TEACHING CELLULAR AUTOMATON CONCEPTS

Through Interdisciplinary Collaborative Learning

JOSEPH J. BIERNACKI, JERRY B. AYERS
Tennessee Technological University • Cookeville, TN 38505

The application of cellular automaton to simulate transport and reaction phenomena is not a conventional topic in most chemical engineering curricula, even at the graduate level. These techniques, however, can be powerful tools for the simulation of processes involving complex boundary conditions, multiple phases and phase transformations, and multiple reactions where traditional continuum approaches are limited, difficult to solve, or even intractable at this time.

The objectives of the course were to teach graduate and undergraduate students about cellular automaton in a collaborative learning environment. Students working together, learning from each other, and teaching each other may be one of the most effective ways to promote student learning. The study of cement hydration and microstructure development was used as a basis for the course, drawing on the interdisciplinary nature of concrete materials research to create cross-disciplinary collaborative learning teams that include undergraduate and graduate students.

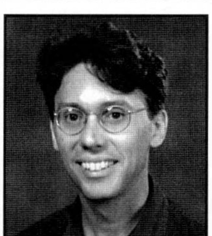
This report is based on the experiences and activities of twelve students, including three senior undergraduates majoring in chemical engineering, five master-level (two civil engineering and three chemical engineering), and four doctoral students (two civil, one chemical, and one mechanical) in a course titled "Interdisciplinary Studies in Multi-Scale Simulation of Concrete Materials." A brief course description and assessment of outcomes is given.

In an effort to facilitate learning, a collaborative environment was created in which students were not only encouraged to work together but were also placed in setting wherein they could build teaming and collaborative skills. Having MS graduate and undergraduate students in the same classroom is not unique; bringing together interdisciplinary teams that include PhD, MS, and undergraduate students, however, is less common, and assessing the efficacy of such a course is even less known.

Combining students across the vast gap between PhD studies and the undergraduate course of study creates several unique problems, including adequate differentiation between requirements and disparity in technical maturity between students. Introducing an interdisciplinary environment further complicates the problem. While this project does not attempt to prove or disprove the proposed benefits of having students *vertically* and *horizontally integrated* in this way, it does propose and demonstrates the use of assessment tools to track student satisfaction, impressions, and performance to ensure continuous improvement and viability of the approach. It is hoped that this introductory paper will help others to construct and test similar models that will eventually lead to new and better learning environments for both graduate and undergraduate students.

ABOUT CELLULAR AUTOMATON

Since cellular automaton is not a common topic in most chemical engineering curriculum, a few notes are provided here with several references. Originally introduced by von Neumann and Ulam in an effort to simulate biological processes such as reproduction, cellular automata are algorithms that define the evolution of states for a system of cells wherein a cell's state is dependent on the state of neighbor-



Joseph J. Biernacki *received his BS from Case Western Reserve University (1980) and his MS (1983) and Doctor of Engineering (1988) from Cleveland State University. He is currently Associate Professor at Tennessee Technological University where he pursues his research interests in synthesis and processing. He is also interested in research on engineering education and dedicates this paper in memory of his colleague and coauthor Jerry B. Ayers.*

Jerry B. Ayers *received his Ed.D in Science Education from the University of Georgia (1967). He served as Associate Vice President for Research at Tennessee Technological University from 1994 until his unexpected death in September, 1999. Prior to that he held positions as Director of the Center of Excellence for Teacher Education Evaluation, Associate Dean of the College of Education, and various faculty appointments at TTU.*

ing cells.[1] Cellular automaton involves dividing a system (a two-dimensional plane, for example) into cells. Then, for each cell, defining a rule or a global set of rules for all cells that govern state transitions from one automaton cycle to the next, from one *time* or system state to the next. For example, the state transition rule for a binary one-dimensional automaton might simply be to change a cell's state from zero to one whenever the sum of the cell's state and its neighbors' states is equal to one. A system of cells based on this state transition rule propagates from automaton cycle-to-cycle, as shown in Figure 1. It can be seen that these rules and the initial and boundary conditions chosen in Figure 1 produce a stable cycle of cell states after five automaton cycles. The ability of cellular automaton to generate complex behaviors based on simple rules has been used by many researchers. In the physical sciences phase transformation as well as chemical reaction and transport processes have been modeled and the mathematical interpretation of automata have been extensively studied.[2] Brieger and Bonomi offer a derivation used in this course that illustrates the connection between probabilistic state transitions and the finite difference solution of the one-dimensional transient diffusion equation.[3]

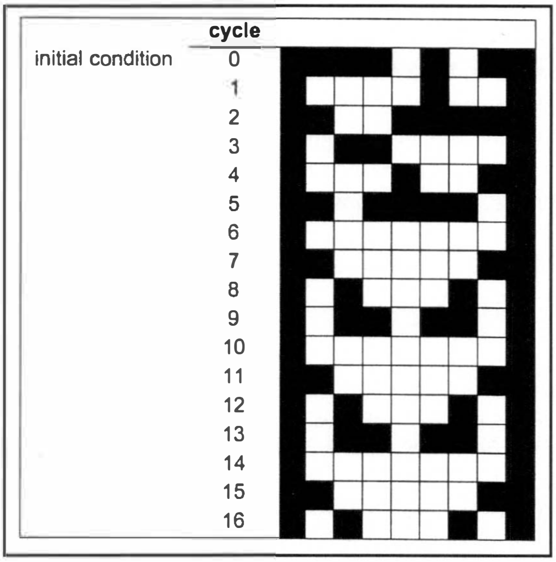


Figure 1. Propagation of cell states for the cellular automaton rule that changes the state from zero (black) to one (white) if the sum of the cell's state and its neighbor's states is equal to one.

Bentz[4] and Bentz, *et al.*,[5] at the National Institute of Standards and Technology (NIST) have pioneered and developed an extensive system of models based on digital image-based processing to simulate cement hydration and microstructure development. Cellular automata are used to subdivide the complex multiphase system of cement particles into cells, each of which are addressed with phase descriptors. Virtual particle systems are constructed that statistically mimic real particles. Appropriate automaton rules describing dissolution, diffusion, and reaction are applied, and the virtual microstructure is permitted to evolve. Characteristics of virtual hydration (such as heat evolution) as well as properties of virtual hydration product (such as porosity and permeability) have been extensively studied and reported.[6,7]

COLLABORATIVE LEARNING, TEAMS, AND INTERDISCIPLINARY ISSUES

Engineering education is faced with new pressures and challenges from industry and accreditation boards to incorporate team-oriented interdisciplinary experiences into the course of study. This current state of heightened awareness is putting pressure on departments and colleges to find ways to create curricular opportunities for students to engage in such experiences. Hicks and Katz[8] list interdisciplinary interaction among five increasing trends in modern research, while Gulden[9] and Mason[10] report improved retention of knowledge and preparedness for advanced studies when such approaches are used. Dahir reports that 80% of employers feel that being able to work in teams is an important attribute in a new graduate, yet only 25% of survey respondents felt that new graduates are adequately prepared to work in teams.[11] Findings of the SUCCEED Engineering Coalition suggest that vertical integration, *i.e.*, freshmen and seniors working together, is also an important aspect of engineering education.[12] They also conclude that "the future...may lie more in...horizontal...components than in...vertical," observing that interdisciplinary integration may be as important as vertical integration. Finally, a flood of recent attention is being given to peer-oriented teaching and learning and collaborative learning (sometimes referred to a cooperative learning).[13-16]

Collaborative learning refers to the trend toward student-centered rather than teacher-centered pedagogy wherein students not only work in teams but are also encouraged to teach and learn from each other.[17,18] Wankat and Oreovicz[18] offer a summary of models to structure teams, nurture teamwork, and promote peer teaching and learning. From these models, the *informal cooperative learning group* and the *formal cooperative learning group* were adopted. The informal model helps students learn to collaborate through short in-class team (group) activities coached by the instructor in a controlled setting. The formal learning group model is intended for long-term tasks and project assignments, much of which is to be completed out of class and without the instructor's immediate participation. The present course uses the concepts of both vertical and horizontal integration and collaborative learning in a research-based environment. Furthermore, students more advanced in their academic training, PhD-seeking students, were placed in mentoring roles.

COURSE OBJECTIVES, SCOPE, AND ASSESSMENT STRATEGY

■ ***Objectives*** The course had two objectives: 1) introducing students to digital image-based simulation using cellular automata, and 2) preparing students to meet the demands of research-oriented careers in which they will formulate relevant research questions, devise methods to investigate their questions, work in teams or small interdisciplinary groups of technical professionals who are at varying levels in their professional development, and report on their findings.

■ ***Scope*** In this course the students learn the basics of cement chemistry and the processes that describe hydration. They then learn to define automaton rules and to write code to simulate dissolution, diffusion, reaction, and precipitation for a two-dimensional, two-solid-phase system in a single fluid media. Concurrently, students learn to use research codes that are capable of simulating the full spectrum of cement phases in three dimensions and are challenged to apply their new knowledge to conduct a research-based term project.

■ ***Assessment Strategy*** Assessment tools were selected to provide pre-course information, midterm information (formative), and post-course information (summative).

1. Student journals (diaries) were used as a real-time ongoing feedback and feed-forward mechanism for course improvement.
2. A pre-course self-assessment of knowledge was used to find out what students believed they knew and what their expectations were. This form of assessment is sometimes called a *background knowledge probe* (reported by Millis and Cottell[16] and Angelo and Cross[19]) and was used to establish an effective starting point for the course.
3. A pre-course test of cognitive knowledge was used to measure what students actually knew and to establish a quantitative knowledge baseline.
4. A midterm assessment of student satisfaction and reactions to the course was used for ongoing course improvement.
5. A post-course test of cognitive knowledge was used to measure what students had learned relative to the pre-course test of cognitive knowledge (item 3 above).
6. An end-of-term (post-course) assessment of student satisfaction and reactions to the course was made.[18]

The results of the post-course test, in combination with assessment of performance on course requirements, was used to evaluate student learning and to gauge satisfaction and reactions to the course. All assessment tools, except for the pre- and post-test, were designed and interpreted by an impartial evaluator other than the instructor. A website containing the assessment instruments as well as a course syllabus and extended reference bibliography is available.[20]

COURSE REQUIREMENTS AND ASSESSING STUDENT PERFORMANCE

Assessment standards were developed for each student level. An attempt was made to align these standards with the ABET 2000 Criterion 3.[21]

■ ***Outcomes and Requirements*** *(what each student was expected to achieve and do)* Outcomes for all students were mapped to the ABET Criterion 3b (ability to design and conduct experiments), 3d (ability to function in multi-disciplinary teams, 3e (ability to identify, formulate, and solve problems), 3g (ability to communicate effectively), 3i (recognize need for and ability to engage in life-long learning), and 3k (ability to use engineering tools). In addition, *an ability to provide guidance and mentoring for junior-level researchers* was an outcome applied to PhD students only.

Table 1 lists the course requirements and relative weight for each element for the different student levels. Notable differences include the form or type of final written report. Undergraduates were required to prepare a laboratory-report style paper, MS students a thesis-style report, and PhD students a publication-style paper. This was done to give each level of students the opportunity to write and be reviewed at what should be their appropriate level. Similarly, MS students were required to write a pre-proposal at the beginning of the term, reflecting on what the team would do for the semester, and PhD students were required to prepare a more detailed proposal at the end of the term, reflecting on the team's findings. While undergraduates were not required to complete this element, they were asked to read and, where possible, to provide feedback to the authors, thereby offering the undergraduates exposure to the proposal process.

■ ***Mapping Outcomes and Requirements*** *(how outcomes were measured)* Each requirement was further mapped to one or more outcome (see Table 2). The key to using the map is to establish rubrics for each requirement that are valid measures of the criterion mastery. An example is included here to clarify how the process works.

Consider the rather difficult-to-assess outcome Criterion 3i, *the ability to recognize need for and engage in life-long learning.* This criterion was mapped to BS requirements 3,

TABLE 1
Weighting Factors for Assessment

Requirement	*BS*	*MS*	*PhD*
Participation in class, scheduled group laboratories, and team activities	5%	5%	5%
Proposal writing: MS (pre-proposal); PhD (full proposal)	NA	5%	10%
Homework (individual assignments)	50%	25%	20%
Written paper: BS (lab report); MS (thesis-styled); PhD (publication-style)	20%	25%	25%
Final presentation	20%	25%	25%
Final exam	NA	10%	10%
Course journal	5%	5%	5%
Total	*100%*	*100%*	*100%*

4, and 7—homework, written paper, and the course journal, respectively. Arguably, one might agree that one measure of the *ability to engage in life-long learning* might be to observe how well a student is able to gather and assimilate information from a variety of resources, such as the library and the internet. In this way, the quality of the literature review would be viewed as one measure of Criterion 3i, linking the written paper requirement to the outcome through a specific rubric. Similarly, connections between other select requirements and their mapped outcomes were made to establish the students' level of mastery of each. One final note is that while an outcome was established regarding mentoring abilities for the PhD students, no requirements were mapped to it. As such, no element of the grade reflected this outcome.

COURSE ASSIGNMENTS

To facilitate learning, course materials were broken into three parts: 1) learning about cellular automata, 2) learning about digital image-based simulation of concrete materials, and 3) doing research. Homework assignments were designed to enable students to learn automata concepts in a step-wise manner through programming assignments while introducing them to existing research codes in a parallel set of assignments.

"Learning About Cellular Automata (Building Cellular Automata Codes)" was a series of eight assignments in which students were required to write their own code to simulate a simple two-dimensional, two-particle reaction-diffusion process. Students were instructed in the use of VisualBasic and wrote code to both simulate the process and visualize the automata in real time.

A parallel set of assignments, "Learning About Digital Image-Based Simulation of Concrete Materials (Learning to Use the NIST Modeling Software)" introduced the students to existing research codes developed by NIST researchers. This assignment set stepped students through the process of building virtual three-dimensional microstructures from real two-dimensional electron micrographs and running hydration simulations on the microstructures they constructed. Parallel lessons covered topics such as the mathematical basis of automata and the statistics of digital image-based processing.

TABLE 2
Assessment Mapping of Outcomes and Course Requirements

	Assessment Tools (Requirements)		
Outcome	*BS Requirement*	*MS Requirement*	*PhD Requirement*
Criterion 3b	7,4,1	1,2,4,7	1,2,4,7
Criterion 3d	1,7	1,2,7	1,2,7
Criterion 3e	3,4,5	2,3,6	2,3,6
Criterion 3g	1,2,4,5,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7
Criterion 3i	3,4,7	3,4,7	3,4,7
Criterion 3k	3,4,5	3,4,5	3,4,5
Mentoring	NA	NA	NA

FORMING TEAMS

Team-oriented research was the primary focus of the course. Numerous researchers suggest strategies for forming teams. These include using personality-type indicators to help establish teams,[22,23] random selection,[24] and choosing teams to be academically balanced.[13,25] In this course it was important to have interdisciplinary teams as well as vertically integrated teams. The small student body, however, limited the possible combinations of individuals. Teams were formed by placing one PhD student on each of four teams and then identifying team members by interest and academic rank. The PhD-level graduate students were placed in a mentoring and leadership role. The hope is that students will not only learn technical content but also critical process and professional development skills through this teaming and peer-oriented mentoring.

A student-interest questionnaire was used that asked a series of five simple questions in an effort to develop an interest profile of the group (*i.e.*, What technical areas of your discipline are you most interested in?). The majority of responses were very helpful in determining the composition of the student body. From that information, teams were formed and appropriate topics identified for the research. Team compositions and topics are summarized in Table 3.

TEXT AND RESOURCES

No traditional text exists from which the course could be taught. Resource materials were assembled from sources including Garboczi, Bentz, and Snyder's *Electronic Monograph on Simulation of Concrete Materials*[26] and Bentz's guide to using the NIST models.[27]

TABLE 3
Teams and Research Topics

Team	*Topic/Title*	*Team Composition*
1	Characterization of Blast Furnace Slag and Blast Furnace Slag Reactions for Use in Blended Slag-Cement Systems	Undergraduate; Chem Eng MS Student; Chem Eng PhD Student; Chem Eng (audit)
2	Kinetics of the Reaction Between Fly Ash and Calcium Hydroxide with Microstructural Applications	Undergraduate; Chem Eng MS Student; Chem Eng PhD Student; Civil Eng
3	Determination and Evaluation of Thermal Conductivity of Neat Cements and Concrete	MS Student; Civil Eng MS Student; Civil Eng PhD Student; Mech Eng
4	Estimation of Transport Properties of Virtual Concrete Microstructure with Fractal Aggregate Distribution	Undergraduate; Chem Eng MS Student; Chem Eng PhD Student; Civil Eng

CHARACTERISTICS OF STUDENTS

■ ***Pre-course self-assessment questionnaire*** During the first class meeting, a questionnaire requesting self-rating of knowledge about the twenty major topics to be included in the course was administered. The rating scale was 5=Extensive knowledge of subject with no need for further study to 1=No knowledge of topic. Fourteen items received ratings at less than 2 (Little knowledge of subject; Need extensive information). There were no differences among the three groups of students in their mean ratings of each item or their mean overall ratings.

The students felt they knew the least about content-based topics such as use of cellular automaton, percolation theory, and cement hydration. They felt they knew the most about process elements such as writing a good research proposal or a good research paper and the role of life-long learning in research and engineering practice. In addition, the students were asked to respond to four questions related to why they enrolled in the course, their learning style, and what they felt they would learn from the course. The students were interested in modeling and simulation, some with emphasis on concrete and related problems. The students hoped to improve their research skills and the majority indicated they were either visual learners or learned by a combination of visual and auditory mean. The results of these pre-course self-assessment questionnaires were used to guide instruction content and approach.

PROMOTING COLLABORATION

Merely placing students in teams does not necessarily create an environment where they will mentor other students. To promote peer-oriented learning, several tactics were used. First, the concepts of peer-oriented collaboration were articulated during the first week of classes and were frequently reinforced thereafter. For example, collaborative learning is not copying from the person most likely to have the correct answer, but rather having that person explain or tutor others in the group toward an independent understanding of the subject. Numerous in-class and in-lab team activities (informal group settings) were scheduled. During informal group sessions, students were typically instructed to work in their formal group team. In this way, students had the opportunity to work as a group under the direct supervision of the instructor, and the instructor had an opportunity to observe group dynamics and work toward *enabling* the team. During these sessions, tasks such as conceptual algorithm design, coding at the computer, or learning to run existing software were used as short in-class or in-lab tutorials.

These sessions were used to promote interaction between introverted team members and to facilitate acquisition of basic knowledge by having the instructor join teams that were perceived to need help in either area.[16] On individual assignments such as homework, students were encouraged to work together, particularly with team members, and to learn from each other (formal group settings). In this environment, teams were on their own to schedule meeting times and achieve their goals, and teams frequently reserved time to meet with the instructor. The instructor also scheduled meetings at critical checkpoints during the semester, providing feedback to the teams. Structured team self-assessment as well as individual self-assessments were used to promote performance awareness among students and to provide a feed-forward mechanism for the instructor to monitor team progress. The self-assessment used also had specific questions regarding peer-oriented interaction and was used to gauge the relative amount of collaboration. Finally, peer review and revising of documents such as proposals and reports was modeled by the instructor and encouraged between team members.

WebBoard, an internet-based communications software, was also used to promote within and between group interaction. Any student could post to the WebBoard course conference, read, and exchange information.

ASSESSMENT

■ ***Midterm Assessment*** A midterm questionnaire was administered that included ten bipolar statements related to the course, eleven open-ended phrases the respondents could complete with one of several choices, and four open-ended questions.

Table 4 shows the mean responses to the ten bipolar statements. Since there were no differences across major or degree level, the data were combined. The students felt the course was about equally divided between a theoretical and a practical orientation. The lowest mean rating was given to the requirement of keeping a journal. The students apparently did not understand the reason for the journal nor how

TABLE 4
Mean Ratings by Students (N=12) to Ten Items at Midterm of Course

#	Stem	Mean
1	Organization of course (Unsuited to objectives 1...6 Well suited)	4.4
2	Work associated with course had (Little relevance 1...6 Great relevance)	4.7
3	Working in groups has been (No value 1...6 Great value)	4.7
4	Laboratory work has been (No value 1...6 Great value)	5.2
5	Computer exercises have been (No value 1...6 Great value)	4.8
6	Keeping a journal has been (No value 1...6 Great value)	3.8
7	Quality of instruction has been (Poor 1...6 Excellent)	4.8
8	Quality of handouts has been (Poor 1...6 Excellent)	4.4
9	Mixtures of students is (Little value 1...6 Great value)	5.0
10	Orientation of the course has been (Theoretical 1...6 Practical)	3.4

to use it in the course. Highest mean ratings were given to laboratory work and the value of having students at three distinct academic levels working together. Thus it appeared that the students had an appreciation for the value of teamwork with individuals from varying backgrounds and degrees of preparation.

In response to the eleven open-ended phrases, students indicated they felt the objectives and plans for the course were explained and organized and that they were being stimulated to think and solve problems. The highest overall ratings were given to questions regarding the willingness of the instructor to provide help and the instructor's appreciation of the student's point of view. The lowest ratings were given to questions related to the practical value of the information presented in the course. Again, there did not appear to be any differences in ratings given by the three levels of students.

Responses to the four open-ended questions provided additional insight into strengths, weaknesses, and needed improvements in the course at midterm. Students indicated that a major strength was the programming and computer skills that they were learning while the major weakness of the course was the workload. Yet, in a free-writing question, students stated that they were "learning through group projects."

TABLE 5
Summary of Pre- and Post-Test Results Based on Objectives of Course

Degree Level	N	Mean Pre-Test	Mean Post-Test
Bachelor's	3	6.7	n/a
Master's	5	7.2	13.6
Doctorate	3	8.0	16.0

■ ***End-of-Term Assessment*** A questionnaire was administered at course completion. The questionnaire included eight bipolar statements related to the course, five open-ended phrases that the respondents could complete with one of several choices, and six open-ended questions.

Responses to the eight bipolar statements were no different across major or degree level, and there were no significant differences between ratings at the midterm and at the end of the course. The average score was 4.58/6.00, with the lowest score being 3.5 for a question related to keeping the course journal. Other questions were related to course organization, workload, group work, laboratory work, quality of instruction, quality of instructional materials, and value of working with students from other disciplines.

In the five open-ended phrases, students were asked to indicate their feeling or opinion by checking the appropriate response for items related to the operation of the course. In general, the students valued the course and the instructor. Seven of ten responses said that the team approach to research with students from different disciplines and at different levels was a positive point of the course. Again, most students felt that the workload was excessive.

Responses to six open-ended questions again reinforced midterm responses to similar questions, showing that the major strengths of the course were the instructor, working in teams, the research project, and the challenge of thinking and problem solving. In general, students endorsed the idea of having students from varying backgrounds and levels being brought together. While they perceived a number of benefits to this approach, their biggest concern was the problem of scheduling times for group work.

■ ***Pre- and Post-Test of Cognitive Knowledge*** A twenty-item test was constructed around the major objectives of the course. It included mutiple-choice and short-answer questions. The test was administered on the first day of the class and again on the last day, so a comparison could be made. All students completed the instrument at the beginning of the class, while only the graduate students completed the post administration of the instrument. Because of the small sample sizes, no results of significance were computed. Table 5 shows a summary of the results of the test administration for those students for which complete data were available.

Raw scores for students enrolled in the MS and PhD programs almost doubled from the beginning to the end of the course. While this is to be expected, the pre- and post-course test enables quantification of learning. And, while there is no standard at this time to compare to the relative pre- and post-test scores, they establish a first data point for future comparative studies of course outcomes.

DISCUSSION

The major questions of this study were "Did it make a difference to have students enrolled in a course who were at the undergraduate, master's, and doctoral levels?" and "Does peer-oriented collaboration promote learning in this environment?" While this study did not attempt to provide a definitive answer to either question, the instructor was able to bring all students into the course at their apparent level of learning as measured by assessment of course requirements. Students felt that the undergraduates learned from the graduate students, and in responses to written questions as well as through interviews, they indicated a generally positive experience.

While the level of interaction between students varied, and while this was difficult to measure, one direct indicator was the log of WebBoard postings. Seventy-eight communications were posted during the sixteen-week semester. The majority of these postings were communications between

Continued on page 315.

Teaching Cellular Automation Concepts

Continued from page 309.

teams or were generally intended for the entire group to read, suggesting that the WebBoard actually promoted collaboration between teams as well as within them. Individual assignments also indicated student collaboration. Individually written computer codes frequently had similar core algorithms, suggesting those team members worked together. Analysis of individually written assignments, however, appeared more independent and were frequently considerably different. Some teams also showed more evidence of collaboration that others and were clearly working together better than others. Such teams had an observably more compatible mix of students.

Peer review of written reports was encouraged but not formally enforced. Revision of team reports, however, was required, producing significant improvement in final documents. Evidence of collaboration was also seen in individual team member reports. Collaborating teams had better integration between individual reports, particularly noted by PhD papers and proposals that clearly brought together the information reported in the individual papers for that team. Of the twelve students in the course, three have gone on to pursue research with the principal author in areas related to the course subject, thereby offering an indirect measure of success of the course.

Finally, students wrote many constructive remarks as part of the assessment process. Some comments stand out, however, as examples that we like to think illustrate the mood and tenor of the activity. This WebBoard entry was made by one of the PhD students at the end of the semester:

> I thought I would utilize the...*conference room* one more time.... I really enjoyed the...interdisciplinary class. The class was both challenging and thought provoking....You think you have a good handle on a material and then you get blindsided with a whole new aspect. I have a deeper appreciation for the other disciplines...

SUMMATION

Experimental courses such as this one should be attempted and studied in a careful and scientific manner. Further work should emphasize controlled evaluation to determine the level of learning and the interaction between students. Other alternative teaching and learning environments should be tested in an effort to optimize learning for all students.

REFERENCES

1. von Neumann, J., "The General and Logical Theory of Automata," in J. von Neumann *Collected Works,* ed. A.H. Taub, Vol. 5, p. 288; *Theory of Self-Reproducing Automata,* ed A.W. Burks, Univ. of Illinois Press, (1966); *Essays on Cellular Automata,* ed. A.W. Burks, Univ. of Illinois Press (1970)
2. Chaudhuri, P.P., D.R. Chowdhury, S. Nandi, and S. Chattopadhyay, *Additive Cellular Automata, Theory and Applications,* Vol. 1, IEEE Computer Society Press, Los Alamitos, CA (1997)
3. Brieger, L., and E. Bonomi, "A Stochastic Cellular Automaton Simulation of the Non-Linear Diffusion Equation," *Physica D.,* **47**, 159 (1991)
4. Bentz, D.P., "Three-Dimensional Computer Simulation of Portland Cement Hydration and Microstructure Development," *J. Am. Ceram. Soc.,* **80**(1), 3 (1997)
5. Bentz, D.P., P.V. Coveney, E.J. Garboczi, M.F. Kleyn, and P.E. Stutzman, "Cellular Automaton Simulations of Cement Hydration and Microstructure Development," *Modeling Simul. Mater. Sci. Eng.,* **2**, 783 (1994)
6. Bentz, D.P., and E.J. Garboczi, "Percolation of Phases in a Three-Dimensional Cement Paste Microstructural Model," *Cem. and Conc. Res.,* **21**, 325 (1991)
7. Coverdale, R.T., E.J. Garboczi, and H.M. Jennings, *Comp. Mater. Sci.,* **3**, 465 (1995)
8. Hicks, M.D., and J.S. Katz, "Where is Science Going?" *Sci., Tech., & Human Values,* **21**(4), 397 (1996)
9. Gulden, W., "Using Physics Principles in the Teaching of Chemistry," *J. Chem. Ed.,* **73,** 771 (1996)
10. Mason, T.C., "Integrated Curricula: Potential and Problems," *J. Teachr. Ed.,* **47**(4), 263 (1996)
11. Dahir, M., "Educating Engineers for the Real World: Survey of Engineers' Education Experience," *Tech. Rev.,* **96**(6), 14 (1993)
12. Marchman, J.F., "A Multi-National, Multi-Disciplinary, Vertical Integrated Team Experience in Aircraft Design," AIAA Paper 98-0822, Aerospace Sciences Meeting, Reno, NV (1998)
13. Johnson, D.W., R.T. Johnson, and K.A. Smith, *Active Learning: Cooperation in the College Classroom,* Interaction Book, Edima, MN (1991)
14. *Collaborative Learning: Underlying Processes and Effective Techniques,* K. Bosworth, and S.J. Hamilton, eds., Jossey-Bass, San Francisco, CA (1994)
15. Bruffee, K.A., *Collaborative Learning: Higher Education, Interdependence, and the Authority of Knowledge,* The Johns Hopkins University Press, Baltimore and London (1993)
16. Millis, B.J., and P.G. Cottell, Jr., *Cooperative Learning for Higher Education Faculty,* Oryx Press (1998)
17. Rubin, L., and C. Herbert, "Model for Active Learning: Collaborative Peer Teaching," *College Teaching,* **46**(1), 26 (1998)
18. Wankat, P.C., and F.S. Oreovicz, *Teaching Engineering,* McGraw-Hill, New York, NY (1993)
19. Angelo, T.A., and K.P. Cross, *Classroom Assessment Techniques: A Handbook for College Teachers,* 2nd ed., Jossey-Bass, San Francisco, CA (1993)
20. Biernacki, J.J., "Interdisciplinary Studies in Multi-Scale Simulation of Concrete Materials." Resources for faculty <http://gemini.tntech.edu/~jbiernacki/Multiscale_Simulation_Course_Info.html> Tennessee Technological University
21. *Engineering Criteria 2000,* 3rd ed., Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology
22. Emanual, J.T., and K. Worthington, "Team-Oriented Capstone Design Course Management: A New Approach to Team Formulation and Evaluation," *Proc. ASEE/IEEE Frontiers in Ed. Conf.,* IEEE, New York, NY, 229 (1989)
23. Sloan, E.D., "An Experimental Design Course in Groups," *Chem. Eng. Ed.,* **38** (1982)
24. Smith, K.A., "Cooperative Learning Groups," in *Strategies for Active Teaching and Learning in University Classrooms,* S.F. Schomberg, ed., Continuing Education and Extension, University of Minnesota, Minneapolis, MN (1986)
25. Goldstein, H., "Learning Through Cooperative Groups," *Eng. Ed.,* 171 (1982)
26. Garboczi, E.J, D.P. Bentz, and K. Snyder, "Electronic Monograph on Simulation of Concrete Materials," <http://ciks.cbt.nist.gov/garboczi>, National Institute of Standards and Technology
27. Bentz, D.P., "Guide to Using CEMHYD3D: A Three-Dimensional Cement Hydration and Microstructure Development Modeling Package," National Institute of Standards and Technology, NISTIR 5977 (1997) ❐