REFLECTIONS ON PROJECT-BASED LEARNING IN GRADUATE COURSES

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Graduate school can be the foundation for a life-long learning experience and a successful career.[1] In today's competitive world, development of effective oral and written communication skills is an essential component of an engineer's education.[1-8] The chemical engineering profession is about generating ideas and communicating them to others, and throughout their careers, most engineers spend considerable time writing memos, reports, or articles.[3,6,7] Oral communication skills (speaking to groups, interpersonal interaction, and questioning[4,5]) are just as important for a successful career. It is essential that the importance of writing and oral presentations be related to the core engineering principles that the students value.[3]

Collaborative learning is well-established as an effective method for teaching engineering students.[4] In the past few years, the author has been involved in teaching first-year graduate courses in chemical reaction engineering and process control. In both courses students have been required to work on a short course-related theoretical project based on a literature search and individual work. In addition to performance on weekly homework assignments and midterm and final tests, the grading has included performance on individual projects.

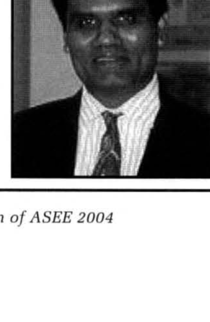
MOTIVATION AND SCOPE

The individual projects are geared toward promoting interactive learning among the class members and providing experience in communication skills and exposure to problem solving in a research environment through use of process modeling techniques in chemical and biological reaction processes and control of chemical and biological processes. The projects are intended to improve ability of students (i) to organize material, (ii) to give clear oral presentations, (iii) to clearly convey ideas, and (iv) to provide practice in preparing brief and detailed reports (initial proposal and final report). Each project brings depth in one topic in a course that emphasizes, in a relative sense, breadth.[9] The course projects allow students to investigate specific topics of interest to them in greater detail than the treatment given that topic in the lectures.[9] An added benefit of the project is that it forces students to work continuously on a particular topic throughout the semester.[4] The projects also foster faculty-student and student-student interactions on course-related topics.

Guideline information on the project, such as motivation, its scope, what is expected in the project, and important deadlines and milestones, is provided, along with the grading policy and course outline, in the first class of the semester. A list of archival journals (by no means exclusive) where the students may be able to locate technical articles needed for the project in the particular course (chemical reaction engineering or process control) is also provided in the first class.

In the reaction engineering course, any topic related to reactive processes, *i.e.*, processes involving reactions with/without other unit operations, is acceptable. The project may deal with

- *Multiphase catalytic/non-catalytic reactors*
- *Reactive separations (e.g., reactive distillation, membrane reactors)*
- *Polymerization reactors*
- *Biochemical reactors*



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- *Environmental applications of reaction engineering*
- *Electrochemical processes*
- *Catalysis*
- *Combustion processes*
- *Reactor stability and dynamics*

The list of areas is included only as a guide and is not exclusive. Projects can concentrate on different theoretical aspects of reaction engineering that include

- *Review of kinetic and reactor models in a particular field (such as biochemical, combustion, electrochemical, polymerization, and petrochemical processes)*
- *Models for a specific problem of interest*
- *Investigation of potential of a reaction process*
- *Reactor optimization*
- *Monitoring and control of reaction processes.*

The course projects allow students to investigate specific topics of interest to them in greater detail than the treatment given that topic in the lectures. An added benefit of the project is that it forces students to work continuously on a particular topic throughout the semester.[4]

In the process control course, any topic related to control of biological, chemical, electrochemical, and environmental processes is considered to be acceptable. Since multi-input (multiple manipulated inputs and disturbances) and multi-output (multiple output variables) processes (MIMO processes) are the mainstays in this course, each project has to deal with a MIMO process. The project may deal with

- *Interaction and structural analysis,*
- *Interaction compensation and multiloop control*
- *Model-based control including model predictive control*
- *Nonlinear multivariable control*
- *Adaptive control*
- *Optimal control*
- *System identification*
- *Controller tuning*
- *Control of unstable processes and processes with unusual dynamics*
- *Survey of applications of adaptive, model predictive, and multivariable nonlinear control*

If it is appropriate, students pursuing thesis work may use a topic that is related to their research, while professional engineers (part-time students) may consider a topic related to their technical work. Located in Chicago, the chemical engineering graduate program at IIT attracts a significant number of industry professionals who are part-time students interested in pursuing a Masters degree in chemical engineering. For these students, the project can be based on the student's ongoing technical work provided that the scope of the work is compatible with the course outline and that the student's employer consents to the use of relevant material for the project. If consent from the industrial supervisor cannot be obtained, the student must do an open literature-based project.

PROJECT PROPOSAL

Whether a project is based on literature search or on the student's current research/work activities, he/she selects a recent journal article (published in the previous five years) dealing with the appropriate course (reaction engineering or process control). This article serves as the core or source article for the project. Next, the student does a preliminary literature search by locating three or four pertinent cross-references, and then meets with the instructor to see if the source article and its topic are appropriate for the course project. If they are deemed not appropriate, the student must expand or modify the literature search to locate another appropriate source article.

Upon receiving the go-ahead from the instructor, the student prepares a project proposal of up to two single-spaced pages. It should be a brief narrative, in the student's own words, on the subject of the source article, its highlights, the objectives and scope of the project, and appropriateness of the project to the course outline. The student must attach the abstract of the source article to his/her proposal.

The project proposal, which is similar to an extended abstract required for presentations at professional society meetings, is due by the end of week five of the semester. The instructor reviews the proposal, evaluates it based on the quality of writing and the student's ability to state concisely the highlights of the source article and the objectives and scope of the project, and assigns a grade for the proposal. A written feedback in the form of suggested changes in writing style and technical content is given to each student. This feedback is useful in conduct of the project and preparation of detailed written report and oral presentation on the project.

CONDUCT OF THE PROJECT AND PRESENTATION PROGRAM

Each student then proceeds with the project by studying the source article and appropriate cross-references. Ongoing dialogue between each student and the instructor (during office hours) regarding the progress of the project and any glitches that may be encountered is encouraged. This dialogue enables the instructor to provide timely feedback regarding the project's progress and to help redirect the student's effort when necessary—the instructor may want to inform the student that more work needs to be done on the project, or if the project is getting overambitious, that the student should scale back his/her effort.

Each student is expected to generate independent numeri-

TABLE 1
Projects in Reaction Engineering Course

Bioengineering
continuous and fed-batch bioreactors; structured models of bacterial growth and product formation; autocatalytic reactions with Michaelis-Menten kinetics: steady state multiplicity; airlift reactors; membrane bioreactors; impact of dispersion on biological reactors; reactions in food systems: vitamin synthesis; sucrose inversion in an immobilized enzyme reactor; gluconic acid production in airlift reactors with immobilized glucose oxidase; beer fermentation using encapsulated acetolactate decarboxylase; immobilized pectinase for fruit juice production; lactose hydrolysis with immobilized β–galactosidase; oligosaccharide synthesis by enzymatic hydrolysis of polysaccharides; enzymatic alchoholysis of palm kernel oil in supercritical CO_2; antibiotics (penicillin and Cephalosporin C) production; delignification of *Eucalyptus globules*; urea reactors; photobioreactors for hydrogen production; growth rate-related changes of the starvation response regulators; energy metabolism of human liver; blood coagulation initiation by tissue factor VIIa; drug-delivery systems using intravenous drug administration; polyurethane-based hollow fiber hemodialyzers; ethylene oxide sterilization of injectable drugs and devices; kinetics of denitrifying bacteria; bioremediation of 2,4-dinitro-toluene; degradation of xeno-biotics in a two-phase bioreactor; phenol degradation in fluidized bed bioreactor

Catalysis and Catalytic Reactors
catalyst deactivation in fixed bed reactors; fluid catalytic cracking; temperature and space time trajectories for fixed bed reactors with catalyst decay; aromatics from liquefied petroleum gas using zeolites; NO_x reduction by hydrocarbons over zeolites; monolithic selective catalytic reduction reactors; oxidation of alkyl aromatics over molecular sieves; homogeneous transition metal catalysts for epoxidation reactions; self-methathesis of linear 1-alkenes; combinatorial chemistry to test catalysts for water gas shift reaction; industrial scale low-temperature water gas shift reactor; slurry reactors for catalytic hydrogenation of 2-butyne-1,4-diol to butenediol; mixed three-phase slurry reactor for methanol synthesis; the UOP Isomar process; catalytic decomposition of hydrogen peroxide; catalytic hydro-treating of unsaturated hydrocarbons; oxidation of n-butane to maleic anhydride; partial oxidation of methane to formaldehyde; methanol and dimethyl ether synthesis; adsorption and desorption of hydrogen by magnesium; $DeSO_x$/$DeNO_x$ reactions on a copper on alumina sorbent catalyst; novel multiphase reactors employing supported glass fiber catalyst; photocatalytic degradation of organic pollutants

Electrochemical Reaction Engineering
role of Nafion in methanol oxidation in direct methanol fuel cells (DMFCs); lead acid batteries: accelerated life testing and grid corrosion; rotating disc electrode study of DMFCs; electrocatalytic methanol oxidation in DMFCs; Pt-Ru anode catalysts for DMFCs; lithium batteries: diffusive transport of lithium, lithium insertion during galvanostatic discharge, and thermal runaway; anodic copper deposition; inhibition of copper corrosion by organic agents; magnesium electrode reactions in molten $MgCl_2$-NaCl mixtures; methanol electrooxidation on platinum (111); cathode electrocatalysts in polymer electrolyte membrane fuel cells and DMFCs; electrocatalytic membrane reactor for synthesis of sorbitol; electroless copper deposition; ion-selective electrodes for tracing metallic concentrations

High Temperature Reactions
methane reforming in thermal diffusion column and pyrolysis reactors; shock tube research: roles in reaction engineering; shock tubes for study of gas phase reactions; chemical and combustion kinetics in shock tubes: laser Schlieren method; thermal decomposition of 2-butyne in shock waves; natural gas combustion in fluidized beds; catastrophic thermal decomposition of toluene diisocyanate

Multiphase Chemical Reactions
fluidized bed reactors: development, four-phase model for catalytic reactions, and removal of sulfur dioxide from flue gases using metal oxide sorbents; fluidized bed combustion; high-pressure removal of hydrogen sulfide using calcium oxide; a revisit to the Claus reaction; reduction of hexavalent chromium by sulfite; flue gas desulphurization; SO_2-limestone reaction under periodically changing oxidizing/reducing conditions; liquid-liquid reaction in a semi-batch plant: nitric acid oxidation of 2-octanol; calcium sulfide formation from calcium oxide upon capture of hydrogen sulfide; mercury capture from flue gases by activated carbon; selenium removal by dry sorbents; hydrofluoric acid etching of silicon surface; oxidation of silicon germanium thin films

Polymerization Reaction Engineering
(co)polymerization: anionic, emulsion, extractive, free-radical, free-radical graft, melt-phase condensation, mixed mode, and step growth; coupling of functionalized chains at the immiscible polymer-polymer interface; attainable regions for polymerization reaction systems; control of polymerization reactors; nonlinear adaptive control of styrene polymerization; state multiplicity in polymerization reactors with recycle; kinetics of reversible A-B propagation polycondensation; (co)polymerization of ethylene, propylene, and styrene; high pressure olefin polymerization; batch polymerization: methyl methacrylate – benzoyl peroxide; production of nonionic surfactants; suspension polymerization of vinyl chloride; vulcanization reaction: cross-linking and network changes; cross-linking in thermosetting powder coatings; reactive polymer blends: nylon-6-acrylonitrile-butadiene-styrene; polycondensation of hydroxyl-functional polydimethyl siloxane; new processes for nylon production

Reactor Design and Operation, Mixing in Reactors, etc.
compartmental models for multi-chamber mixed reactors; time-dependent turbulent mixing in stirred reactors; computational fluid mixing models for reactors; energy management in reactors with flow reversal; nonideal reactors with complex reactions; nonisothermal reactors with variable density; chaos in tubular reactors with recycle; residence time distribution based on measured velocity and turbulent fields; new design formulation for multiple reactions; perturbations around steady-states: Monte Carlo method in reaction kinetics; supercritical fluid reactions; fine chemicals manufacture; oxidation of hydrocarbons to carboxylic acids; oxidation of cerous or manganese ions dissolved in H_2SO_4; the environment and reaction engineering; water quality modeling

Separation with Reactions
reactive distillation: ethyl acetate distillation and quantitative optimization; dynamic interfacial tension variation in an acidic oil/alkali/surfactant system; H_2S removal by zinc oxide - titanium oxide sorbents; chromatographic reactors; liquid-phase membrane reactors; membrane reactors for hydrogen production

cal illustrations pertaining to key concepts that are developed and/or discussed in the source article. This reinforces the key concepts in the source articles and also leads to better understanding of the required analytical and computational techniques. The exercise involves moving beyond what is currently known and provides additional insight and more calculations.[9] Further, the illustrations help in better preparation of the written report and oral presentation near the end of the semester.

TABLE 2
Projects in Process Control Course

Adaptive Control
applications: distillation column, polymerization reactor, and tubular enzyme reactor for extracorporeal leukemia treatment; strategies

Controller Tuning and Control of Open-Loop Unstable Processes
PID controller tuning: desired closed-loop responses, industrial applications, integral mode control and direct synthesis, integrating processes, and non-isothermal CSTR; external versus internal open-loop unstable processes; analytical rules for model reduction and controller tuning; gain margin and sensitivity-based PID controller design; chaotic behavior with control valve saturation; feedback control of competing autocatalators

Model-Based Control
model predictive control: chemical vapor deposition, composites manufacturing, exothermic reactions, inferential, input-output models, linear programming-based, multi-stage flash desalination, neural network-based, on-line tuning, periodically forced chemical reactors, polyethylene production, pulp digestion, refinery debutanizer, and review of applications; improved dynamic matrix control (DMC); neural nets-based dynamic optimization and universal DMC; frequency-domain closed-loop identification; double filter internal model controller for ill-conditioned distillation columns; modified Smith predictor for unstable processes; control in the presence of strong directionality and model errors; Tennessee Eastman challenge problem; supervisory control based on off-line identification

Nonlinear Control
set-based control for dead-time compensation; dynamic simulation for process identification and control; indirect feedforward control; feedback control of distributed parameter systems; nonlinear dynamic analysis for process identification and control; control of a polymerization reactor with singular characterization matrix; control of anaerobic digestion, nutrient-removing activated sludge systems, and mesophilic and thermophilic anaerobic sludge digesters; control strategies for high temperature, short-time pasteurization

Structural and Interaction Analysis
decentralized control: genetic algorithm for structure selection, pairing criteria; multivariable decoupling and multi-loop controllers; relative interaction array; structural analysis and output feedback control; online closed loop identification; dynamic output feedback control of minimum phase processes; closed loop identification and control loop reconfiguration; inverted decoupling; Nyquist-based PID controllers; dynamic structural transformations for distillation column control; selection of distillation control configuration; control of continuous copolymerization reactors; robust control: complex biological processes and distillation; decentralized control of supercritical fluid extraction; partial control of fluidized catalytic crackers

Survey Papers and Miscellaneous
process plant control: automated safety assessment, internet-based, and role of recycle; multiple oscillations in control loops; advanced process control; distillation column control; plant automation with fieldbus; control of high temperature polymerization; multi-path ultrasonic flow meters: control implications; closed loop supersaturation control of batch crystallization; control problems in materials processing; control of polymer electrolyte membrane fuel cells

In week seven, the instructor classifies the class projects into multiple groups for oral presentations near the end of the semester. The projects are arranged into sessions according to the different areas, with presentations belonging to one area being given in a consecutive manner. In organizing the sessions, emphasis is placed on the common underlying ideas in different area units to help tie the presentations together and to provide better understanding of the material learned in the class to various application areas.[5] This organization is intended to mimic the organization of technical sessions at professional society meetings.

Since oral presentations are time-consuming, they are arranged outside the lecture periods so that they do not occur at the expense of instruction time. A program of the presentations, containing information such as session name, day, time period, student name, and project title, is then distributed to all class members. The grouping of presentations described above is useful for the instructor and class members in understanding the similar and distinct features of presentations in the same area. The schedule for presentations is finalized after receiving feedback from students on the order they prefer for presentations belonging to a particular session.

A condensed list of topics spanned by the projects in the chemical reaction engineering course is provided in Table 1. For the sake of brevity, recurring words such as analysis, design, kinetics, modeling, and mechanism have not been included in the topics. The listing pertains to the course offerings in the following spring semesters, with the class strength being indicated in parentheses: 1997 (30), 1999 (33), 2001 (28), and 2002 (52).

A similar condensed list of topics for projects in the process control course is provided in Table 2, also with recurring words such as analysis, control, design, modeling, multivariable, and nonlinear being omitted for the sake of brevity. The listing pertains to the course offerings in the following spring semesters, with the class strength being indicated in parentheses: 1999 (34), 2003 (20), and 2004 (20).

WRITTEN REPORT

A detailed written project report is due by the end of week twelve of the semester. The suggested length of the report is twelve pages or less, inclusive of abstract, bibliography, figures and tables. The technical journal article is the standard for the written report.[3] The report thus includes an abstract, an introduction, a theoretical development section, the results and discussion, the conclusions and recommendations, and bibliography. The student can cut/scan and paste the key tables and figures from the source article and the three or four pertinent cross-references. The report should focus on the highlights in these articles, the student's interpretation and critique of them, independent numerical illustrations developed by the student, and any recommendations the student has about additional applications. The report should be cohesive and not compartmentalized with respect to different articles. For example, the student should not report highlights of the source article first and then those of the cross-references.

The instructor reviews each report prior to the start of oral presentations and notes any questions he has about the report and any clarifications that are needed. These matters are resolved in the discussion period following the student's oral presentation and, if necessary, in a separate meeting between the instructor and the student at a later time.

ORAL PRESENTATION AND PEER REVIEW

Each student gives a brief oral presentation pertaining to the highlights of his/her written report to the class. The presentation, which is focused on the source and auxiliary articles, is given at the end of the semester during weeks 14 and 15 of class. A student can use the multimedia presentation facilities at IIT or, if preferred, give a presentation based on Power Point or transparencies. A laptop computer, an overhead projector, and an Elmo projector (for projecting hardcopy material) are available in the meeting room, usually an auditorium.

Earlier in the semester the instructor emphasizes that use of excessive equations should be avoided in oral presentations. Equations should be used only when needed to illustrate key concepts and milestones in the articles. The same thing goes for figures and tables from the source and auxiliary articles and to illustrations generated by the student. The visual aids should not be a word-to-word copy of the student's written report. The students must make sure that their presentations will answer the three main questions

- *What was done?*
- *How was it done?*
- *What was the significance of the study?*[8]

Preparation of effective visual aids is an important skill in engineering, whether they are presented in a report, a poster, or a transparency, and many of the same skills are required in the preparation of each case.[4] Nirdosh[8] has provided several useful tips on critical aspects associated with classroom oral presentations, on preparation of visual aids, mental preparation before delivering the talk, delivery of the talk, actions to avoid during presentation, and the instructor's checklist for giving feedback to students.

Each oral presentation is kept under twenty minutes, inclusive of questions and discussion by class members. Typically, the student presentation is limited to about 15 minutes, leaving at least five minutes for questions and discussion. Each presentation begins with the instructor's brief introduction of the presenter and the title of the presentation. Participation by class members as audience and questioners in the presentations of their peers is highly appreciated and encouraged. Such participation is a good learning experience for the students and allows them to see practical applications, some of which rely on the material covered in the course and others which complement the course material.

Each oral presentation is followed by a question-and-answer period, which is highly effective for keeping the class engaged in the presentations which in turn results in generating excellent questions. This peer questioning also helps develop the communication skills of the students.[9] The way a person asks and answers questions has a significant impact in the working environment. The students learn about (and practice) how to ask, as well as how to answer, open-ended and closed-ended questions.[5]

Class participation picks up after two or three presentations on the first day of presentations. The instructor also provides constructive feedback to the presenter in front of the entire class. This helps to improve the quality of subsequent presentations since the students better understand the standards expected for their presentations.[9]

As a way to assess the effectiveness and utility of the project presentations, the class members are asked to provide anonymous written feedback on both the strengths and the weaknesses of each presentation. This feedback assists the students in maintaining the strengths and working on the weaknesses in order to improve their overall seminar presentation skills. The written feedback consists of a duly filled-out oral-presentation evaluation form that is distributed to the class by the instructor. The form enables the students to provide information on items such as organization (overview of presentation, summary, flow, targeting of audience, use of time), poise and appearance, delivery of presentation (eye contact, voice, rate of delivery), visual aids (neatness, font size, titles and labels, use of space), content (level of information, adequate discussion and analysis, summary), answering questions (conciseness, poise, interaction with audience, overall answer), appropriateness of the project to the course content, and overall effectiveness of the presentation. The presentation evaluation form is not shown here since similar forms have been provided elsewhere.[3,5] The result is that at the end of the presentation, each student has large amount of anonymous feedback from other students.[9]

By requiring students to conduct a formal review of another student's presentation, they are forced to consider what elements comprise an effective presentation.[3,10] The high value of peer review has often been documented in the literature.[3,9-11] The students do an excellent job of identifying both the strengths and the weaknesses in the presentations of their fellow students. The peer review also aids the students in recognizing the strengths and weaknesses of their own oral and written reports.[9]

This peer review is not used to determine an individual's grade on the project and hence it is nonbinding. For the instructor, its only use is to aid in assessing the effectiveness of the course. The experience of the author has been that students accept, appreciate, easily implement, and listen to the feedback they receive from their peers *vis-á-vis* the feedback received from instructor. Student feedback concerning the peer reviews has been uniformly positive.

After each four presentations, the class takes a ten-minute break. During each break and at the end of each presentation session, the class members are encouraged to discuss the key technical features of the presentations they just heard. The presentation session concludes with brief comments by the instructor on the relevance of each presentation to the course content.

Requiring oral presentations helps students develop their powers of communication and persuasion. It not only prepares them for making effective presentations, but it also helps them acquire confidence for their eventual entry into academia or industry.[8] Invariably, the students who present later in the progression make fewer mechanical or lack-of-preparation errors. It is obvious they have learned from watching and evaluating the previous speakers. This is taken into account while grading oral presentations in order to minimize the disadvantage to students who presented earlier.[3]

During each presentation, the instructor also completes the presentation evaluation form mentioned earlier and assesses how much the student learned from the project. The form is useful in grading each oral presentation and project. Grade for the project is based on the initial proposal, the written report, and the oral presentation. In future course offerings, following the suggestion of an anonymous referee, the author will consider using peer evaluation in arriving at the grade for the oral presentation.

CLOSURE

Unlike ordinary lecture courses, these courses require a significant amount of student/instructor interaction outside the scheduled class time. During the course of the semester, the instructor has private review meetings, when necessary, with each student. Considering the rewards of this exercise, for both the instructor and students, it is well worth the effort. The course projects provide access to immediate and extended applications of the material taught in the course for the instructor and class members. The material in some of the course projects can be incorporated as case studies, short homework problems, and computer assignments in future offerings of the course, which is a distinct benefit for the instructor.

The instructor should extend and tune the course material in subsequent offerings to keep pace with recent advances in the course area. The instructor and the students have the pleasure of listening to oral presentations, which range from good to excellent, and the students are able to pick up a few tips on how to make their own presentations and visual aids more effective and engaging. The project presentations also contribute to preparing graduate students for future presentations at other venues, such as professional society meetings.

Incorporation of a course project allows students to focus on one particular topic in reaction engineering or process control and to share with the class what they learned in the process, and adds depth to the breadth of material covered in these courses. The course project brings many positive factors to the learning environment of the class.[9] The projects enable students to seek education beyond the classroom, to observe and listen, to learn from their peers, to learn techniques they can use to make their presentations engaging and understandable,[1] and to understand the broader context of their and their peers' projects.[1]

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