. The education must include a comprehensive exposure to core courses integrated with process-safety problems as well as a limited number of specific process safety engineering courses. Chemical engineering departments must also produce an appropriate number of MS and PhD graduates whose degree programs are focused on process safety engineering problems. Also, to help our graduate students transition into industry, the research we conduct should help industry in a practical and immediate manner. This can be ensured by seeking adequate input from industry as well as other stakeholders.

Public perception of the process industry is significantly affected by process plant accidents. The significant societal role played by industry is largely overlooked when catastrophic accidents occur. The best way to change that perception is through adoption of proactive programs by both industry and universities.

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