Final Report for Period: 07/2008 - 06/2009
Submitted on: 09/26/2009
Principal Investigator: Nersessian, Nancy J.
Award ID: 0411825
Organization: GA Tech Res Corp - GIT
Submitted By:
Nersessian, Nancy - Principal Investigator
Title:
Laboratory learning: Model-based reasoning in biomedical engineering research and instructional laboratories

Project Participants

Senior Personnel

Name: Nersessian, Nancy
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Newstetter, Wendy
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Osbeck, Lisa
Worked for more than 160 Hours: Yes
Contribution to Project:
Coding development and assessment.

Name: Malone, Kareen
Worked for more than 160 Hours: No
Contribution to Project:
She started work with us on the previous grant under the supplement for premilimary research on gender. She now has a Spencer Research Award to investigate issues pertaining to gender and minorities in biomedical engineering labs, and is continuing participation in our research group.

Post-doc

Name: Sun, Yanlong
Worked for more than 160 Hours: Yes
Contribution to Project:
Primarily developing the model-based reasoning assessment instrument and evaluating outcomes in PBL classes.

Name: Fasse, Barbara
Worked for more than 160 Hours: Yes
Contribution to Project:
Ethnographic data collection and analysis for the bio-robotics lab.

Name: Chandrasekharan, Sanjay
Worked for more than 160 Hours: Yes
Contribution to Project:
He is working on the cross-lab comparison of cognitive and learning practices.

Graduate Student

Name: Hsi, Idris
Worked for more than 160 Hours: Yes
Contribution to Project:

Ethnographic data collection. Data management.

Name: Wyche, Susan
Worked for more than 160 Hours: Yes
Contribution to Project:
Ethnographic data collection

Name: Patton, Christopher
Worked for more than 160 Hours: Yes
Contribution to Project:
Ethnographic data collection

Name: Harmon, Mary
Worked for more than 160 Hours: Yes
Contribution to Project:
Ethnographic data collection. She started for the project as an REU and is now a PhD student with a project GRA>

Name: Vattam, Swaroop
Worked for more than 160 Hours: No
Contribution to Project:
Coding - received cours credit.

Name: Dow, Steven
Worked for more than 160 Hours: No
Contribution to Project:
Ethnographic data collection. Received credit for course proect.

Name: Venkataramani, Arvind
Worked for more than 160 Hours: Yes
Contribution to Project:
Ethnographic data collection. Received course credit and then a project GRA.

Name: Atkinson, Robin
Worked for more than 160 Hours: Yes
Contribution to Project:
Data transcription and management. Paid as GRA by the University of West Georgia and from the project budget.

Name: Sambasiva, Nithya
Worked for more than 160 Hours: No
Contribution to Project:
Data collection in undergraduate instructional lab. Receiving course credit.

Name: Fennimore, Todd
Worked for more than 160 Hours: Yes
Contribution to Project:
He is working on ethnographic data collection in the instructional labs and coding and cross-lab comparison for the research labs.

Name: Richardson, Jahmeilah
Worked for more than 160 Hours: Yes
Contribution to Project:
She has done ethnographic data collection in the instructional labs and transcription.

Name: Barrett, John
Worked for more than 160 Hours: No
Contribution to Project:
He is a graduate student at the Univeristy of West GA coding transcripts under the supervision of Lisa Osbeck

Name: Bilgen, Aras

Worked for more than 160 Hours: Yes

Contribution to Project:
He has been colleting and analyzing data from the instructional labs.

Name: Gardner, Christina

Worked for more than 160 Hours: Yes

Contribution to Project:
She assisted in the assessment of learning in the instructional labs and contributed to the development of the 'Sense Making Sorter' instrument.

Undergraduate Student

Name: Mahmoudi, Dillon

Worked for more than 160 Hours: Yes

Contribution to Project:
Data analysis of computer programs created and used by Lab D and analysis of research notebooks for case study. Has been receiving course credit.

Name: Tullis, Paul

Worked for more than 160 Hours: No

Contribution to Project:
He is assisting in data coding for course credit as an undergraduate researcher.

Name: Santos, Enrique

Worked for more than 160 Hours: No

Contribution to Project:
He assisted in the development of the database of BME problems for the undergraduate courses and in website development.

Name: Stuckey, Christopher

Worked for more than 160 Hours: No

Contribution to Project:
He developed an analysis of experimentation in computational environments using the bio-robotics lab. He received course credit.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Name: Baker, Kristin

Worked for more than 160 Hours: Yes

Contribution to Project:
She assisted in ethnographic data collection in undergraduate instructional labs in systems physiology and neural engineering.

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2007 2006

REU Funding: REU supplement

Name: Schultz, Jennifer

Worked for more than 160 Hours: Yes

Contribution to Project:
She is assisting with data base construction and management. Her research project is centered on the nature of analogy use by lab

researchers. In Spring 2008 she received a GA Tech President's Undergraduate Research Award.

Years of schooling completed: Sophomore

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2007 2007

REU Funding: REU supplement

Name: Chevonski, Michael

Worked for more than 160 Hours: No

Contribution to Project:

He assisted in the ethnographic study of the systems physiology undergraduate instructional lab.

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2008 2007

REU Funding: No Info

Organizational Partners

State university of west georgia

Two faculty, one undergraduate, and one graduate student have been working on our project.

Other Collaborators or Contacts

Christophe Heintz, a postdoctoral fellow at the Konrad Lorenz Institute, Vienna, Austria spent Fall semester 2008 conducting research with us as part of his fellowship there.

Activities and Findings

Research and Education Activities:

In this final year we have focused primarily on assessing our problem-driven learning classes and instructional labs.

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

All project participants are receiving training in ethnography and/or cognitive-historical analysis. Nersessian has taught graduate course on 'cognition and culture' and 'cognitive models of science and technology' that the new project graduate students participated in. In Spring 2007 the new postdoc co-taught a course and received metoring on teaching from Nersessian. Both PIs had special mentoring meetings with the REUs, and two were also supervised by two graduate students. We continue to write articles for publication with former postdocs and graduate students, and to provide professional mentoring to them and former undergrads.

On the GA Tech campus, we have become known as 'the' place for ethnographic training and so have a significant number of students from programs such as Human-Centered Computing who come to us to do supervised projects. Osbeck and Malone are training MS graduate and undergraduate researchers at the University of West Georgia in ethnographic observation, interview, and data analysis methods.

Outreach Activities:

Newstetter, W. Designing Learning Environments for 21st Century Learners and Learning. Invited plenary. University of Wisconsin-Stout. February 2009

Newstetter: Learning in 21st century research sites. Invited talk 2008 PKAL Roundtable on the Future Undergraduate STEM Learning Environment. March 2008.

Newstetter: Built pedagogies: Designing spaces for 21st century learners. Invited talk Harvey Mudd College.February 2008.

Newstetter: Writing for Publication. NSF Engineering Education Program workshop. September 2007

Newstetter:Integrative Problem Solving and Learning across Disciplinary Divides. Invited talk at Nanyang University Singapore Distributed learning and collaboration workshop. June 2007

Newstetter: Crossing the science/engineering divide:Design principles for interdisciplinary learning environments. International conference on research in engineering education. June2007.

Newstetter: Integrative Problem Solving and Learning Across Disciplinary Divides. Invited talk at Rensselear University.May 2007

Newstetter: The challenge of interdisciplinary engineering: Designing learning environments for integrative problem solving. Invited talk Ryerson University, Department of Medical Physics. April 2007

Newstetter: Integrative Problem Solving and Learning across Disciplinary Divides. Invited talk Purdue University Department of Engineering Education April 2007

Newstetter, W. & Nersessian: (2007) Crossing the Science/engineering divide: Design principles for interdisciplinary learning environments. Submitted International Conference
on Research in Engineering Education.

Newstetter: Creating spaces to support communities of learners Project Kaliedoscope Planning Facilities for Undergraduate science and Mathmatics, Raleigh NC March 2006

Newstetter: (July, 2006) Laboratory Learning: Cognitive and Learning Practices in University Research Laboratories. Cognitive Science Society Conference, symposium, Vancouver Canada.

Newstetter:(2006) Problem-based Learning Workshop. ASEE 06 Chicago.

Newstetter: February 2007--Integrative Problem Solving and Learning across Disciplinary Divides. Montana State University. College of Engineering Seminar Series.

Newstetter: December 2006-- Creating Integrative Thinkers and Problem solvers for Healthcare Innovation. Project Kaleidoscope sponsored talk. Young Biology Teachers Conference, Wuhan, China

Newstetter: June 2006--Problem-based Learning: Creating Cognitive Apprenticeships for Undergraduate Learning. What the Best Teachers Do Summer Institute, Montclair, NJ.

Newstetter: July 2006--Creating Cognitive Apprenticeships for Undergraduate Learning. Engineering Education Leadership Institute, Detroit, MI.

Newstetter: March 2006?Creating spaces to support communities of learners. Project Kaleidoscope Planning facilities for Undergraduate Science and Mathematics. Meredith College, Raleigh, NC.

Newstetter: Creating Cognitive Apprenticeships for Undergraduate Learning . Project Kaleidoscope National Colloquium in Kansas City, October 2005.

Newstetter: 'The nature of learning on the frontiers of science,' Whitaker Educational Summit Meeting, March 2005

Newstetter: 'The nature of learning on the frontiers of science,' EDUCATE conference. Emory University, February 2005.

Nersessian: 'Interdisciplinarity on the benchtop,' Workshop on the Philosophy of Interdisciplinarity, Georgia Institute of Technology, September 2009

Nersessian: 'Engineering models: model-based problem solving in biomedical engineering,' Department of Philosophy, University of Toronto, CA, September 2009

Nersessian: 'Engineering models: model-based problem solving in a neural engineering laboratory,' Neurophilosophy Colloquium, Georgia State University, September 2009

Nersessian: 'Engineering analogies' symposium on Analogies and Models in Science Practice and Learning, Cognitive Science Society Annual Meeting, Amsterdam, July 2009

Nersessian: 'Modeling practices in conceptual innovation' workshop on Concepts and Investigative Practices, Technical University, Berlin, May 2009

Nersessian: 'Mental modeling in conceptual change,' American Education Researchers Association Conference, symposium Beyond Cognitive Conflict: Mechanisms and Instructional Strategies that Promote Conceptual Change, April 2009

Nersessian: 'Engineering models: model-based simulation in biomedical engineering,' Workshop on Cognitive Theories of Science & Religion, Johns Hopkins University, March 2009

Nersessian: 'Model-based problem solving in interdisciplinary engineering sciences: investigations of practice and learning,' Peabody College of Education, Vanderbilt University, February 2009

Nersessian: 'Learners in complex settings: model-based simulation in biomedical engineering,' Harvard Graduate School of Education, March 2009

Nersessian: 'Boundary Objects, Trading Zones, Adaptation Spaces: How to create interdisciplinary emergence?' conference on Integrating Services, Integrating Research for Co-Occurring Conditions, NIDA, March 2009

Nersessian: 'Engineering models: model-based simulation in biomedical engineering,' 2nd International Conference of the Society for Psychology of Science and Technology, Berlin, July 2008

Nersessian: 'Simulative modeling in interdisciplinary engineering sciences,' workshop on Cultures and Styles of Scientific Practice, Fondation des Treilles, France, May 2008

Nersessian: 'Learners in complex settings,' symposium on REESE sponsored research, Cognitive Science Society Annual Meeting, Washington, DC

Nersessian: 'Designing environments for agentive learning,' Open Learning Interplay, Hewlett Foundation, Carnegie Mellon University, March 2008

Nersessian: 'How do engineering scientists think?' Society for Theoretical and Philosophical Psychology, February 2008

Nersessian: 'Agentive learning in biodmeical engineering,' Open Learning Workshop,Carnegie Mellon University, December 2007

Nersessian: 'Constructing to discovery,' 2nd European Cognitive Science Conference, Delphi, Greece, July 2007

Nersessian: 'Constructing to discovery,' Southern Society for Psychology and Philosophy, April 2007

Nersessian: 'Reasoning with models in scientific discovery,' American Philosophical Association, March 2007

Nersessian: 'Model-based reasoning in interdisciplinary engineering,' Workshop on the Technological Sciences, Eindhoven, the Netherlands, January 2007

Nersessian: "Putting a thought on the benchtop': The distribution of representation in model-based reasoning in a BME research lab,' Cognitive Science Society Conference, symposium, July 2006, Vancouver, CA

Nersessian: 'Interdisciplinarity on the benchtop,' NSF workshop: The scientific basis of innovation and discovery, May 2006

Nersessian: 'Boundary objects, trading zones, adaptation spaces: How to create interdisciplinary emergence?' Invited NSF plenary for SLC PI meeting, November 2006

Nersessian: 'Interdisciplinarity on the benchtop,' Radcliffe Institute for Advanced Study, Public Lecture, March 2006

Nersessian: 'Interdisciplinarity on the benchtop,' 2nd Biennial Conference of the Russian Cognitive Science Society, St. Petersburg, Russia, Invited Plenary, June 2006

Nersessian: 'Interdisciplinarity on the benchtop,' Connecticut College, May 2006

Nersessian: 'Model systems in biomedical engineering,' Harvard Univeristy, Department of History of Science, October 2005

Nersessian: 'Distributed model-based reasoning in science,' Philosophy of Science Association, November 2004

Nersessian: 'Model-based reasoning in distributed cognitive systems,' University of Torino, Italy, December 2004

Nersessian: 'Inquiry: How does science work?' Rutgers University, February 2004, NSF-sponsored workshop on inquiry in science and science learning

Nersessian: 'Model-based reasoning practices in science,' invited presentation to National Academies of Science committee on K-8 science education, March 2005

Nersessian: 'Model-systems in bio-engineering research laboratories' History of Science Department, Harvard University, October 2005

Malone: 'Using Lacan to think through the subject of discourse in psychology' American Psychological Association National Meeting, Toronto, CA August, 2009

Malone: Symposium Presentation for the Society for Theoretical and Philosophical Psychology, Division 24 of the American Psychology Association, Miami, FL. February, 2008.

Malone: 'Logic of the Subject and the Other: Research Science, Race, Gender.' American Psychological Association Annual National Conference. San Francisco, August 2007

Malone: A Qualitative and Theoretical Analysis of Race & Gender: Performativity and Its Constraints. International Society of Theoretical Psychology. Toronto, Canada, June 2007

Malone: 'Knowledge Making, Gender Identity and Desire in a Research Lab' Emory University, February 2005

Malone & Bernard:'The Production of Gender and Knowledge in a Science Lab.' symposium, American Psychological Association, National Convention, Washington, D.C., August 2005

Malone, Newstetter, Barabino: 'Valuing diversity as it happens: Exploring laboratory interactions when more is going on than science.' ASEE/IEEE Frontiers in Education Conference San Diego, 2006

Malone & Barabino:'Narrations of Race in the STEM Research Settings: Identity Formation and its Discontents.' Conference: Advancing the

Status of Diverse Women in Science, Technology, Engineering & Mathematics. Jackson State University, November 2006

Malone & Bernard:'The Production of Gender and Knowledge in a Science Lab.' Symposium, the American Psychological Association, National Convention, Washington, D.C., August 2005

Malone:'Knowledge Making, Gender Identity and Desire in a Research Lab' The Psychoanalytic Studies Program: Emory University Colloquium lecture, Atlanta Georgia. February 2005

Osbeck: 'Cognition in transition,' American Psychological Association Annual Meeting, Boston. August 2008

Osbeck: Organized symposium for first annual meeting of the Society for Theoretical and Philosophical Psychology: What psychologists can learn from studying scientists. February 2008

Osbeck: 'Critical transdisciplinary engagement through the psychology of science.' International Society for Theoretical Psychology, York University, Ontario, June, 2007.

Osbeck, Newstetter,& Nersessian: 'Positioning in the laboratory.' Presented at the inaugural meeting of the International Society for Psychology of Science. Mexico. October 2006.

Osbeck: 'What is learning?' University of West Georgia, Center for Teaching and Learning, April 2005

Osbeck, L. & Nersessian, N.'The distribution of representation,' International Post Cognitivist Psychology Conference, Glasgow, Scotland. July 2005

Osbeck & Good: (University of Durham, UK) (2005, August). 'Representing representation: Representation as practice.' also presented at the 113th Annual Meeting of the American Psychological Association, Washington, DC. August 2005

Harmon: 'Cognitive partnerships on the bench top: Designing to support scientific researchers,' conference on Designing Interactive Systems, Cape Town, South Africa, January 2007

Patton: 'Paradigm shifting in a distributed cognitive system,' Cognitive Science Student Conference, Georgia Tech, April 2005

Journal Publications

Newstetter, Wendy C., "Designing cognitive apprenticeships for biomedical engineering", Journal of Engineering Education, p. 207, vol. 94, (2005). Published,

Newstetter, Wendy C., "Fostering Integrative Problem Solving in Biomedical Engineering: The PBL Approach", Annals of Biomedical Engineering, p. , vol. 34, (2006). Published,

Malone, K., Nersessian, N., Newstetter,N., "Gender Writ Small: Gendered Enactments and Gendered Narratives about Lab Organization and Knowledge Transmission in a Bio-Medical Engineering Lab Research Setting.", Journal of Women & Minorities in Science & Engineering., p. 61, vol. 11, (2005). Published,

Kurz-milcke, E., Nersessian, N & Newstetter, W., "What has history to do with cognition? Interactive methods for studying research laboratories.", Cognition and Culture, p. 663, vol. 4, (2004). Published,

Nersessian, N.J., "The cognitive-cultural systems of the research laboratory", Organization Studies, p. 125, vol. 27, (2006). Published,

N.J. Nersessian, "Model-based reasoning in distributed cognitive systems", Philosophy of Science, p. 699, vol. 72, (2006). Published,

Osbeck, L., Malone, K., & Nersessian, N., "Reflections on critical engagement with the mainstream psychology.", Theory and Psychology, p. , vol. 17, (2007). Published,

Osbeck, L., Malone, K., & Nersessian, N., "Dissenters in the Sanctuary: Evolving frameworks in "mainstream" cognitive science.", Theory and Psychology., p. 243, vol. 17, (2007). Published,

Malone, K. & Kelly, S., "Women in Science: Should we bother with a Psychoanalytic Viewpoint?", Psychoanalysis, Culture & Society, p. 207, vol. 10, (2006). Published,

Osbeck, L. & Nersessian, N., "The distribution of representation.", Journal for the Theory of Social Behavior, p. 141, vol. 36, (2006). Published,

Chandrasekharan, S. & Nersessian, N.J., "Counterfactuals in science and engineering", Behavioral and Brain Sciences, p. 454, vol. 30, (2007). Published,

Nersessian & Chandrasekharan, "Hybrid analogies in conceptual innovation in science", Jounral on Cognitive Systems Research, p. 178, vol. 10, (2009). Published,

Chandrasekharan, "Building to Discover: A common coding model", Cognitive Science, p. 1059, vol. 33, (2009). Published,

Chandrasekharan, Mazelek et al., "Ideomotor design", Cognitive Systems Research, p. , vol. , (2009). Submitted,

Chandrasekharan, Osbeck, "Rethinking Situatedness: Environment structure in the time of common code", Theory and Psychology, p. , vol. , (2009). Accepted,

Osbeck, "The Critical Place of Personalism", New Ideas in Psychology, p. , vol. , (2009). Accepted,

Osbeck, "Transformations in Cognitive Science: Implications and issues posed", Journal of Theoretical and Philosophical Psychology, p. 16, vol. 29, (2009). Published,

Osbeck, Nersessian, "Forms of Positioning in Interdisciplinary Science Practice and their Epistemic Effects", Journal for the Theory of Social Behaviour, p. , vol. , (2009). Submitted,

Osbeck, Nersessian, "Emotion in Research Practice: An analysis of interview data from engineering science laboratories", Journal of Psychology of Science and Technology, p. , vol. , (2009). Submitted,

Osbeck, Gardner, Nersessian, Ross, Newstetter, "Distinguishing Forms of Sense Making in Science Learning: Methodological innovations and challenges", Cognition and Instruction, p. , vol. , (2009). Submitted,

Malone, Barbarino, "Logic of the Subject and the Other: research identities and race", Annual Review of Critical Psychology, p. , vol. , (2009). Accepted,

Nersessian, "How do Engineering Scientists Think? Model-based reasoning in interdisciplinary engineering", Topics in Cognitive Science, p. , vol. , (2009). Accepted,

Newstetter, Nersessian, "Learning on the Frontiers of Science", Journal of the Learning Sciences, p. , vol. , (2009). under revision,

Newstetter, W, Behravesh, E. Nersessian, N. Fasse, B., "Design principles for problem-driven learning laboratories in biomedical engineering education", Annals of Biomedical Engineering, p. , vol. , (2009). Submitted,

Books or Other One-time Publications

Newstetter, W., Kurz-milcke, E., &
Nersessian, N., "Agentive learning in engineering
research labs", (2004). refereed conference proceedings, Published
Collection: Proceedings of 2004 FIE Conference.
Bibliography: [CD ROM] Savannah, Ga. IEEE.

Newstetter, W., Kurz-milcke,E., &
Nersessian, N., " Cognitive partnerships on the bench
tops.", (2004). Refereed conference proceedings, Published
Editor(s): Yasmin Kafai & William Sandoval
Collection: Proceedings of 2004 ICLS Conference
Bibliography: AACE

Newstetter, Wendy C., "Problem-based learning in biomedical
engineering", (2005). Conference proceedings, Published
Editor(s): Jack Linehan
Collection: Whitaker Biomedical Engineering
Summit II
Bibliography: Whitaker Foundation Publication

Nersessian, N.J., "Interpreting scientific and engineering practices: Integrating the cognitive,
social, and cultural dimensions", (2005). book chapter, Published
Editor(s): M. Gorman, et al.
Collection: Scientific and Technological Thinking
Bibliography: Hillsdale, NJ: Lawrence Erlbaum

Nersessian, Kurz-Milcke, Davies, "Ubiquitous computing in science and engineering research laboratories: A case study from biomedical engineering", (2005). book chapter, Published
Editor(s): G. Kouzelis, et al.
Collection: In-Use Knoweldge
Bibliography: Berlin: Peter Lang

Nancy J. Nersessian, "Creating Scientific Concepts", (2008). Book, Published
Bibliography: MIT Press

Sun, Y., Newstetter, W., Nersessian, N.J., "Promoting model-based reasoning in problem-based learning
", (2006). Refereed Conference Proceediings, Published
Editor(s): N. Myiake, R. Sun
Collection: Proceedings of the Cognitive Science Society 28
Bibliography: Cognitive Science Society

Nersessian, N.J., "How Science works: Model-based reasoning in scientific practice", (2008). book chapter, Published
Editor(s): R. A. Duschl, R. E. Grandy
Collection: Teaching Scientific Inquiry: Recommendations for Research and Implementation
Bibliography: Rotterdam, NL: Sense Publishers

Nersessian, N.J., "Mental modeling in conceptual change", (2008). book chapter, Published
Editor(s): S. Vosniadou

Collection: International Handbook of Conceptual Change
Bibliography: London: Routledge

Malone, K., Newstetter, W. Barabino, G., "Valuing diversity as it happens:
Exploring laboratory interactions when
more is going on than science.", (2006). Refereed Conference Proceedings[CD-Rom] San Diego, CA., Published
Bibliography: ASEE/IEEE Frontiers in Education

Osbeck, L., Newstetter, W., &
Nersessian, N., "Positioning in the laboratory.", (2006). Refereed Conference proceedings, Published
Bibliography: International Society for Psychology of
Science

Osbeck, Nersessian, Malone, Newstetter, "Science as Psychology: Sense-making and Social Identity in Science Practice", ( ). Book, contracted with Cambridge University Press, projected 2009 completiion
Bibliography: Cambridge Univeristy Press

Nersessian and Patton, "Model-based reasoning in interdisciplinary engineering", (2009). book chapter, Published
Editor(s): Meijers, A.
Collection: Handbook of the Philosophy of Technology and Engineering Sciences
Bibliography: Amsterdam: Elsevier

Harmon and Nersessian, "Cognitive partnerships on the benchtop: designing to support scientific researchers", (2008). refereed Conference Proceedings, Published
Collection: Proceedings of DIS 2008
Bibliography: ACM SIGGRAPH ARTS

Newstetter, N
Nersessian, N., "Learners in complex settings: Agentive learning in university research laboratories ", (2009). conference proceedings, Published
Collection: Proceedings of 2009 NARST Conference.
Bibliography: [CD ROM]Garden Grove, CA.

Newstetter, W., Johri, A., & Wulf, V., "Laboratory Learning: Industry and University Research as Sites for Situated and Distributed Cognition", (2008). conference proceedings, Published
Collection: Proceedings of International Conference of Learning
Sciences 2008
Bibliography: [CD-ROM]

Web/Internet Site

URL(s):

http://www.bme.gatech.edu/pbl/internal/problemsList.php

Description:

This site contains a database of PBL problems for use in high school, college or graduate schools. It also contains some useful instructions to the PBL facilitator who might use the problems.

Other Specific Products

Product Type:

Data or databases

Product Description:

We have created a co-web archive of all transcribed interviews and other material collected on the three research labs that it is possible to sanitize.

Sharing Information:

We will make as much of the data we have collected on the research labs available to other researchers when requested by them.

Product Type:

Teaching aids

Product Description:

We are developing design features of models of problem-driven instructional labs in a format that will transfer across many STEM disciplines.

Sharing Information:

We will link the final product off of the pbl web page, and we will present the material in conference presentations and publications.

Product Type:

assessment instrument

Product Description:

We have developed a qualitative assessment instrument we call the "Sense Making Sorter." The Sense-Making Sorter is a one-page form developed to summarize and organize evaluations of sense-making practices across three phases of inquiry. Although derived from an open-coding process, the form enables researchers to code student products (lab notebooks in our case) efficiently and uniformly. For each learning artifact, raters assign 0, 1, or 2 points to each of five sense-making practice dimensions, yielding a possible total of 10 (the ?total sense-making score?). Group averages (e.g. between course formats) can be compared for either the total sense-making score and/ or for each of the three phases of sense-making.

Sharing Information:

We are publishing it along with a description of how it was developed and can be used.

Contributions

Contributions within Discipline:

This is an interdisciplinary project focused on learning where Cognitive Science, Learning Sciences, Science and Technology Studies, and Engineering Education Research are the principal fields. The laboratory plays a central role in the education of undergraduate and graduate science and engineering students, yet practices in research and instructional labs have rarely been the focus of research on learning. Additionally, although problem-based learning has been extended from its origins in medical schools to other disciplinary settings, to the best of our knowledge, it has not been incorporated as a method into instructional laboratories. Finally, in many areas of K-16 education there is significant interest in and work on the development of 'model-based' science curricula. We expect our analysis of the nature of model-based reasoning and understanding to contribute to these efforts.

Contributions to Other Disciplines:

Nearly twenty years ago, the National Science Foundation realized the value of having undergraduates engage in meaningful research ideally as a member of a research lab (NSF, 1989). While funding for such opportunities and the recognition if their value of have grown, it will never be possible to place all students in research settings. We are seeking ways to retool traditional science and engineering instructional labs so that they better replicate the kinds of research environments from which undergraduates seem to reap such benefits. Our comparative studies of research labs and instructional labs has allowed us to see where there is alignment in activity type, social configuration, tool use and reasoning and where these two sites differ dramatically. We are able to do this by investigating both sites using ethnographic methods that capture practices as they unfold day to day. This work will lead to new models for science learning in instructional labs that will bring all students closer to the work of scientists as they work and learn at the benchtop.

Contributions to Human Resource Development:

We believe that NSF should be contributing to research about how best to educate future generations of scientists and engineers. Researching and designing undergraduate learning environments that replicate early and afford the kinds of problem solving that drive discovery at the frontiers of science is a promising avenue for improving education. We have been developing new models for instructional science and engineering labs that aim to do this. We take a problem-based learning (PBL) approach, which engages students in developing original questions and protocols for answering these questions while also honing their laboratory skills and techniques. These new models challenge the prevalent models of instructional labs that enact a recipe following approach with no original work required of the students. In these labs, students learn not only from succeeding but also from failing, an important lesson for anyone doing original research. Open-ended questions and collaborative team projects help students begin to see how their own personal goals might align with the enterprise of science-making. This

we hope will lead to changed worldviews and the development of science-making identities, fundamental to sustaining future scientists towards advanced degrees and research success.

In addition, all but 2 of our undergraduate students have gone on to graduate school in STEM fields or medicine. The other two are working in computer science positions.Two of our former CS undergraduates, after a couple of years working in CS positions, were accepted this Fall into the New School for Social Research -- one had never considered graduate school as an option until he worked on our project and discovered research. Several of our MS students are currently in PhD programs in STEM fields.

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

This research contributes directly to the training of engineers and scientists who are addressing some of the most important medical problems facing people today, such as heart disease, stroke, paralysis, and neurological impairments.

Conference Proceedings

Categories for which nothing is reported:

Contributions: To Any Resources for Research and Education

Any Conference

Over the course of this research we have been engaged in the study of practitioners (graduate students, undergraduates, postocs, PIs) in sites of STEM research with the objective of understanding cognition and learning in interdisciplinary settings and translating findings about their cognitive practices, the learning challenges associated with these practices, and the community practices that lead to successful learning into designs for instructional settings. We have also been engaged in using our findings to further cognitive science research on mental modeling, analogy, imagistic reasoning, conceptual change, distributed cognition, and interdisciplinary reasoning and problem solving.

Two chief motivations underlay the choice of biomedical engineering research sites as models for classrooms. First, research laboratories are central to all graduate education in science and engineering. They are also where science and engineering identity trajectories at the undergraduate level are often strengthened and career paths that include graduate school become a vision. Second, learning in interdisciplinary fields such as biomedical engineering challenges students to merge science and engineering concepts, models, and methods, which can often be - or seem to be - at odds with one another. In most science and engineering fields, the research laboratory is a prime locale for developing practices that lead to successful melding in problem solving.

This project built upon our prior investigation of two research labs: one in tissue engineering, the other in neural engineering, and on our initial development of modified-Problem Based Learning graduate and undergraduate classes in the new BME program. In this phase, we 1) continued our analyses of the labs and classrooms; 2) developed ways of assessing mastery of model-based reasoning as a means of problem solving; 3) added an out-of-domain research lab in Bio-robotics to address robustness of transfer of learning findings; 4) developed several models of Problem Driven Learning instructional labs; and 5) conducted a controlled study between our PDL instructional lab in systems physiology and a traditional technique driven instructional lab, and further refined and implemented the PDL lab an additional time.

To conduct this research, we built an interdisciplinary research group (***C***ognition and ***L***earning in ***I***nterdisciplinary ***C***ultures) with expertise in cognitive psychology, philosophy and history of science, learning sciences, cognitive anthropology, linguistics, humanistic psychology, computer science, gender & science, and biomedical engineering. There have been 6 Sr. Personnel, 4 PostDocs, 14 Graduate Students (MS and PhD), and 7 Undergrads involved in conducting this research (not all funded by NSF). We extended the project beyond our original 2007 date because of lag times in scheduling of courses by the BME department and because of the need bring up to speed the new students and postdocs added in the third year of our project.

We characterize our research as transformative and translational. It is transformative along three dimensions. First, as an emergent interdiscipline, biomedical engineering integrates the tools, knowledge, and methods from engineering and the sciences towards both basic biological research and the development of healthcare applications. While this integration is critical to advances in biology and in addressing problems associated with disease prevention, detection

and treatment, it creates unique challenges for BME educators. Unlike other post-secondary courses of study in engineering that have evolved to have well-practiced traditions regarding course content and sequencing instantiated in a myriad assortment of textbooks, BME is still in the throes of developing those traditions both in the classroom and the instructional laboratory and our research has been impacting not only the educational program at GA Tech, but also programs at other institutions through our outreach activities. Second, in addition to our findings, our research methodology has been influencing the new engineering education PhD programs at Purdue and VA Tech, where Newstetter is now a member of the advisory boards. Third, it is providing novel insights for the cognitive and learning sciences in that studies of cognition and learning in interdisciplinary contexts are scant, as are studies of graduate students as learners and undergraduates as researchers. The latter represents a potentially new paradigm in learning sciences research. Rather than taking the customary approach of studying the practices of experts in a field and using these to guide novice instruction, our goal has been to understand both the challenges to learning and what makes for successful learning in complex settings of STEM practice and use that understanding to design educational environments that support complex learning in formal instructional settings. In the laboratory investigations we have sought to understand 1) the reasoning and problem-solving strategies that drive the work of the research lab (cognitive practices) and 2) how lab newcomers apprentice to and learn these strategies (learning practices). With this understanding, our goal has been to design BME instructional settings – classroom and laboratory – that better approximate the ecological features that support rich, robust learning in complex settings. As such, these efforts represent a *translational* model of educational research in which findings from studying complex in-the-world learning environments are appropriately translated into design principles (Brown, 1992; Brown & Campione, 1994) for classrooms.

Building a culture committed to problem-driven learning

Over the last five years, we have learned a great deal about how to design and implement curricula at the post secondary level that strives to develop model-based reasoning and problem solving capabilities in engineering students. We began this work with the belief that problem-based learning (PBL), widely utilized in medical education to develop hypothetic-deductive reasoning and in K-12 for content engagement and mastery, could be modified to support engineering education, where modeling and model-based reasoning are central. We characterize our modified PBL approach as problem-driven learning (PDL), perhaps a seemingly trivial distinction. However, as we have observed in the research laboratories, the problem does not merely situate or anchor learning; rather it compels, provokes and drives it forward. This relentless need to make progress in a complex problem space is what we have tried to replicate in the design of our classrooms. This endeavor has involved the design, development and assessment of two learning environments and the development and evaluation of assessment instruments.

I. A first methods course-How to think like an engineer

Over the course of our research, we have iteratively designed/refined a first course in engineering problem solving, a methods course, that utilizes a problem-driven learning approach. To arrive at a stable but flexible version of this course, we used a *design studies* approach in which we ran a variety of test problems generated by biomedical engineering faculty (See http://www.bme.gatech.edu/pbl/),assessed the appropriateness and learning possibilities of each, identified where students needed more support and developed it, and experimented with assessment instruments. The course enrolls approximately 80 students in the Fall semester, 180 in the Spring, and 30 in the Summer. The students meet once a week together in a lecture format where they are introduced to various areas of research in biomedical engineering. At the start of the semester the students are divided into problem-driven learning sections of 8 students who meet twice a week with a faculty facilitator to discuss their progress working on the problems as a group outside of the class meetings.

We sought to make this an *agentive learning* experience for the students so we worked to apply the design principles that we developed from the research laboratory investigations.

A. Learning is driven by the need to solve complex problems.

Knowledge building in the labs is driven by the need to solve problems. Much work goes into continually re-articulating the larger problem and determining tractable pieces through which progress can be made. In working toward solutions, multiple questions need to be addressed; multiple forms of activity need to be undertaken; and multiple forms of data generation, gathering, and analysis need to be undertaken. The complex, ill-defined nature of the problems promotes the distribution of problem solving activities across a community of researchers.

B. Organizational structure is largely non-hierarchical

Knowledge building on the frontiers of science and especially, though not exclusively, at the crossroads of two or more disciplines is most often distributed across individuals while accruing individually. The lab director has the big picture in mind, but s/he does not have all the knowledge, the skills, or the expertise to answer all the questions or resolve all the problems. Actually, no one does. Rather it is the group as a whole that possesses the expertise to move forward. This means that the oft-studied distinction between novice and expert is of less importance here. In a sense, everyone is a novice, which affirms the new lab member's status as not especially remarkable. What is of importance here is how in this nonhierarchical setting the newcomer can envision herself as a major group player, perhaps even the expert in her particular domain or part of the greater problem space. This is a great motivator for the learner to find more and more venues for developing knowledge and a scientific identity.

C. Learning is relational

Conducting research requires lab members to be agents in forming relationships. In our investigation of the research labs we witnessed researchers forming relationships both with people and with the technological artifacts they design and build to carry out their research (9). In the instructional design project, we focused on the former. Research requires developing independence but interdependence as well. As we saw in the lab studies, a great deal of lab knowledge resides in the heads, experiences and notebooks of the various members. As repositories of scientific and engineering know-how, senior lab members become identified with specific lab devices, techniques, research questions, and evolving protocols, assays, and devices. Newcomers to the lab need to develop relationships with these people, learning to ask questions and seek advice to get access to this knowledge. And in developing relationships, they learn about the senior lab members' experiences with particular devices and the requisite aspects of lab history that are often poorly chronicled in other places. With strong social relationships comes the potential for a wealth of problem-solving capacity and knowledge acquisition. But the lab newcomer has to develop the habit of first identifying and then going to people in the know.

D. Multiple support systems foster resilience in the face of impasses and failures.

The social aspect of learning is critical for another reason. Learners need to understand that setbacks, frustration, and uncertainty are constant companions in doing the work of science. In the face of these repeated setbacks, learners need a sense that they are not alone, that their failure is not singular but is rather a feature of lab life. This sense of membership mitigates the feeling of futility that could pervade the community. Having relationships with others in times of failure affords two things: a point for commiseration and solidarity and potential partners for problem solving. Without the close social fabric of the lab, such experiences of failure would be experienced in isolation. Instead, "failure" in the lab becomes an opportunity to deepen one's understanding of the project under investigation, the nature of research, and the ethos of the community.

E. Building serves as entrée

One of the features we have found most interesting in regards to laboratory learning is how quickly newcomers find ways to make contributions to the work of the lab. An activity commonly taken up by newcomers is building, the activity that tends to drive research in both labs. Building artifacts affords immediate opportunities for rapid participation and, importantly, the build-up of requisite knowledge. Building affords a ready and easy opportunity for membership in and contribution to the lab setting, which serves as first steps towards full membership. At the same time, the numerous jobs to be tackled or sub-problems to be addressed allow for researchers to become free agents of their learning, much more so than in a traditional apprenticeship situation where practices are relatively static and entry points much more prescribed. The wide open knowledge frontier and relatively flat hierarchy

make for hospitable first beginnings for new lab members, even undergraduate students.

Taken together, we characterize the educational model derived from the study of learning in research settings as *agentive.* In an agentive learning environment, students are agents of their own learning and in determining a course of action. In this sense, they are actively constructing understanding and knowledge as they work through problems. In the research labs, learners enlist and interact with people and laboratory tools and devices. They develop strategies for solving the problems that arise, for dealing with impasses and failure and for seeking help with they experience difficulties. They utilize their hands and minds to solve open-ended, ill-constrained and ill-structured problems. They build when required to do so; they do research and then use this research to guide decision-making. When in an agentive learning environment, students need to become self-directed, empowered learners and problem solvers, who utilize previous learning experiences for the current learning situation, all features of what is called "constructivist learning."

Beginning from these principles, we have developed a significant system of scaffolding that makes it possible for teams of first year biomedical engineers to tackle complex, open-ended problems without undue frustration and failure. The scaffolding structure consists of

- Three carefully sequenced problems
- Specially designed PDL learning spaces to support collaborative problem-solving and model-based reasoning.
- Assessment rubrics/sheets for scoring the problem presentations
- Student writing guidelines for developing the reports that are the culmination of each problem
- Faculty facilitators for each team of eight students

The three problems have been designed for redundancy and re-visitation of topics from different perspectives and to facilitate "readiness for learning" in future courses. Each problem reveals a different facet of biomedical engineering from screening and detection of cancer using technologies that span protein changes (proteomic strategies) to the whole body (fMRI), to experimental design for detecting sources of error in biometric devices to modeling/simulation as a method of hypothesis testing. The questions are open-ended, ill-constrained and ill-structured demanding an investigation of the intersection between technology and human physiology (interlocking models). Each requires the students to discover the resources they will need to solve the problem, to move from the qualitative to the quantitative, and to develop analytical frameworks developed from the data. The course goal is to have the student teams practice engineering problem solving with the facilitation of a faculty member. Since the building is new, the rooms for this course were designed to suit the PDL processes. Two were also constructed with small observation rooms from which we could observe and video the classes without interfering with the activities. The PDL rooms are small with seating for ten

and writable walls floor to ceiling. These walls are the starting point for developing model-based reasoning in that students use them as part of the problem solving apparatus. The facilitator invites the team to sketch out concepts, to develop schematics for their strategies, to model mechanism at different levels. For instance, a team might be asked from their research to develop a time-line of cancer from the gene to the body. Such a scheme is the beginning of a model of cancer that will, in a later course be revisited when they are solving another problem on treatment or detection at the cell level. At the end of the course, the objective is for students to have developed a new understanding of problem-solving that utilizes provisional models as the starting point for investigation and design.

II. Analysis of model-based reasoning in PDL

To assess whether students were developing MBR practices in the first methods course, we developed a series of assessment instruments over the years. Our first three instruments, which progressed from an open-question format-pre-post "nature of models" to a scenario of design format (pre-post format), were helpful in assessing model understanding but failed to assess whether students were able to utilize MBR in problem solving. We determined that a final exam in which they were asked to solve a problem would be appropriate for this determination. We developed a problem for the final that called on strategies/approaches they had practiced in all three problems. In the first couple of iterations, we carefully directed students to follow specific steps, thus constraining the possibility for spontaneous use of models. But that showed us only that they could call forth models when asked to do so, but we had no evidence that MBR had in fact become ingrained as a developing practice. Our next and final move was to give students a problem and ask them to detail how they would go about solving it like a biomedical engineer using resources from the course that would be helpful in crafting an approach – that is, to lay out their problem solving strategies. Over two semesters, we collected a total of 100 exams -50 each term, developed a coding scheme and analyzed the exams. In the coding scheme, we looked for evidence that students spontaneously used models before a hypothesis when answering the problem. Over the two terms, we found that eighty-six percent (86%) of the students followed this strategy of developing a provisional model first, which could then inform a hypothesis.

III. Redesign of the instructional laboratories to be more agentive

To assess the feasibility of translating principles of agentive learning environments to BME laboratory instruction, we conducted a comparative study of two sections of the Systems Physiology I lab, the most technique-driven lab in the Georgia Tech BME laboratory sequence. Prior to the study, the control section, which had been developed in 2002, very much mirrored a cell biology laboratory. A legacy course developed at the inception of the undergraduate curriculum, it followed the biology model of technique-driven bench top activity. Students practiced cell-based techniques such as Western blot or PCR by following protocols and keeping lab notebooks of their procedures and outcomes. The lab culminated in a more open exercise where they had to propose two techniques

they had practiced as tools for answering a question they had developed from the literature.

Prior to the reported study, it had been hypothesized that this lab was not serving the development of biomedical engineering skills so we conducted a qualitative investigation of the lab over a semester to better understand how the various lab activities were unfolding to support or discourage learning. This investigation entailed the generation of extensive field notes derived from continuous observations of student pairs at work on the bench tops as well as assessment of their lab notebooks, presentations, tests and final projects. Students were also interviewed informally as they worked in the lab. Data collected and then analyzed during the term suggested four major failings of this laboratory model of learning.

1. The design of the lab made it possible for students to follow the various procedures, such as a Western blot, without fully understanding the underlying mechanisms of the test itself. This was particularly evident in the lab reports when students attempted to figure out where their experiments had gone wrong. According to the lab director, *"…the explanations of what went wrong usually went something like---the TA, he told me wrong or the moons weren't lined up… and just some crazy explanations, and they really didn't have any scientific merit."* It was apparent that with such shallow understanding of the techniques, students would be unable to generalize use of these tests to other situations or to trouble-shoot when they failed. They were "mindlessly" going through the procedures without understanding the scientific basis of the established protocols.
2. From the student perspective, there was no coherence between the labs. Each lab was experienced as an isolated set of procedures that had little or no relationship to the lab of the previous or following week. While an expert may have been capable of making the links, the students were not. Thus the labs were experienced as a series of disjointed physical bench top tasks that just needed to be completed. The labs were also not coordinated with the lecture course they were attached to, so there was little opportunity for the students to make connections between the procedure and the course content..
3. With the students working in pairs, many unnecessarily redundant conversations occurred because the teaching assistants were failing to utilize questions arising in one pair to leverage a whole class discussion. The pair wise configuration of parallel tasks was not conductive to a sense of the whole lab as a learning community. The instructional staff failed to leverage pair-based questions for teachable moments for the whole class.
4. The lab structure failed to clarify or bring home the connection between the various techniques and their practical uses in industry or research. Such a failing led students to dismiss the bench top work as so much busy work.

The redesign of the lab using agentive principles addressed three of the four problems: shallow understanding, the lab as a learning community and the practical uses of the technique in authentic settings. By situating the desired

learning outcomes in the context of problems to be solved, it was hypothesized that learning would be deeper, the lab community could be leveraged for better learning and that students would have a better sense of the global applications of the techniques. The problem of coherence between labs was not addressed in the redesign as we wanted to replicate in the new model the sequencing of activities found in the legacy model.

Throughout the semester, uniform assessment strategies were applied in both the control and experimental sections. Data from the comparative assessment comprised:

- Post-lab quizzes
- Student lab notebooks of their experiments.
- Final project presentations and reports
- End-of-term student survey
- End-of-term comprehension test

The final normalized comparison of post-lab quizzes between the groups did not yield significant differences between sections, a reassuring finding in that we did not cause undue harm in the experimental section given the very unstructured, and ill-constrained nature of the problem given the groups. Oral presentation scores for the experimental section were significantly higher than the control and although the report did not yield significant differences, the presentation scores of the experimental section were significantly higher. A final survey was provided to students after the completion of the term assessing student perception. Students in the experimental section perceived themselves to be able to better identify strategies to address lab objectives and better learn from their failures while those in the control section perceived themselves to be able to better execute the lab procedure and felt more confident in the lab. End-of-term comprehension test examining students to apply gained knowledge in three areas: (A) definitions, (B) instrumentation, and (C) experimental design. For each category of question, the experimental section performed significantly better than their control counterparts, suggesting that they could better apply what they had learned in the classroom.

Assessing students learning via analysis of their lab notebooks proved an interesting challenge and led to the development of a new instrument. The laboratory notebooks were kept by each student while completing the required laboratory assignments. Each group of students received exactly the same detailed instructions on how to keep a laboratory notebook. We examined the notebooks based on our assumption that because they are meant to be records of the steps taken by the student during the course of the exercise, they represent learning in progress in this context. In other words, our assumption is that the notebooks provide the most useful inscriptions of learning process available to us. Our effort to describe and compare practices resulted in our developing the *Sense-Making Sorter* (SMS) to classify our impressions of the cognitive activities reflected in the production of the notebooks. In the course of our analysis we substituted “sense-

making practices" for "reasoning" in an effort to be more inclusive of some of the kinds of activities we began to think important to the process of understanding. The *Sense-Making Sorter* (SMS) emerged from our effort to characterize the notebooks across the two conditions of the undergraduate physiology course for biomedical engineering students: a traditional instructional laboratory course and a course in which problem-driven design principles were used to create a learning environment characterized by student responsibility for learning. The Sense-Making Sorter is a one-page form developed to summarize and organize evaluations of sense-making practices across three phases of inquiry. Although derived from an open-coding process, the form enables researchers to code new material (lab notebooks) efficiently and uniformly. For each learning artifact (notebook), raters assign 0, 1, or 2 points to each of five sense-making practice dimensions, yielding a possible total of 10 (the total sense-making score). Group averages (e.g. between course formats) can be compared for either the total sense-making score and/ or for each of the three phases of sense-making.

We used the SMS to compare practices evidenced in the laboratory notebooks of students in the two versions of the course. Application of the Sense-Making Sorter to the notebook lab exercises reveals consistently higher averages and individual scores for each phase of sense making in the problem-driven group, both across lab exercises and for each of the exercises most closely comparable across problem-driven and technique-driven groups. Although no perfect scores (10 points) were obtained, scores for the problem-driven group are roughly double those of the technique-driven group when the high consistency ratings are used. Furthermore, the highest overall sense making scores were achieved in the problem-driven group, particularly for the histology lab exercise, with very few of the technique-driven group achieving an overall sense making score of four or above.

Overall, our first attempt to translate agentive learning principles into a problem-driven instructional lab were deemed such a success that the next semester all sections of the lab were run this way (with alterations based on the assessments and instructor and TA experiences) and work is underway by the faculty to expand the lab's problem-driven elements even further.

IV. Incubator model of faculty development

A by-product of this work is a very promising approach to faculty development that we term the "incubator model". In our incubator model, which we have instituted for the last eight years, all faculty members, junior to eminent senior scholar, participate as faculty facilitators in the first methods course. While they participate in an innovative alternative pedagogy, they do not have to design and implement it. The problems, the assessment strategies, the forms of interactions and the spaces have all been designed, developed and tested. There is, so to speak, no overhead for them in moving in a new instructional direction. Prior to facilitating the first time, new faculty are introduced to the PDL approach, to facilitation as a form of instruction, to the learning outcomes associated with each problem and the assessment methods used in the course by the course director. Since during any term as many as 14 other faculty are facilitating simultaneously on the same

problem, the new faculty member has many potential mentors available. They soon find that running the PDL groups is very much like running a research lab meeting, so similar in fact, that it is common for junior faculty to share with the course director that they are finding positive spillover effects from PDL to their management of their research lab. In reverse, learning to better manage PhD students translates back into facilitation skills in the first methods course. As facilitators of the student teams, the faculty observe undergraduate students up close and come to see the talents and strengths of very young students. An additional effect of this close interaction is that departmental faculty now host large numbers of undergraduates in their research labs. At last analysis, close to 65% of BME undergrads had worked in a research lab before graduating. It is fair to say that the first methods course has helped to create a departmental culture that values undergraduate participation as early as freshman year and the number of research awards and scholarships that have accrued to the undergrads is notable as a result. A further spillover effect is that instructors of instructional laboratories and classes in several areas have been moving forward on their own to more problem-driven models of learning. We highlight the latest by-product below.

V. Problem-solving studios

A by-product of the incubator model of faculty development is a new concept we are experimenting with that we call "problem solving studio". In this model, traditional engineering and bioscience courses are reworked as PDL with an architecture studio twist. Course redesigns emanated from faculty experiences in the first methods course and a desire to bring more team problem-solving into lecture courses. The first faculty member to experiment with this concept redesigned an engineering course in Conservation Principles for design studio space. Using four student configurations, large paper pads where the teams could work on problems and the instructor could collect "data" on student problems, he was able to significantly increase student success in this very challenging course. More recently, a cell biology course was totally reworked from strict lecturing to lecture, journal article discussion and group problem solving. Rather than merely memorize the content, student teams had to use the content to design interventions in the cancer cycle based on the literature. Many faculty are now vying for the studio space so they can create redesigns of traditional lecture courses.

Investigations of Research Laboratories

Our findings over the five years are numerous and are reported in a range of publications. We have presented them in detail in our annual reports and in this final report we will focus mainly on those directly related to learning issues. In conducting our research on the three research laboratories, we collected data intensively for each lab for 2 years, with 2 years of follow-up. At the outset we framed the labs as distributed cognitive-cultural systems, and so one objective was to determine the way cognition and culture are mutually implicated in their research practices. In the period of this grant, we conducted the follow up collection

for the tissue engineering and neural engineering labs, and the intensive and follow up collection for the bio-robotics lab. The follow up in the tissue engineering enabled both the development of a long-term learning study for one participant and of a study of an entire experimental investigation by another. In the follow up of the neural engineering lab we captured a significant burst of creativity in the work of three researchers that occurred when one created a computational simulation (not a standard practice in this lab) of their physical MEA dish model of neural processing. Several novel concepts were formed and a long-sought control structure was determined in interaction between the computational model and physical model. This work has been making a significant impact on their field and our analysis provides significant insights into creative cognitive processes.

Data collection and follow up in the bio-robotics lab concentrated on their two types of research projects, an academic stream that explores basic questions in robotics and computer science and a product-based stream, where Lab-R's expertise in robotics and computer science is used to develop applications for government agencies, competitions, and other researchers, primarily biologists. Regardless of whether the research project centers on academic contribution to the field or creating a product for a funding agent, the common goal is a deliverable, tangible product. The problems associated with this the "deliverable" drive the learning experience for the participants. A significant finding was that what we call the *culture of competence* is what affords agentive learning in Lab R. The primary research that students perform in this lab centers on writing computer programs that will enable a physical artifact to do a task. Thus, the basic unit of activity in this lab is programming or code writing. It is interesting to observe that the majority of researchers are senior undergraduates or MS students in CS, not PhD students (there were only 3 of these). The entry-level programming skill set is at the expert level. These are proficient programmers. This fluency in the native language of the lab's work allows them to feel confident immediately to join the conversation with the PI and the PhD project manger. Identifying an area of interest is easy because their previous experience has alerted them to what they want to know more about or what they need to practice or what they are skilled at doing that can contribute to this project. Confidently, they select a problem for themselves within the larger problem set of making the artifact perform and take charge of the research necessary to solve that problem.

This culture of competence also means that the group discourse is at a colleague-to-colleague level. Although there clearly is an organizational structure that defines who reports to whom, who is the owner of what, who has a history here who is just passing through, the shared high-level programming skill affords an egalitarian work space from the outset. This culture of competence, in conjunction with the modular plug-in quality of the work and the work culture, creates learning that often is an extension of previously acquired skills. The learning is in the form of how to implement skill to solve a problem. Using one's skill and knowledge of programming, the student goes fishing for inspiration on the Internet. Taking algorithms found there, tweaking, re-writing, or in some instances, being inspired to use them as the basis to implement a novel program that might solve the problem. For example, in problem related to the need to save power in their robotic devices,

one student "googled" papers until he found a couple containing algorithms that might work for this application. He eliminated it down to one and then worked on making it fit his needs. Following that it was tried out on the artifact. His learning was less in the skill improvement, because he is already a talented programmer, and much more in process of how to implement a program in a novel way to solve a problem.

The data we collected comprises: 235 interview and 59 research meeting completed transcripts (from audio and video recordings) on research, learning, creation and use of technology, and gender; field notes on over 800 hours of observation of researchers working, in research meetings, and in journal clubs; and various data pertaining to the historical evolution of the labs, such as notebooks, grant proposals, outputs of artifacts, pictures of artifacts and of changing lab configurations, emails, and web sites. Largely consistent with the aims of "grounded theory," we have been coding analytically and inductively (Straus & Corbin 1998) enabling core categories (and eventually theory) to emerge from the data and remain grounded in it, while being guided broadly by our initial research questions. Coding began with weekly collaborative meetings by two Ph.D.-level psychologists with qualitative methods expertise. A small sample of interviews were analyzed progressively line-by-line from beginning to end, with the aim of providing an initial description for most if not all passages in the interview. A description and code was recorded only when both researchers were in full agreement about its fit and relevance to the passage and, initially, there was no attempt to minimize the number of coding categories.

Two main approaches to developing codes proved most productive. One was consistent with classic grounded coding approaches that emphasize the emergence of themes and codes from described units of text. The second approach arose in closer connection with on-going ethnographic field observations in the labs. Initial codes were presented in our bi-weekly research group meetings (all had read the transcripts in advance) and codes were discussed until there was agreement. Descriptions and codes were revisited throughout the process in keeping with new discussion on the text, as well as new observations in the laboratories. Codes were then analyzed for conceptual similarities, overlap, and distinction, and were grouped together under super-ordinate headings, and so forth until no further reductions could be made. Once codes were established several student researchers were trained on these, with special emphasis on the codes that had been collected under the category "model-based cognition" and a larger number of transcripts were "high level" coded for instances of these. Again at least two researchers looked at the same transcripts and resolved any conflicting interpretations through discussion.

We coded each lab separately and then merged the biomedical engineering (tissue and neural engineering) labs since our codes transferred robustly across them. Since the primary reason for conducting research in the bio-robotics lab was to see if the "agentive learning" principles (see section on learning below) we developed from the BME labs would transfer to an out of domain environment, we coded mainly for learning and kept a separate code file. In addition to developing grounded coding schemes, we have developed longitudinal case studies of several

lab individual members and of one group of researchers as they worked on a project over 2 years, a case study of the nature of experimentation in a computational environment (bio-robotics), and detailed case studies of specific technological artifacts as they were designed, used, and redesigned by the various labs.

Several highly salient categories emerged in coding for cognitive practices. Of the fully transcribed interviews 18% are coded. In this process, 79 categories emerged that transferred across the two labs. Of these 27 were particularly robust, and in all 11 super-ordinate categories were constructed. To demonstrate the range of emergent codes, the 11 super-ordinate categories are: agency, analogy, history, identity, limitations, model-based cognition, norms, pragmatic, problem formulation, seeking coherence, and visualization. As one example from a super-ordinate category, in the 18% coded transcripts 389 instances fall under the category "model-based cognition." (If we add "analogy" which is a specific type of model that we coded for separately, the total rises to 723.)

Three particularly empirically and theoretically robust notions, in particular, influenced out designs of learning environments:

- Model-based cognition
- Cognitive partnering
- Interlocking models

In each laboratory, the research is driven by the need to formulate and solve complex, cross-domain problems. Because it would be either impossible or unethical to experiment on animals or humans, each laboratory needs to design and build physical *in vitro* simulation models to investigate *in vivo* phenomena. So, e.g., the tissue engineering laboratory designs and builds simulation devices such as models of vascular tissue or models that replicate the force of blood flowing through arteries. One researcher referred to this practice of constructing model-based simulations as, "putting a thought into the bench top to see if it works," which we considered a particularly apt intuitive description of their cognitive practices. These models are hybrid entities, reflecting the labs as engineering and biological environments, and reflected in the characteristics of the researcher-learners who are part of an educational program aimed explicitly at producing interdisciplinary, integrative thinkers. By "model-based cognition" we mean that researchers understand, explain, and reason by means of structured representations of phenomena, devices, and methods, both mental and physical models.

During the course of learning to become a researcher and designing and conducting one's research, researchers form relationships with other researchers and with certain artifacts essential to their research; we categorize forming these relationships as "cognitive partnering." Forming relations with others requires developing a healthy mix of independence and interdependence, fostered by lab mentoring practices. Forming relationships with artifacts – simulation devices – is particularly noteworthy. As the researcher matures, the simulation device is conceived as a partner in research. In one sense, it marks coming to understand the research through the lens of what the device affords and constrains, but goes

beyond this to an understanding of the devices as possessing quasi-independence – as distinct from the "thought" the researcher put "into the bench top." This transition is marked by using increasingly anthropomorphic language that attributes agency to the artifact, such as "the cells once they are in the matrix will reorganize it and secrete a new matrix and kind of remodel the matrix into what they think is most appropriate" (construct device, Lab A) or "yeah, seven parameters it has to look at in order to decide what's a burst" (MEA dish model, Lab D). Finally, "interlocking models" provides a way to categorize integrative interdisciplinary thinking at the individual level, and practices at the system level. Again, linguistic markers provide evidence for conceptual integration, for instance, "it was necessary to shear precondition these derived cells at an arterial shear rate." "An arterial shear rate" marks an integrated biological and engineering conception of an artery, while the entire sentence expresses an integration of biological and engineering materials and methods.

Although we have singled out specific categories because of their relation to the learning research discussed in the next section, members of our research group have been engaged in following out the implications of many of the other categories emerging from our coding. Particularly noteworthy, led by Lisa Osbeck, we all are engaged in writing a book for a general psychology audience that takes a novel look at scientists at work on the frontiers of research through the lenses of problem-solving, emotion, identity, gender, race, and learning. Our data provide rich insights into the "scientist as acting person" and hope that the book will be sufficiently engaging to lure advanced some undergraduates into considering STEM careers. Two research "spin offs" are worth noting. The research by our most recent postdoc, Sanjay Chandrasekharan, into model-building practices has led to a research project funded by the NSF Creative IT program (PI: Ali Mazalek). The research by Kareen Malone under the supplement has led to a Spencer Foundation grant to study issues pertaining to gender and race in the biomedical engineering field.

Over the course of this research we have been engaged in the study of practitioners (graduate students, undergraduates, postocs, PIs) in sites of STEM research with the objective of understanding cognition and learning in interdisciplinary settings and translating findings about their cognitive practices, the learning challenges associated with these practices, and the community practices that lead to successful learning into designs for instructional settings. We have also been engaged in using our findings to further cognitive science research on mental modeling, analogy, imagistic reasoning, conceptual change, distributed cognition, and interdisciplinary reasoning and problem solving.

Two chief motivations underlay the choice of biomedical engineering research sites as models for classrooms. First, research laboratories are central to all graduate education in science and engineering. They are also where science and engineering identity trajectories at the undergraduate level are often strengthened and career paths that include graduate school become a vision. Second, learning in interdisciplinary fields such as biomedical engineering challenges students to merge science and engineering concepts, models, and methods, which can often be - or seem to be - at odds with one another. In most science and engineering fields, the research laboratory is a prime locale for developing practices that lead to successful melding in problem solving.

This project built upon our prior investigation of two research labs: one in tissue engineering, the other in neural engineering, and on our initial development of modified-Problem Based Learning graduate and undergraduate classes in the new BME program. In this phase, we 1) continued our analyses of the labs and classrooms; 2) developed ways of assessing mastery of model-based reasoning as a means of problem solving; 3) added an out-of-domain research lab in Bio-robotics to address robustness of transfer of learning findings; 4) developed several models of Problem Driven Learning instructional labs; and 5) conducted a controlled study between our PDL instructional lab in systems physiology and a traditional technique driven instructional lab, and further refined and implemented the PDL lab an additional time.

To conduct this research, we built an interdisciplinary research group (***C***ognition and ***L***earning in ***I***nterdisciplinary ***C***ultures) with expertise in cognitive psychology, philosophy and history of science, learning sciences, cognitive anthropology, linguistics, humanistic psychology, computer science, gender & science, and biomedical engineering. There have been 6 Sr. Personnel, 4 PostDocs, 14 Graduate Students (MS and PhD), and 7 Undergrads involved in conducting this research (not all funded by NSF). We extended the project beyond our original 2007 date because of lag times in scheduling of courses by the BME department and because of the need bring up to speed the new students and postdocs added in the third year of our project.

We characterize our research as transformative and translational. It is transformative along three dimensions. First, as an emergent interdiscipline, biomedical engineering integrates the tools, knowledge, and methods from engineering and the sciences towards both basic biological research and the development of healthcare applications. While this integration is critical to advances in biology and in addressing problems associated with disease prevention, detection

and treatment, it creates unique challenges for BME educators. Unlike other post-secondary courses of study in engineering that have evolved to have well-practiced traditions regarding course content and sequencing instantiated in a myriad assortment of textbooks, BME is still in the throes of developing those traditions both in the classroom and the instructional laboratory and our research has been impacting not only the educational program at GA Tech, but also programs at other institutions through our outreach activities. Second, in addition to our findings, our research methodology has been influencing the new engineering education PhD programs at Purdue and VA Tech, where Newstetter is now a member of the advisory boards. Third, it is providing novel insights for the cognitive and learning sciences in that studies of cognition and learning in interdisciplinary contexts are scant, as are studies of graduate students as learners and undergraduates as researchers. The latter represents a potentially new paradigm in learning sciences research. Rather than taking the customary approach of studying the practices of experts in a field and using these to guide novice instruction, our goal has been to understand both the challenges to learning and what makes for successful learning in complex settings of STEM practice and use that understanding to design educational environments that support complex learning in formal instructional settings. In the laboratory investigations we have sought to understand 1) the reasoning and problem-solving strategies that drive the work of the research lab (cognitive practices) and 2) how lab newcomers apprentice to and learn these strategies (learning practices). With this understanding, our goal has been to design BME instructional settings – classroom and laboratory – that better approximate the ecological features that support rich, robust learning in complex settings. As such, these efforts represent a *translational* model of educational research in which findings from studying complex in-the-world learning environments are appropriately translated into design principles (Brown, 1992; Brown & Campione, 1994) for classrooms.

Building a culture committed to problem-driven learning

Over the last five years, we have learned a great deal about how to design and implement curricula at the post secondary level that strives to develop model-based reasoning and problem solving capabilities in engineering students. We began this work with the belief that problem-based learning (PBL), widely utilized in medical education to develop hypothetic-deductive reasoning and in K-12 for content engagement and mastery, could be modified to support engineering education, where modeling and model-based reasoning are central. We characterize our modified PBL approach as problem-driven learning (PDL), perhaps a seemingly trivial distinction. However, as we have observed in the research laboratories, the problem does not merely situate or anchor learning; rather it compels, provokes and drives it forward. This relentless need to make progress in a complex problem space is what we have tried to replicate in the design of our classrooms. This endeavor has involved the design, development and assessment of two learning environments and the development and evaluation of assessment instruments.

I. A first methods course-How to think like an engineer

Over the course of our research, we have iteratively designed/refined a first course in engineering problem solving, a methods course, that utilizes a problem-driven learning approach. To arrive at a stable but flexible version of this course, we used a *design studies* approach in which we ran a variety of test problems generated by biomedical engineering faculty (See http://www.bme.gatech.edu/pbl/),assessed the appropriateness and learning possibilities of each, identified where students needed more support and developed it, and experimented with assessment instruments. The course enrolls approximately 80 students in the Fall semester, 180 in the Spring, and 30 in the Summer. The students meet once a week together in a lecture format where they are introduced to various areas of research in biomedical engineering. At the start of the semester the students are divided into problem-driven learning sections of 8 students who meet twice a week with a faculty facilitator to discuss their progress working on the problems as a group outside of the class meetings.

We sought to make this an *agentive learning* experience for the students so we worked to apply the design principles that we developed from the research laboratory investigations.

A. Learning is driven by the need to solve complex problems.

Knowledge building in the labs is driven by the need to solve problems. Much work goes into continually re-articulating the larger problem and determining tractable pieces through which progress can be made. In working toward solutions, multiple questions need to be addressed; multiple forms of activity need to be undertaken; and multiple forms of data generation, gathering, and analysis need to be undertaken. The complex, ill-defined nature of the problems promotes the distribution of problem solving activities across a community of researchers.

B. Organizational structure is largely non-hierarchical

Knowledge building on the frontiers of science and especially, though not exclusively, at the crossroads of two or more disciplines is most often distributed across individuals while accruing individually. The lab director has the big picture in mind, but s/he does not have all the knowledge, the skills, or the expertise to answer all the questions or resolve all the problems. Actually, no one does. Rather it is the group as a whole that possesses the expertise to move forward. This means that the oft-studied distinction between novice and expert is of less importance here. In a sense, everyone is a novice, which affirms the new lab member's status as not especially remarkable. What is of importance here is how in this nonhierarchical setting the newcomer can envision herself as a major group player, perhaps even the expert in her particular domain or part of the greater problem space. This is a great motivator for the learner to find more and more venues for developing knowledge and a scientific identity.

C. Learning is relational

Conducting research requires lab members to be agents in forming relationships. In our investigation of the research labs we witnessed researchers forming relationships both with people and with the technological artifacts they design and build to carry out their research (9). In the instructional design project, we focused on the former. Research requires developing independence but interdependence as well. As we saw in the lab studies, a great deal of lab knowledge resides in the heads, experiences and notebooks of the various members. As repositories of scientific and engineering know-how, senior lab members become identified with specific lab devices, techniques, research questions, and evolving protocols, assays, and devices. Newcomers to the lab need to develop relationships with these people, learning to ask questions and seek advice to get access to this knowledge. And in developing relationships, they learn about the senior lab members' experiences with particular devices and the requisite aspects of lab history that are often poorly chronicled in other places. With strong social relationships comes the potential for a wealth of problem-solving capacity and knowledge acquisition. But the lab newcomer has to develop the habit of first identifying and then going to people in the know.

D. Multiple support systems foster resilience in the face of impasses and failures.

The social aspect of learning is critical for another reason. Learners need to understand that setbacks, frustration, and uncertainty are constant companions in doing the work of science. In the face of these repeated setbacks, learners need a sense that they are not alone, that their failure is not singular but is rather a feature of lab life. This sense of membership mitigates the feeling of futility that could pervade the community. Having relationships with others in times of failure affords two things: a point for commiseration and solidarity and potential partners for problem solving. Without the close social fabric of the lab, such experiences of failure would be experienced in isolation. Instead, "failure" in the lab becomes an opportunity to deepen one's understanding of the project under investigation, the nature of research, and the ethos of the community.

E. Building serves as entrée

One of the features we have found most interesting in regards to laboratory learning is how quickly newcomers find ways to make contributions to the work of the lab. An activity commonly taken up by newcomers is building, the activity that tends to drive research in both labs. Building artifacts affords immediate opportunities for rapid participation and, importantly, the build-up of requisite knowledge. Building affords a ready and easy opportunity for membership in and contribution to the lab setting, which serves as first steps towards full membership. At the same time, the numerous jobs to be tackled or sub-problems to be addressed allow for researchers to become free agents of their learning, much more so than in a traditional apprenticeship situation where practices are relatively static and entry points much more prescribed. The wide open knowledge frontier and relatively flat hierarchy

make for hospitable first beginnings for new lab members, even undergraduate students.

Taken together, we characterize the educational model derived from the study of learning in research settings as *agentive.* In an agentive learning environment, students are agents of their own learning and in determining a course of action. In this sense, they are actively constructing understanding and knowledge as they work through problems. In the research labs, learners enlist and interact with people and laboratory tools and devices. They develop strategies for solving the problems that arise, for dealing with impasses and failure and for seeking help with they experience difficulties. They utilize their hands and minds to solve open-ended, ill-constrained and ill-structured problems. They build when required to do so; they do research and then use this research to guide decision-making. When in an agentive learning environment, students need to become self-directed, empowered learners and problem solvers, who utilize previous learning experiences for the current learning situation, all features of what is called "constructivist learning."

Beginning from these principles, we have developed a significant system of scaffolding that makes it possible for teams of first year biomedical engineers to tackle complex, open-ended problems without undue frustration and failure. The scaffolding structure consists of

- Three carefully sequenced problems
- Specially designed PDL learning spaces to support collaborative problem-solving and model-based reasoning.
- Assessment rubrics/sheets for scoring the problem presentations
- Student writing guidelines for developing the reports that are the culmination of each problem
- Faculty facilitators for each team of eight students

The three problems have been designed for redundancy and re-visitation of topics from different perspectives and to facilitate "readiness for learning" in future courses. Each problem reveals a different facet of biomedical engineering from screening and detection of cancer using technologies that span protein changes (proteomic strategies) to the whole body (fMRI), to experimental design for detecting sources of error in biometric devices to modeling/simulation as a method of hypothesis testing. The questions are open-ended, ill-constrained and ill-structured demanding an investigation of the intersection between technology and human physiology (interlocking models). Each requires the students to discover the resources they will need to solve the problem, to move from the qualitative to the quantitative, and to develop analytical frameworks developed from the data. The course goal is to have the student teams practice engineering problem solving with the facilitation of a faculty member. Since the building is new, the rooms for this course were designed to suit the PDL processes. Two were also constructed with small observation rooms from which we could observe and video the classes without interfering with the activities. The PDL rooms are small with seating for ten

and writable walls floor to ceiling. These walls are the starting point for developing model-based reasoning in that students use them as part of the problem solving apparatus. The facilitator invites the team to sketch out concepts, to develop schematics for their strategies, to model mechanism at different levels. For instance, a team might be asked from their research to develop a time-line of cancer from the gene to the body. Such a scheme is the beginning of a model of cancer that will, in a later course be revisited when they are solving another problem on treatment or detection at the cell level. At the end of the course, the objective is for students to have developed a new understanding of problem-solving that utilizes provisional models as the starting point for investigation and design.

II. Analysis of model-based reasoning in PDL

To assess whether students were developing MBR practices in the first methods course, we developed a series of assessment instruments over the years. Our first three instruments, which progressed from an open-question format-pre-post "nature of models" to a scenario of design format (pre-post format), were helpful in assessing model understanding but failed to assess whether students were able to utilize MBR in problem solving. We determined that a final exam in which they were asked to solve a problem would be appropriate for this determination. We developed a problem for the final that called on strategies/approaches they had practiced in all three problems. In the first couple of iterations, we carefully directed students to follow specific steps, thus constraining the possibility for spontaneous use of models. But that showed us only that they could call forth models when asked to do so, but we had no evidence that MBR had in fact become ingrained as a developing practice. Our next and final move was to give students a problem and ask them to detail how they would go about solving it like a biomedical engineer using resources from the course that would be helpful in crafting an approach – that is, to lay out their problem solving strategies. Over two semesters, we collected a total of 100 exams -50 each term, developed a coding scheme and analyzed the exams. In the coding scheme, we looked for evidence that students spontaneously used models before a hypothesis when answering the problem. Over the two terms, we found that eighty-six percent (86%) of the students followed this strategy of developing a provisional model first, which could then inform a hypothesis.

III. Redesign of the instructional laboratories to be more agentive

To assess the feasibility of translating principles of agentive learning environments to BME laboratory instruction, we conducted a comparative study of two sections of the Systems Physiology I lab, the most technique-driven lab in the Georgia Tech BME laboratory sequence. Prior to the study, the control section, which had been developed in 2002, very much mirrored a cell biology laboratory. A legacy course developed at the inception of the undergraduate curriculum, it followed the biology model of technique-driven bench top activity. Students practiced cell-based techniques such as Western blot or PCR by following protocols and keeping lab notebooks of their procedures and outcomes. The lab culminated in a more open exercise where they had to propose two techniques

they had practiced as tools for answering a question they had developed from the literature.

Prior to the reported study, it had been hypothesized that this lab was not serving the development of biomedical engineering skills so we conducted a qualitative investigation of the lab over a semester to better understand how the various lab activities were unfolding to support or discourage learning. This investigation entailed the generation of extensive field notes derived from continuous observations of student pairs at work on the bench tops as well as assessment of their lab notebooks, presentations, tests and final projects. Students were also interviewed informally as they worked in the lab. Data collected and then analyzed during the term suggested four major failings of this laboratory model of learning.

1. The design of the lab made it possible for students to follow the various procedures, such as a Western blot, without fully understanding the underlying mechanisms of the test itself. This was particularly evident in the lab reports when students attempted to figure out where their experiments had gone wrong. According to the lab director, *"…the explanations of what went wrong usually went something like---the TA, he told me wrong or the moons weren't lined up… and just some crazy explanations, and they really didn't have any scientific merit."* It was apparent that with such shallow understanding of the techniques, students would be unable to generalize use of these tests to other situations or to trouble-shoot when they failed. They were "mindlessly" going through the procedures without understanding the scientific basis of the established protocols.
2. From the student perspective, there was no coherence between the labs. Each lab was experienced as an isolated set of procedures that had little or no relationship to the lab of the previous or following week. While an expert may have been capable of making the links, the students were not. Thus the labs were experienced as a series of disjointed physical bench top tasks that just needed to be completed. The labs were also not coordinated with the lecture course they were attached to, so there was little opportunity for the students to make connections between the procedure and the course content..
3. With the students working in pairs, many unnecessarily redundant conversations occurred because the teaching assistants were failing to utilize questions arising in one pair to leverage a whole class discussion. The pair wise configuration of parallel tasks was not conductive to a sense of the whole lab as a learning community. The instructional staff failed to leverage pair-based questions for teachable moments for the whole class.
4. The lab structure failed to clarify or bring home the connection between the various techniques and their practical uses in industry or research. Such a failing led students to dismiss the bench top work as so much busy work.

The redesign of the lab using agentive principles addressed three of the four problems: shallow understanding, the lab as a learning community and the practical uses of the technique in authentic settings. By situating the desired

learning outcomes in the context of problems to be solved, it was hypothesized that learning would be deeper, the lab community could be leveraged for better learning and that students would have a better sense of the global applications of the techniques. The problem of coherence between labs was not addressed in the redesign as we wanted to replicate in the new model the sequencing of activities found in the legacy model.

Throughout the semester, uniform assessment strategies were applied in both the control and experimental sections. Data from the comparative assessment comprised:

- Post-lab quizzes
- Student lab notebooks of their experiments.
- Final project presentations and reports
- End-of-term student survey
- End-of-term comprehension test

The final normalized comparison of post-lab quizzes between the groups did not yield significant differences between sections, a reassuring finding in that we did not cause undue harm in the experimental section given the very unstructured, and ill-constrained nature of the problem given the groups. Oral presentation scores for the experimental section were significantly higher than the control and although the report did not yield significant differences, the presentation scores of the experimental section were significantly higher. A final survey was provided to students after the completion of the term assessing student perception. Students in the experimental section perceived themselves to be able to better identify strategies to address lab objectives and better learn from their failures while those in the control section perceived themselves to be able to better execute the lab procedure and felt more confident in the lab. End-of-term comprehension test examining students to apply gained knowledge in three areas: (A) definitions, (B) instrumentation, and (C) experimental design. For each category of question, the experimental section performed significantly better than their control counterparts, suggesting that they could better apply what they had learned in the classroom.

Assessing students learning via analysis of their lab notebooks proved an interesting challenge and led to the development of a new instrument. The laboratory notebooks were kept by each student while completing the required laboratory assignments. Each group of students received exactly the same detailed instructions on how to keep a laboratory notebook. We examined the notebooks based on our assumption that because they are meant to be records of the steps taken by the student during the course of the exercise, they represent learning in progress in this context. In other words, our assumption is that the notebooks provide the most useful inscriptions of learning process available to us. Our effort to describe and compare practices resulted in our developing the *Sense-Making Sorter* (SMS) to classify our impressions of the cognitive activities reflected in the production of the notebooks. In the course of our analysis we substituted “sense-

making practices" for "reasoning" in an effort to be more inclusive of some of the kinds of activities we began to think important to the process of understanding. The *Sense-Making Sorter* (SMS) emerged from our effort to characterize the notebooks across the two conditions of the undergraduate physiology course for biomedical engineering students: a traditional instructional laboratory course and a course in which problem-driven design principles were used to create a learning environment characterized by student responsibility for learning. The Sense-Making Sorter is a one-page form developed to summarize and organize evaluations of sense-making practices across three phases of inquiry. Although derived from an open-coding process, the form enables researchers to code new material (lab notebooks) efficiently and uniformly. For each learning artifact (notebook), raters assign 0, 1, or 2 points to each of five sense-making practice dimensions, yielding a possible total of 10 (the total sense-making score). Group averages (e.g. between course formats) can be compared for either the total sense-making score and/ or for each of the three phases of sense-making.

We used the SMS to compare practices evidenced in the laboratory notebooks of students in the two versions of the course. Application of the Sense-Making Sorter to the notebook lab exercises reveals consistently higher averages and individual scores for each phase of sense making in the problem-driven group, both across lab exercises and for each of the exercises most closely comparable across problem-driven and technique-driven groups. Although no perfect scores (10 points) were obtained, scores for the problem-driven group are roughly double those of the technique-driven group when the high consistency ratings are used. Furthermore, the highest overall sense making scores were achieved in the problem-driven group, particularly for the histology lab exercise, with very few of the technique-driven group achieving an overall sense making score of four or above.

Overall, our first attempt to translate agentive learning principles into a problem-driven instructional lab were deemed such a success that the next semester all sections of the lab were run this way (with alterations based on the assessments and instructor and TA experiences) and work is underway by the faculty to expand the lab's problem-driven elements even further.

IV. Incubator model of faculty development

A by-product of this work is a very promising approach to faculty development that we term the "incubator model". In our incubator model, which we have instituted for the last eight years, all faculty members, junior to eminent senior scholar, participate as faculty facilitators in the first methods course. While they participate in an innovative alternative pedagogy, they do not have to design and implement it. The problems, the assessment strategies, the forms of interactions and the spaces have all been designed, developed and tested. There is, so to speak, no overhead for them in moving in a new instructional direction. Prior to facilitating the first time, new faculty are introduced to the PDL approach, to facilitation as a form of instruction, to the learning outcomes associated with each problem and the assessment methods used in the course by the course director. Since during any term as many as 14 other faculty are facilitating simultaneously on the same

problem, the new faculty member has many potential mentors available. They soon find that running the PDL groups is very much like running a research lab meeting, so similar in fact, that it is common for junior faculty to share with the course director that they are finding positive spillover effects from PDL to their management of their research lab. In reverse, learning to better manage PhD students translates back into facilitation skills in the first methods course. As facilitators of the student teams, the faculty observe undergraduate students up close and come to see the talents and strengths of very young students. An additional effect of this close interaction is that departmental faculty now host large numbers of undergraduates in their research labs. At last analysis, close to 65% of BME undergrads had worked in a research lab before graduating. It is fair to say that the first methods course has helped to create a departmental culture that values undergraduate participation as early as freshman year and the number of research awards and scholarships that have accrued to the undergrads is notable as a result. A further spillover effect is that instructors of instructional laboratories and classes in several areas have been moving forward on their own to more problem-driven models of learning. We highlight the latest by-product below.

V. Problem-solving studios

A by-product of the incubator model of faculty development is a new concept we are experimenting with that we call "problem solving studio". In this model, traditional engineering and bioscience courses are reworked as PDL with an architecture studio twist. Course redesigns emanated from faculty experiences in the first methods course and a desire to bring more team problem-solving into lecture courses. The first faculty member to experiment with this concept redesigned an engineering course in Conservation Principles for design studio space. Using four student configurations, large paper pads where the teams could work on problems and the instructor could collect "data" on student problems, he was able to significantly increase student success in this very challenging course. More recently, a cell biology course was totally reworked from strict lecturing to lecture, journal article discussion and group problem solving. Rather than merely memorize the content, student teams had to use the content to design interventions in the cancer cycle based on the literature. Many faculty are now vying for the studio space so they can create redesigns of traditional lecture courses.

Investigations of Research Laboratories

Our findings over the five years are numerous and are reported in a range of publications. We have presented them in detail in our annual reports and in this final report we will focus mainly on those directly related to learning issues. In conducting our research on the three research laboratories, we collected data intensively for each lab for 2 years, with 2 years of follow-up. At the outset we framed the labs as distributed cognitive-cultural systems, and so one objective was to determine the way cognition and culture are mutually implicated in their research practices. In the period of this grant, we conducted the follow up collection

for the tissue engineering and neural engineering labs, and the intensive and follow up collection for the bio-robotics lab. The follow up in the tissue engineering enabled both the development of a long-term learning study for one participant and of a study of an entire experimental investigation by another. In the follow up of the neural engineering lab we captured a significant burst of creativity in the work of three researchers that occurred when one created a computational simulation (not a standard practice in this lab) of their physical MEA dish model of neural processing. Several novel concepts were formed and a long-sought control structure was determined in interaction between the computational model and physical model. This work has been making a significant impact on their field and our analysis provides significant insights into creative cognitive processes.

Data collection and follow up in the bio-robotics lab concentrated on their two types of research projects, an academic stream that explores basic questions in robotics and computer science and a product-based stream, where Lab-R's expertise in robotics and computer science is used to develop applications for government agencies, competitions, and other researchers, primarily biologists. Regardless of whether the research project centers on academic contribution to the field or creating a product for a funding agent, the common goal is a deliverable, tangible product. The problems associated with this the "deliverable" drive the learning experience for the participants. A significant finding was that what we call the *culture of competence* is what affords agentive learning in Lab R. The primary research that students perform in this lab centers on writing computer programs that will enable a physical artifact to do a task. Thus, the basic unit of activity in this lab is programming or code writing. It is interesting to observe that the majority of researchers are senior undergraduates or MS students in CS, not PhD students (there were only 3 of these). The entry-level programming skill set is at the expert level. These are proficient programmers. This fluency in the native language of the lab's work allows them to feel confident immediately to join the conversation with the PI and the PhD project manger. Identifying an area of interest is easy because their previous experience has alerted them to what they want to know more about or what they need to practice or what they are skilled at doing that can contribute to this project. Confidently, they select a problem for themselves within the larger problem set of making the artifact perform and take charge of the research necessary to solve that problem.

This culture of competence also means that the group discourse is at a colleague-to-colleague level. Although there clearly is an organizational structure that defines who reports to whom, who is the owner of what, who has a history here who is just passing through, the shared high-level programming skill affords an egalitarian work space from the outset. This culture of competence, in conjunction with the modular plug-in quality of the work and the work culture, creates learning that often is an extension of previously acquired skills. The learning is in the form of how to implement skill to solve a problem. Using one's skill and knowledge of programming, the student goes fishing for inspiration on the Internet. Taking algorithms found there, tweaking, re-writing, or in some instances, being inspired to use them as the basis to implement a novel program that might solve the problem. For example, in problem related to the need to save power in their robotic devices,

one student "googled" papers until he found a couple containing algorithms that might work for this application. He eliminated it down to one and then worked on making it fit his needs. Following that it was tried out on the artifact. His learning was less in the skill improvement, because he is already a talented programmer, and much more in process of how to implement a program in a novel way to solve a problem.

The data we collected comprises: 235 interview and 59 research meeting completed transcripts (from audio and video recordings) on research, learning, creation and use of technology, and gender; field notes on over 800 hours of observation of researchers working, in research meetings, and in journal clubs; and various data pertaining to the historical evolution of the labs, such as notebooks, grant proposals, outputs of artifacts, pictures of artifacts and of changing lab configurations, emails, and web sites. Largely consistent with the aims of "grounded theory," we have been coding analytically and inductively (Straus & Corbin 1998) enabling core categories (and eventually theory) to emerge from the data and remain grounded in it, while being guided broadly by our initial research questions. Coding began with weekly collaborative meetings by two Ph.D.-level psychologists with qualitative methods expertise. A small sample of interviews were analyzed progressively line-by-line from beginning to end, with the aim of providing an initial description for most if not all passages in the interview. A description and code was recorded only when both researchers were in full agreement about its fit and relevance to the passage and, initially, there was no attempt to minimize the number of coding categories.

Two main approaches to developing codes proved most productive. One was consistent with classic grounded coding approaches that emphasize the emergence of themes and codes from described units of text. The second approach arose in closer connection with on-going ethnographic field observations in the labs. Initial codes were presented in our bi-weekly research group meetings (all had read the transcripts in advance) and codes were discussed until there was agreement. Descriptions and codes were revisited throughout the process in keeping with new discussion on the text, as well as new observations in the laboratories. Codes were then analyzed for conceptual similarities, overlap, and distinction, and were grouped together under super-ordinate headings, and so forth until no further reductions could be made. Once codes were established several student researchers were trained on these, with special emphasis on the codes that had been collected under the category "model-based cognition" and a larger number of transcripts were "high level" coded for instances of these. Again at least two researchers looked at the same transcripts and resolved any conflicting interpretations through discussion.

We coded each lab separately and then merged the biomedical engineering (tissue and neural engineering) labs since our codes transferred robustly across them. Since the primary reason for conducting research in the bio-robotics lab was to see if the "agentive learning" principles (see section on learning below) we developed from the BME labs would transfer to an out of domain environment, we coded mainly for learning and kept a separate code file. In addition to developing grounded coding schemes, we have developed longitudinal case studies of several

lab individual members and of one group of researchers as they worked on a project over 2 years, a case study of the nature of experimentation in a computational environment (bio-robotics), and detailed case studies of specific technological artifacts as they were designed, used, and redesigned by the various labs.

Several highly salient categories emerged in coding for cognitive practices. Of the fully transcribed interviews 18% are coded. In this process, 79 categories emerged that transferred across the two labs. Of these 27 were particularly robust, and in all 11 super-ordinate categories were constructed. To demonstrate the range of emergent codes, the 11 super-ordinate categories are: agency, analogy, history, identity, limitations, model-based cognition, norms, pragmatic, problem formulation, seeking coherence, and visualization. As one example from a super-ordinate category, in the 18% coded transcripts 389 instances fall under the category "model-based cognition." (If we add "analogy" which is a specific type of model that we coded for separately, the total rises to 723.)

Three particularly empirically and theoretically robust notions, in particular, influenced out designs of learning environments:

- Model-based cognition
- Cognitive partnering
- Interlocking models

In each laboratory, the research is driven by the need to formulate and solve complex, cross-domain problems. Because it would be either impossible or unethical to experiment on animals or humans, each laboratory needs to design and build physical *in vitro* simulation models to investigate *in vivo* phenomena. So, e.g., the tissue engineering laboratory designs and builds simulation devices such as models of vascular tissue or models that replicate the force of blood flowing through arteries. One researcher referred to this practice of constructing model-based simulations as, "putting a thought into the bench top to see if it works," which we considered a particularly apt intuitive description of their cognitive practices. These models are hybrid entities, reflecting the labs as engineering and biological environments, and reflected in the characteristics of the researcher-learners who are part of an educational program aimed explicitly at producing interdisciplinary, integrative thinkers. By "model-based cognition" we mean that researchers understand, explain, and reason by means of structured representations of phenomena, devices, and methods, both mental and physical models.

During the course of learning to become a researcher and designing and conducting one's research, researchers form relationships with other researchers and with certain artifacts essential to their research; we categorize forming these relationships as "cognitive partnering." Forming relations with others requires developing a healthy mix of independence and interdependence, fostered by lab mentoring practices. Forming relationships with artifacts – simulation devices – is particularly noteworthy. As the researcher matures, the simulation device is conceived as a partner in research. In one sense, it marks coming to understand the research through the lens of what the device affords and constrains, but goes

beyond this to an understanding of the devices as possessing quasi-independence – as distinct from the "thought" the researcher put "into the bench top." This transition is marked by using increasingly anthropomorphic language that attributes agency to the artifact, such as "the cells once they are in the matrix will reorganize it and secrete a new matrix and kind of remodel the matrix into what they think is most appropriate" (construct device, Lab A) or "yeah, seven parameters it has to look at in order to decide what's a burst" (MEA dish model, Lab D). Finally, "interlocking models" provides a way to categorize integrative interdisciplinary thinking at the individual level, and practices at the system level. Again, linguistic markers provide evidence for conceptual integration, for instance, "it was necessary to shear precondition these derived cells at an arterial shear rate." "An arterial shear rate" marks an integrated biological and engineering conception of an artery, while the entire sentence expresses an integration of biological and engineering materials and methods.

Although we have singled out specific categories because of their relation to the learning research discussed in the next section, members of our research group have been engaged in following out the implications of many of the other categories emerging from our coding. Particularly noteworthy, led by Lisa Osbeck, we all are engaged in writing a book for a general psychology audience that takes a novel look at scientists at work on the frontiers of research through the lenses of problem-solving, emotion, identity, gender, race, and learning. Our data provide rich insights into the "scientist as acting person" and hope that the book will be sufficiently engaging to lure advanced some undergraduates into considering STEM careers. Two research "spin offs" are worth noting. The research by our most recent postdoc, Sanjay Chandrasekharan, into model-building practices has led to a research project funded by the NSF Creative IT program (PI: Ali Mazalek). The research by Kareen Malone under the supplement has led to a Spencer Foundation grant to study issues pertaining to gender and race in the biomedical engineering field.