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A Systems Model of Innovation Processes in University STEM Education

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ABSTRACT

Drawing upon understanding of innovation processes in other domains, we construct a model of the innovation system for science, technology, engineering, and math (STEM) education. The model suggests that higher educational innovation in research universities is severely disadvantaged in many regards. Paramount is the lack of a natural innovator. The model suggests a number of organizational and structural factors that must be addressed to bolster the prospects of educational improvement at research universities. Lacking is motivation for faculty to undertake STEM innovation.

JEL Classification : I23; O31; O32

Keywords *: STEM; Supply-Demand Considerations; Discipline Specific & Discovery-Based Study*

1) BACKGROUND

We are investigating whether innovation models and experiences from outside the education arena can help elucidate educational innovation processes.[2] Innovation has been extensively studied in science and technology (S&T) – i.e., the processes whereby research findings are drawn upon to develop, improve, and market/disseminate products and services.[3] Reflections on corresponding processes in other arenas, such as public health and transportation, may also lend insights on higher educational change processes.[4]

We address the processes by which innovation takes place in STEM (science, technology, engineering, and math) education in universities. For our purposes, innovation refers specifically to STEM faculty members improving their teaching and mentoring, based on the absorption of research-based knowledge.

[1] The authors gratefully acknowledges the valuable assistance of Georgia Tech students, David Johnson and Sarah Oliver for helping us research the literature for this paper. Contact Alan Porter at alan.porter@isye.gatech.edu.

[2] NSF project #0352239 on "Research Knowledge Utilization in Education."

[3] Freeman, Chris and Soete, Luc (1997). The Economics of Industrial Innovation. Third Edition. MA: MIT Press; von Hippel, E. (1988) The Sources of Innovation, Oxford, Oxford University Press; Kline, S.J., and Rosenberg, N. "An Overview of Innovation," in National Academy of Engineering, The Positive Sum Strategy, Washington, DC: National Academy Press, 1986; and The Process of Technological Innovation. Lexington, MA: Lexington Books, 1990.

[4] For example, see Transportation Research Board, Managing Technology Transfer: A Strategy for the Federal Highway Administration. National Academies Press, 1999.

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We began this study by focusing on "research knowledge utilization" (RKU) in education. This compares to S&T innovation processes wherein research findings are utilized in generating new technologies and applying those commercially. Nominally, one could take the stance of a design engineer who reaches out to tap frontier knowledge on a technical issue to achieve target performance in a new product. That engineer "utilizes" research-based knowledge. We consider the professor as the engineer's college education counterpart, the potential key "user" of research-based knowledge.

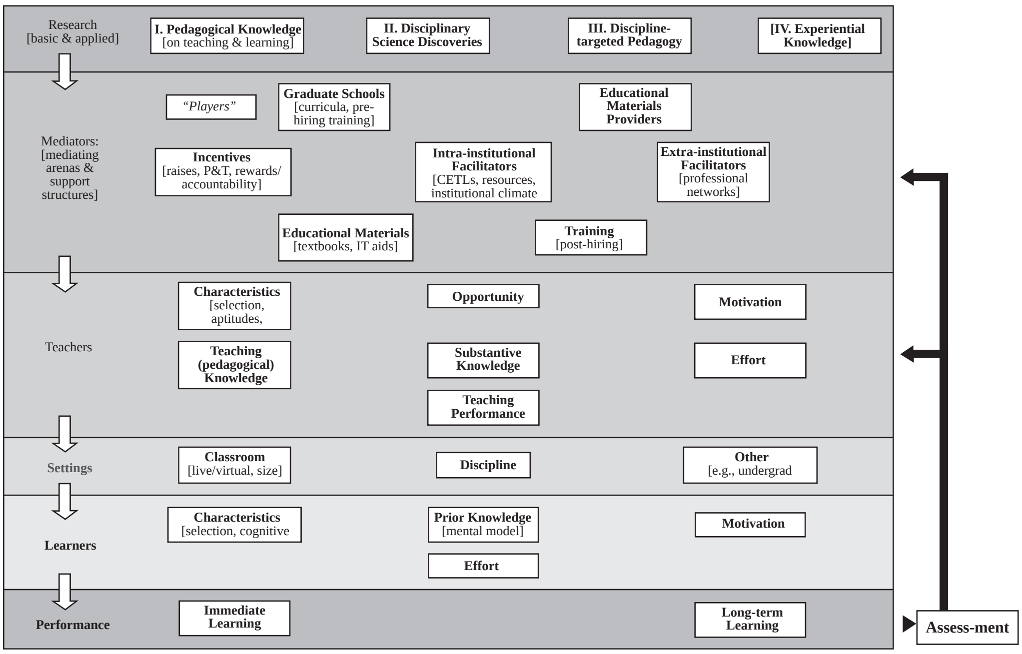
We undertook an extensive review of the literature, availing ourselves of databases such as ERIC and text mining tools to profile education research. We also engaged in discourse with persons more knowledgeable than we are about educational practices, research endeavors, and the linkages between knowledge and practice. These sources of knowledge confirmed that the educational arena is vast and complex. We determined to focus on STEM education processes at research universities, but contrast them with analogous processes in other college settings as well. We particularly seek to elucidate linkages between research findings and teaching practices.

2) THE MODEL

Figure 1 offers a systems level model of the processes of research knowledge transfer. It aims to capture the key players and processes involved in the application of research knowledge to inform STEM education and teaching performance. Influence arrows could be drawn in – we have tried, but the results were pretty cluttered.

Fig. 1

Research Knowledge Transfer in Support of the STEM Teaching Function in Higher Education



Bases For The Model

In devising this model, we borrowed concepts readily. In particular, the compilation of models in Cruickshank (1990) was a rich resource, albeit emphasizing K-12 education. This source also tabulates several extensive sets of variables. We tried to be selective in our model in representing system level variables – i.e., those amenable to policy influence. Put another way, we choose not to detail all the "micro" level factors that impinge on success in education. For instance, we have included Learner "Characteristics" in the model. This could be broken out to address demographics, social class and background, prior training attributes, and so forth. One of Cruickshank's tables (#7) compiles 85 variables pertaining to teacher effectiveness, tallying how widely they appear in ten reviews. This is a telling reminder of the extraordinary complexity in delivering effective teaching. It also suggests that effective experimental research design with complete controls over such interacting forces and factors is an extreme challenge.

Stark and Lowther[5] pick up Schwab's[6] theme of four essentials in educating – the learner, the teacher, the milieu, and the subject matter. They point out several elements of an "academic plan" – other terminology that seems akin to our use of "system:"

1. Specification of what knowledge, skills and attitudes are to be learned
2. Selection of content
3. Structure intended to lead to desired educational outcomes for learners of various types
4. Processes by which learning may be achieved
5. Materials to be used in the learning process
6. Evaluation strategies
7. Feedback loop that fosters adjustments in the plan to increase learning.

General Observations On The Model

The general influence flow is from top to bottom as a system. The system depicted in Figure 1 contains many interacting elements and processes. In assessing the performance of a given faculty member, department, or university, we need to deal with this complexity. First, note that such performance only indirectly bears on the ultimate goal – student outcomes, and those are multi-faceted. Major distinctions among learning purposes come to bear in STEM college education – intellectual development, but also personal development, social development, and job-oriented skill acquisition[7]. We see our ultimate modeling objective to be generation of policy recommendations on ways to improve STEM learning. The interplay of so many elements challenges efforts to assess what matters, under what conditions.

Key to our objectives is to explore how institutional characteristics affect learner (as well as teacher) motivations. Performance is probably affected more by learner motivation than any other variables because this primarily impacts level of effort (we explore later). Do one's peers promote learning as an aim? Do incentives such as retaining a Georgia state HOPE scholarship affect learning (via the desire to maintain required GPA)?

[5] Stark, J.S., and Lowther, M.A., Designing the Learning Plan: A Review of Research and Theory Related to College Curricula, National Center for Research to Improve Postsecondary Teaching and Learning, University of Michigan, 1986 (p. 6).

[6] Schwab, J.J., The Practical 3: Translation into Curriculum, School Review 81 (4), 501-522, 1973.

[7] Grenn, P.J., and Stark, J., op.cit., p. 7.

The following subsections describe, in turn, each of the segments of our model (Figure1):

1. Research
2. Mediators
3. Teachers
4. Settings
5. Learners
6. Performance
7. Assessment

Research

Unlike the situation in S&T innovation, we are dealing with three relatively distinct types of research knowledge. We are expressly interested in how each of the three forms impacts teaching and learning. There are other forms of knowledge, indicated as "#IV – experiential" (Figure 1), that hold great value, but are not our main emphasis. We suspect that each of the three types of research knowledge differs in whom it affects, and through what mediators.

Mediators

Under mediators, we distinguish seven types. The upper tiers are "players" – individuals or groups that act upon research knowledge. They do so via various factors (shown in second and third tiers) – including infrastructures, reward systems, programs (training), and educational content and technology. The top tier also tends toward earlier-acting entities.

As a system, the fact that mediation appears to play essential roles is important. We hypothesize that direct access to research knowledge is far more prevalent in certain situations than in others, and that this benefits innovation. In contrast, industrial S&T innovation seems far more apt to have the pivotal innovator (e.g., design engineer) directly access research knowledge, especially applied research findings (Figure 3, addressed later). However, the engineer also benefits from more or less direct linkages internally in the firm to the research unit, if there is one; with external knowledge producers in universities, not-for-profits, government labs, suppliers, and even customers; and mediators such as professional and trade associations.

Teachers

Who are the innovators? We posit that teachers (faculty) play this pivotal role. Teachers, even at the university level, play multiple roles, such as: transmitting knowledge, motivating students to learn, selecting and organizing content to be treated, and serving as role models. So, excellence in teaching is itself multidimensional.

Settings

Context could affect many facets of STEM innovation – e.g., how classroom settings compare against other settings, as settings in which to convey particular knowledge. RKU also seems likely to vary considerably by discipline (department).

Another key contextual element is discipline. We want to gauge the degree to which our STEM innovation system conclusions generalize across disciplines. How much variance relates to discipline vs. institution? Can we measure the extent that peer-to-peer messages reinforce these?

Learners: It seems more productive for us not to delve into "micro" aspects of teaching and learning. But in our comparative modeling, we should not ignore student differences among and within institutions (e.g., economic class, educational background, intelligence).

Performance

Student outcomes are not a deterministic result of a simple additive or linear process: e.g., learning achievements are a function of: learning mode + teaching method + learner attributes + teacher attributes + organizational context[8]. Enhancing STEM learning in research universities faces challenges in that the dependent variables (student outcomes) are multifaceted and the independent variables interact complexly (Figure 1).

Assessment

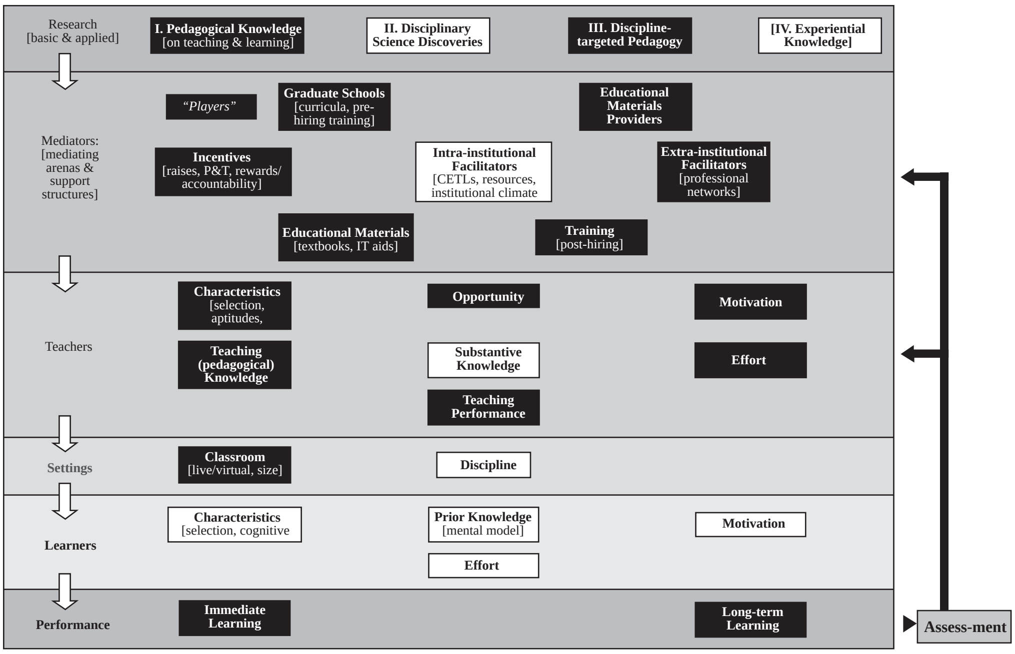
A major feedback loop is nominally indicated by "Assessment." This could (and should) entail feedback to mediators (e.g., institutional incentives and support) and teachers (e.g., motivation, effort, performance), with eventual impacts on immediate and long-term student learning.

3) SPECIALIZING THE MODEL TO RESEARCH UNIVERSITIES

Figure 2 highlights what we consider to be the relative strengths and weaknesses for STEM innovation at the research university. We posit that the blackened elements are relatively inactive.

Fig. 2

Research Knowledge Transfer in Support of the STEM Teaching Function in Research Universities



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[8]Grenn, P.J., and Stark, J., *Approaches to Research on the Improvement of Postsecondary Teaching and Learning*, National Center of Research to Improve Postsecondary Teaching and Learning, Working Paper, University of Michigan, 1986 (p. 19).

The image of the research university keys on the primacy of research performance for the success of a faculty member. An inherent advantage of the research university in this regard is that the faculty member takes on dual roles of researcher and teacher, thus offering direct linkage to the latest in the field. The "direct connection" seems strongest in advanced courses or individual interactions specialized to the given professor's research domain. The advantage seems less in conveying basic disciplinary knowledge in lower level classes.

This research primacy affects many other facets of our model:

- Pedagogical knowledge and pedagogical research, even discipline-targeted, carry essentially no value, so there are bleak prospects for RKU involving Types I and III research.

- Certain mediating factors suffer. Downplaying the role of teaching relative to research signals that one need not incorporate any pedagogical training in the graduate curriculum. Hence, next generation faculty are almost totally ignorant. As Nowlis et al. (1968 – quoted in Wulf et al., 2004, p. 4-5) put it, "It is sometimes wryly noted that college teaching is the only profession requiring no formal training of its practitioners."

- In the absence of a generally supportive climate toward STEM teaching excellence and innovation, the role of special support organizations becomes paramount (whereas other college settings may have more pervasive support for teaching and learning excellence).

- Research university faculty characteristics favor the qualities that make for outstanding researchers, not those of outstanding teachers. Teaching knowledge is presumed to derive totally from experiential knowledge – serving as a TA in grad school, learning by doing as a young faculty member (possibly with some extra time provided for class preparation and/or lab start- up).

- Time is of the essence. Given limited time, the savvy faculty member will minimize effort expended on teaching to maximize research activity. As Kurt Gramoll put it (seminar at Georgia Tech, Sep. 23, 2004), the strongest motivation for an engineering faculty member at a research university to be interested in STEM innovation is the prospect of saving time for research. The motivation of enhancing student learning is distinctly esoteric or idiosyncratic to individuals. As Thomas Reeves summarized (same seminar) a successful STEM innovation at the Air Force Academy, students and faculty agreed that this problem-based learning approach led to greatly enhanced learning. However the innovation was shelved because it required higher time commitment of faculty and of students that neither was inclined to make.

- An exception, wherein the advantage would seem to lie with the research university, arises in undergraduate research. Our study focuses on undergraduate education, but graduate education is concurrently taking place at research universities as well. So, there is potential for undergraduates to learn from graduate students, as well as faculty, in research.

Differences in organizational arrangements may work to the advantage of one type of college over others. In considering prospects for educational innovation at research universities compared to other colleges, some additional factors include:

- relative availability of co-op opportunities
- percentage of students partaking of learning abroad opportunities
- relative reliance on on-campus vs. distance learning
- extent of groupwork.

4) IMPLICATIONS OF THE MODEL

In this section we compile a variety of observations to illustrate how the RKU model can stimulate thinking about the system to promote STEM innovation. These are coarsely organized into the seven model segments, followed by consideration of a pervasive issue – motivation.

Segment-specific Implications

Research

An article about engineering education suggests that those who perform pedagogical research often are not knowledgeable about the subject matter being taught, and thus are at a disadvantage to provide the necessary discipline-based pedagogical knowledge. **Supply and demand** considerations pertain; our hypothesis is that demand for outputs of pedagogical research sources is very weak at research universities. Glassick argues that scholarship includes discovery, integration, application, and teaching.[9] Yet Research Universities continue to recognize only those scholarly research endeavors that discipline-specific and discovery-based.

With respect to Type II research (advances in the field, e.g., chemistry), the faculty play dual professional roles – as researchers and as teachers conveying cutting edge research advances (content, methods). However, with exceptions, we hypothesize that they are not direct purveyors of Type I pedagogical research knowledge and probably not very much of Type III, discipline-focused pedagogical knowledge. As collected in Faculty Time, Academic Excellence, Doyle found that overall faculty spent approximately ten percent of their time in the pedagogical research and curriculum development field.[10] This dual role issue seems to be widely recognized, but not heavily researched.

Even if teachers are successful STEM innovators, in research universities they are unlikely to get much support from their colleagues. Educational innovation is not part of the core mission of research universities, so resistance to change is pervasive, even if innovative teachers are successful. Katkin notes that it is difficult to engage scientists in innovative practices of undergraduate education.[11] Typical faculty in research universities do not see the need for additional professional development because they see themselves as finished products.[12] Consequently, Huber claims faculty "do not usually see their own teaching and learning as a matter for scholarly inquiry and communication."[13] According to the results of a 2001 survey, Reinventing Undergraduate Education: Three Years After the Boyer Report, only five percent of respondents indicated improving pedagogy as the most important action the research university could take to improve undergraduate education.[14] In follow up interviews and discussions with 200 faculty and administrators, respondents

[9] Glassick, Charles E. Scholarship Assessed: Evaluation of the Professoriate. San Francisco: Jossey-Bass Inc., 1997. (22).

[10] Doyle, Michael P.(2002) *Faculty Time, Academic Excellence: A Study of the Role of Research in the Natural Sciences at Undergraduate Institutions*. Research Corporation, Tucson, AZ.

[11] Katkin, Wendy. The Boyer Commission Report and Its Impact on Undergraduate Education. New Directions for Teaching and Learning, no. 93, Spring 2003. (p.25).

[12] We are indebted to Daryl Chubin for these insights.

[13] Huber, Mary Taylor. Reflections on The Carnegie Academy for the Scholarship of Teaching and Learning. Chapter 1. Disciplinary Styles in Scholarship of Teaching: Exploring the Common Ground. Washington, DC: American Association for Higher Education and the Carnegie Foundation for the Advancement of Teaching. 2002. p.25.

[14] Boyer Commission on Educating Undergraduates in the Research University, S.S.Kenny (chair). Reinventing Undergraduate Education: Three Years After the Boyer Report. State University of New York-Stony Brook, 2002. (Appendix Table 2, p.32).

reported faculty, "have difficulty seeing the connections between their teaching and student learning."[15]

Mediators

As per Figure 2, we perceive that most of the seven types of mediators identified are not effective at promoting STEM innovation. "Leakage" was suggested by Debra Fowler of Georgia Tech as a way to think about the transfer of research knowledge. One might seek to estimate how effectively researchers communicate with mediators; how well mediators convey to potential innovators (teaching faculty); and how well they translate into actions to improve learning. For instance, might there be ways to enhance communication/transfer (reduce leakage) from the results generated from NSF research grants to the STEM innovation system? In this regard, NSF recently implemented a policy of returning proposals that did not explicitly address in the Project Summary how the proposed research would meet "Criterion II," the broader impacts of the activity. The AAAS and the National Action Council for Minorities in Engineering believe that, if more research funding agencies placed greater emphasis on Criterion II-like factors, this would lead to "collapsing the distinction between research and education." [16]

Incentives appear paramount at research universities. "The Lilly Study" addressed the balance between research and teaching emphases at research universities, concluding that, although an institutional goal in support of an equal balance of research and teaching is perceived, this goal is not supported by faculty or administration.[17] The farther one is from teaching, and the closer one is to administration, the more that person will tend to favor research over teaching.[18] Diamond found, in a 5-year follow-up to the Lilly Study, that personal and institutional priorities have shifted toward favoring a better balance between research and teaching.[19] However, resources, hiring criteria and reward system remain disproportionately skewed towards disciplinary (scientific, not pedagogical) research.[20]

Intra-institutional support at research universities is of particular interest as it is potentially malleable. We identify "Incentives" separately in the model to spotlight their key role. Another, not unrelated, dimension concerns the resources available for teaching, learning support, and advanced technology. Teaching load might well be considered as part of the equation here. Institutional climate refers to a variety of indicators that convey that teaching is important – e.g., a college website stressing the learning approach emphasized at that institution. Special units set up to encourage good teaching may play important roles (e.g., at Georgia Tech, this is CETL -- Center for the Enhancement of Teaching and Learning). Such structures, plus affirmation at various administrative levels, seem particularly critical in delivering support for innovation (in curriculum, technology, learning approaches, etc.). In assessing these kinds of centers' role in research universities, it may be necessary to distinguish campus-wide centers from those that focus on STEM areas. At Georgia Tech, CETL services appear to outstrip demand for them.

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[15] Katkin., Wendy. p.33.

[16] Malcom, S.M., Chubin, D.E., and Jesse, J. K., *Standing Our Ground*, AAAS and NACME, October 2004, p. 25.

[17] Gray, Peter. *The National Study of Research Universities on the Balance Between Research and Undergraduate Teaching*. Center for Insturctional Development, Office of Evaluation and Research, Syracuse University, 1992. (10).

[18] Gray, Peter. (13).

[19] Diamond, Robert M. *Changing Priorities at Research Universities, 1991-1996.* Based on: The National Study of Research Universities on the Balance between Research and Undergraduate Teaching (1992). Carnegie Foundation for the Advancement of Teaching, 1998. (3).

[20] Diamond, Robert M. (3).

Extra-institutional support includes an impressive array of professional organizations, conferences, and journals addressing STEM college teaching to greater or lesser degrees. We could distinguish additional interactions in our model. For example, Donna Llewellyn, head of Georgia Tech's CETL, says that interchange among such center professionals at POD Network and other meetings is especially valuable in sharing experiential knowledge (what others are trying and how it is working). In addition, there are resources available via the Internet; one example is mentornet, a nonprofit e-mentoring network that addresses the retention and success of those in engineering, science and mathematics, particularly but not exclusively women.[21] However, we perceive that these elements are not prominent influences upon behavior of research university faculty.

For instance, disciplinary teaching journals appear to be a rich resource, but we wonder who takes advantage of them? For instance, The American Biology Teacher is described as covering both discipline-focused content and learning, as well as teaching research. It presents specific how-to-do-it suggestions for the classroom and laboratory, field activities, interdisciplinary programs, and articles on recent advances in biology and life science. Another potentially interesting interaction concerns how developers of innovative STEM materials (text, IT aids, etc.) market these, and to whom.

Teachers

Faculty act within institutional contexts, including both departmental and overall institutional policies, resources, and practices.The context is significant because institutional and departmental policies shape the norms that influence faculty behavior.[22] Tenure-track faculty, especially, have considerable autonomy, but their actions and preferences are influenced by institutional and departmental norms.[23] Braxton's study reveals faculty norms supported 3 of 6 recommendations to improve undergraduate education: systematic program of advisement, feedback on student performance, and fostering an egalitarian and tolerant classroom climate. The disturbing finding was the remaining three recommendations that were not supported by norms: learning about students, encouraging faculty to student contact, and concern to improve teaching.[24]

Professors may innovate within their teaching, but not enter the public discourse, no less perform pedagogical research. [I don't understand this sentence. Words missing??]

Settings

Distinguish the classroom from other teaching/learning contexts. This seems important in that much of the RKU literature in education presumes classroom settings. Much of that literature also concerns K-12 teaching and learning. As the model implies, K-12 education differs significantly from STEM at research universities. Among the key distinctions, we suggest:

- the dual role (research university teachers taking teaching as a secondary role)
- children vs. adult learners (different degrees of self-responsibility, motivators, prior knowledge, issues).

This implies that we may not learn much pertinent to research knowledge transfer processes in STEM university education from the K-12-intensive, RKU in education literature.

[21] See www.mentornet.net.

[22] Braxton, John M. *The Implication of Teaching Norms for the Improvement of Undergraduate Education*. The Journal of Higher Education, Volume 67, No. 6, 1996; Eimers, Mardy T. *The Implications of Teaching Norms for the Improvement of Undergraduate Education in Teaching-Oriented Colleges*. ASHE Annual Meeting Paper. 1998; Quinn, Jennifer Woods. *Faculty Perceptions of a Teaching Norm at Five Institutions.* (Apr 1994). American Educational Research Association (AERA) Annual
Meeting Paper;

[23] Braxton, John M. (604); Eimers, Mary T. (3).

[24] Braxton, John M. (616-617).

Learners

We point toward motivational issues, treated in the following sub-section.

Performance

We see performance as centering, for students, on STEM learning, and for faculty, on STEM innovation. One could further separate performance dimensions:

a. the education of STEM college students about STEM topics
b. the education of non-STEM college students about STEM topics
c. the education of future K-12 STEM teachers
d. education of graduate students.

Also note that the sub-section just below on Motivation focuses on factors affecting Performance.

Assessment

We don't break out the many assessment issues in detail, but note that this is the glue that effects the incentive structures so central to research university STEM innovation. Faculty seem to lend greater credence to research evaluation than to teaching evaluation.

Motivation in the Research University

For both teachers and learners, we suggest a general expectancy motivational model at work. This implies that performance is a result of motivation determining effort, in conjunction with ability. A general expectancy model of motivation proposes that performance is a result of three multiplicative terms:

[Effort as f(Motivation)] X [Performance as f(Effort)] X [Reward as f(Performance)]
where "f" = function of, and "X" implies a multiplicative relationship

If any of the three linkages is low, performance will be low. All are perceptual – e.g., does the teacher or learner expect that putting in extra effort will enhance his/her performance? Does she expect that enhanced performance will lead to reward? And, is that reward highly salient?

Do research universities motivate effort to innovate in STEM teaching? Not very well. For instance, despite the proliferation of faculty/teaching development centers on the campuses of research universities, faculty have been reluctant to seek assistance. They do not perceive that utilization of the centers' resources would procure benefits to themselves. So why bother?[25]

Do teachers expect that performance will be proportionately rewarded? In response to a recommendation by the Boyer Commission (1998), to "Change Faculty Reward Systems", the Boyer Report (2001) survey revealed thirty-five percent of respondents indicated undergraduate teaching as a major consideration in promotion and tenure. Thirty percent indicated that undergraduate teaching receives limited consideration in promotion and tenure decisions and twenty-three percent acknowledge variation by department.[26] Survey results were split on the question of whether a change in faculty reward systems has occurred in the last three years (forty-five percent yes, forty-eight percent no).Only seven

[25]Katkin, Wendy. p.33.
[26]Boyer 2001. Exhibit 24. p.25.
[27]Boyer 2001. Exhibit 25. p.26.

percent of respondents indicated offering faculty awards and incentives as one of two most important actions their research university had taken in the last three years to improve undergraduate education.[28] Huber further insists that teaching is not part of the reward system.[29] Given the confusion of whether such changes are in place or not, it is not surprising that in follow up discussions, faculty revealed their belief that in reality such guidelines were not currently being applied in P&T decisions and the overwhelming emphasis continues to remain on research productivity.[30] Diamond (1996), following up the Lilly Study (1992), reports that despite institutional shifts toward a greater balance between research and teaching, respondents' perceptions are that promotion, tenure and merit pay policies continue to reward research over teaching.[31] Complaints centralized around mixed messages received by faculty from the institution in the form of institutional rhetoric advocating a balance between teaching and research, but institutional practices and resources lacking in support of such a goal.[32]

Do faculty consider that the proferred rewards are valuable to them? The Boyer (2001) survey highlighted the existence of certain reward structures currently in place in research universities: curriculum development grants (81%), salary supplements (22%), recognition awards for instruction (99%), and recognition awards for other undergraduate focused activities (47%).[33] However, in follow-on interviews and discussions, faculty acknowledged these reward structures were not influential in motivating them to devote more attention to teaching.[34] Other motivational factors were mentioned which negated the rewards offered:

- time constraints
- personal interest in research over teaching
- perception that the P&T process does not value undergraduate teaching, and
- the lack of information/knowledge on what to do.[35]

Such a motivational model points to incentives as important determinants of motivation. We hypothesize that this is a key difference between research universities and other college settings – that strong teaching performance is not as salient to research university faculty because they perceive themselves rewarded primarily for research activities. This appears to have had a major spillover effect on recruiting and maintaining undergraduates to pursue science majors. Because of poorly taught introductory undergraduate science and math courses, a "mass defection" has occurred away from the sciences.[36] The problem extends into graduate school. From 1993-2000, STEM graduate programs have experienced a decrease in enrollment by an average of more than 14%. Math (32%), Engineering (25%), and the Physical Sciences (18%) have experienced the greatest drops in enrollment.[37]

[28] Boyer 2001. Appendix Table 1. p.31.

[29] Huber, Mary Taylor. p.28.

[30] Katkin, Wendy. p.35.

[31] Gray, Peter. *The National Study of Research Universities on the Balance Between Research and Undergraduate Teaching*. (1992). Supported by Grant from Carnegie Foundation and supported by the Lilly Endowment, Inc.

[32] Gray, Peter. p.66.

[33] Boyer 2001. Exhibit 26. p.26.

[34] Boyer 2001. p.24.

[35] Boyer 2001. p.24.

[36] National Research Council. (2003). *Improving Undergraduate Instruction in Science, Technology, Engineering and Mathematics: Report of a Workshop*. Steering Committee on Criteria and Benchmarks for Increased Learning from Undergraduate STEM Instruction. Richard A. McCray, Robert DeHaan, and Julie Anne Schuck (Eds). Committee on Undergraduate Science Education, Center for Edcuation, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. p.6.

[37] NRC (2003), p.6.

Faculty reward systems deserve scrutiny to ascertain the extent to which they weigh teaching and learning. The 1998 Boyer Report, Reinventing Undergraduate Education: a Blueprint for America's Research Universities, describes the current reward system as one based primarily, if not exclusively, on research productivity. Salary recommendations and decisions regarding promotion and tenure largely ignore teaching considerations. The Boyer Report even goes so far as to claim that pre-tenure faculty with expressed interests in experimental or innovative undergraduate courses, or who spend extra time on undergraduate activities, will be counseled toward more productive uses of their time.[38]

Furthermore, in Scholarship Reconsidered, 83 percent of surveyed research university faculty rated publishing very important to attain tenure[39] In contrast, 10 percent deemed student evaluations of courses very important for attaining tenure. The need for change is recognized.[40]

Further issues arise. There is a sociological need to maintain one's reputation as a researcher.[41] Young faculty feel pressure to establish themselves as researchers, and this translates into poor teaching quality.[42] The NRC observes that, as a result of current anti-teaching structures, faculty heavily rely on a narrow range of familiar, outdated pedagogical tools.[43] Beyond P&T, Kremer reports that able researchers received a greater percentage salary increase than teachers with strong service records.[44]

Committed teachers at research universities constitute a minority. Kremer uses cluster analyses to classify faculty into five discrete types. At one large university, a cross-departmental study identified a preponderance (44%) as "Researchers," considerably outweighing those emphasizing Teaching (14%) and those balancing Teaching and Service (10%). Our Georgia Tech CETL colleagues, Debra Fowler and Donna Llewellyn, speculated that faculty attitudes toward teaching at research universities would break out something like:

· So committed to teaching as to become active pedagogy researchers	<3%
· Not pedagogical researchers, but users of pedagogical research findings to improve their own teaching	10-15%
· Not much attuned to the pedagogical literatures, but really good teachers	20-25%
· Don't particularly care about their teaching effectiveness	>50%

This section has explored motivational issues for STEM education at research universities. This pervades the system model (Figure 2) well beyond the "Incentives" box in the Mediators segment. Enhancing STEM innovation requires significant change in faculty motivators.

[38] Boyer 1998. p.32.

[39] Boyer, Ernest L. (1990). *Scholarship Reconsidered: Priorities of the Professoriate.* The Carnegie Foundation for the Advancement of Teaching. Jossey-Bass Inc., Publishers. San Francisco.

[40] See, for example, http://www.thenationalacademy.org/Resources/facrewardessay.html.

[41] Serow, Robert C. (2000) "Research and teaching in a research university". *Higher Education* vol.40 pages 449-463. Pg. 453.

[42] Boyer (1990) pg. 48

[43] National Research Council, 2003. (67).

[44] Kremer, John. (1991). "Identifying Faculty Types Using Peer Ratings of Teaching, Research, and Service." *Research in Higher Education* Vol. 32 No. 4, Human Sciences Press, Inc. pg. 356

5) COMPARING INNOVATION SYSTEMS
STEM at Research Universities vs. Engineering in Technology-intensive Firms

Figures 1 and 2 present a complex systems model for STEM innovation at research universities. While this model derives in part from our knowledge of S&T innovation processes in industry and government, it differs considerably. Examination of industrial innovation using an analogous model should only be carried forward to identify creative possibilities.

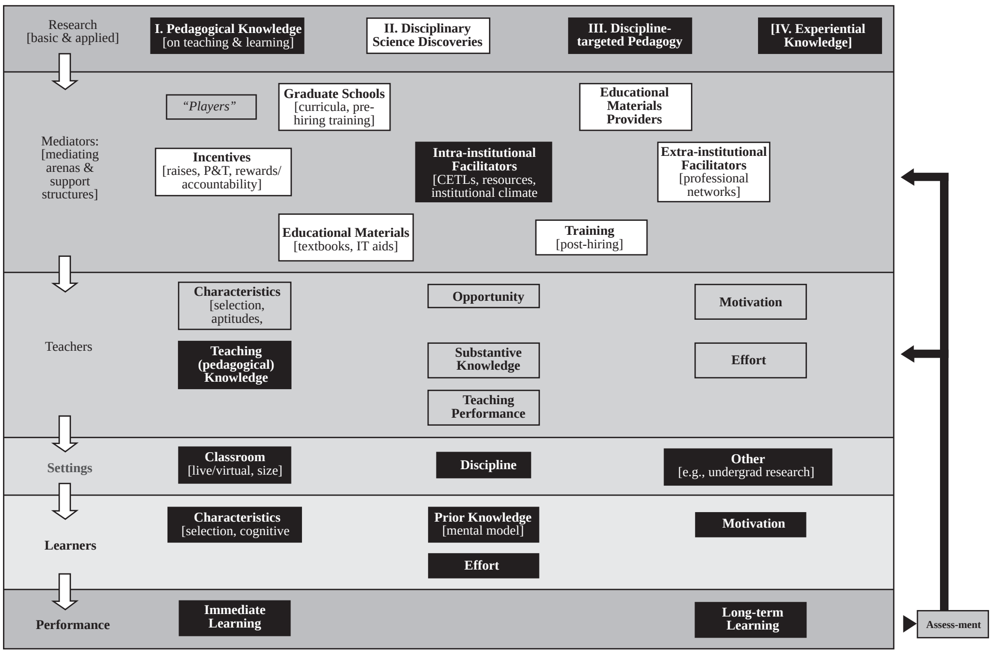

Figure 3 adapts our STEM RKU model to the professional engineer performing his or her role in the technology-intensive firm. Of course, factors related to teaching and student learning just don't pertain, so they are darkened. The engineer draws on disciplinary science discoveries that have become part of his/her basic knowledge and understanding through pre-hiring undergraduate and graduate training and possibly work experience. Many larger firms provide time off and financial support for additional training, including acquisition of higher degrees. Vendors provide detailed performance data on new equipment, materials, and so on. Professional networks are very active as well, providing technical journals and meetings as well as informal exchange of issues and solutions to problems. Incentives and performance assessments are directed toward the single engineering role, which if performed to the firm's expectations will result in new or improved products and processes.

What seems striking to us, in contrast to the teaching role in a research university, is the relative absence of conflict among competing demands on the engineer's time. In contrast to the "Dual Role" conflict for the research university professor, the industrial innovator enjoys relative alignment of motivators. A large number of mediating factors work together to support excellence in a single role, engineering performance. A mutually reinforcing system of incentives, effort, substantive knowledge, and knowledge-enhancing support structures works to motivate innovation. In turn, that contributes to the engineer's individual performance, the firm's objectives, and economic growth.

This contrast in degree of alignment between technological innovation (Figure 3) and STEM teaching improvement in research universities (Figure 2) points to a core concern:

> *If we want better undergraduate learning at research universities, how can we align the operative influences to reward excellent teaching (or other ways of attaining the goal)?*

The "innovation" objectives, in addition to the innovators (the people) and the influences acting on them, differ sharply. As per Figure 3, the ends of industrial innovation are new products and processes. In contrast, in Figure 2, the ends are behavioral changes in one set of people (students), affected by the actions of the institutional system and by another set of people (teachers). Furthermore, "learning" entails multiple possible goals – one framework distinguishes 1) conceptual and factual knowledge, 2) critical thinking and problem-solving skills, and 3) professional or career skills.[45] Furthermore, in judging university effectiveness, is accountability to the student, funders, and/or broader society? Green and Stark go on to mention a number of factors incorporated in our model, in wondering about roles:[46]

> *… Influence that organizational characteristics exert indirectly through one or more mediators, e.g., students, faculty, specific teaching and learning practices, curriculum development, or accountability mechanisms.*

With those cautions in mind, we offer the following general notions from studies of the industrial innovation system:

- Cooperative engagement of all the stakeholders in an eventual innovation early on in the development process works better than stagewise-independent activities – i.e., it is less effective to have researchers "toss their results over the transom" to designers, who, in turn, do likewise to the manufacturers, etc.

- The importance of innovation in most technology-based industrial organizations benefits from general consensus. In university education, the need for change in learning seems much less obvious to the various parties at interest. Particularly at research universities, institutional reputation (and well-being) does not depend much upon "new and improved" learning processes and performance. Nor do individuals' (teachers and learners) incentives relate clearly to educational innovation.

- Depth vs. Breadth tradeoffs seem pronounced in terms of curriculum. What balance gives students the best advantage?

An innovation perspective draws attention to the roles of "innovator" and "change agent." Those suggest damning gaps in research universities where institutional support groups (e.g., Georgia Tech's CETL) find a glaring lack of demand for their services. Baldly put, the "innovators" (faculty) are not inclined to do much innovating. Loosely analogous to the advantages of "market pull" over "technology push" in industrial innovation, units such as CETL can't push very far unless university reward structures generate pull.

As mentioned under "Mediators," we hypothesize that direct access to research knowledge by innovators is advantageous. We suggest examining alternative organizational arrangements to facilitate this for STEM in research universities.

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[45]Grenn, P.J., and Stark, J., *op.cit*, p. 17.

[46]Grenn, P.J., and Stark, J., *op.cit.*, p. 15.

6) USING THE MODEL TO EXPLORE STEM INNOVATION PROSPECTS AND POLICIES

This section offers a range of issues for further study.

Is our bleak assessment of the situation in research universities (Figure 2) justified? If so, solutions must be system oriented, primarily to affect motivation toward STEM teaching innovation and learning performance. It might be worthwhile to compile experiences of what has worked to alter the low priority on teaching. Evaluation of the extent to which researchers deliver on their NSF "broader impact" proposal claims could be a powerful lever.

The systems-based models represented in the Figures warn us that just affecting a single factor, e.g., faculty motivation, is likely to be damped out by the complex of inertial system processes. Coordinated policy and actions at national and institutional levels would have best chances of resulting in major change. For instance, the near-total absence of professional training for faculty to be teachers is one element to be treated in conjunction with others (Figure 1). Such training (e.g., familiarizing doctoral students with learning principles[47] would be more appreciated were research university faculty hiring practices to emphasize teaching preparation and portfolios.

Each of the seven mediating elements warrants investigation to understand the roles it plays in STEM innovation. We are particularly interested in variability. For instance, what percentage of new PhD graduates receives any training in teaching? What training elements are becoming more prevalent and how effective are they? Do these differ among disciplines? Between new hires at research universities and PUIs?

Pursuing the notion of research knowledge "leakage," it might be fruitful to track successful STEM innovations back to the knowledge generation and transfer routes that underlie them. If our model is right that "mediators" are vital to STEM research knowledge utilization, these could prove illuminating.

Assessment is important. We recognize the interplay among basic research (e.g., pedagogy), institutional research, policy analysis, and evaluation research.[48]

We see potential in comparing STEM teaching performance:

1) Between Research Universities and Primary Undergraduate Institutions generally;

2) With benchmark research universities that are treating STEM teaching as a priority with radically altered incentive structures.

We are pursuing comparisons between research universities and other colleges in terms of propensities toward STEM innovation. We don't detail these here, but note a few challenges. For both teachers and students (learners), we believe that "selection" warrants study. For instance, inclination toward teaching, training in pedagogy, and teaching-relevant experience seem apt to be less relevant to hiring at a research university than in other college settings. Students and teachers alike, in choosing colleges, presumably match their attributes and objectives with their perceived situational assessments of research universities vs. alternatives.

Furthermore, the lack of motivation to improve one's teaching ability at a research university would imply less ongoing training participation there, as compared to other college settings. Gottlieb and Keith (1997) found that individual academic orientation for either teaching or research correlated with the number of weekly hours spent on that activity. Moreover, research-oriented faculty were found to perceive conflicts with teaching requirements. A

[47] Donovan, M.S., Bransford, J.D.,a nd Pellegrino, J.W. (eds.), *How People Learn*, National Academy Press, Washington, DC, 2000 & 2004.

[48] Grenn, P.J., and Stark, J., *op. cit.*, p. 5.

little pedagogical knowledge might go a long way. Might research universities make major gains by modest 'required' pedagogical exposure – e.g., one-day orientation for new faculty on active learning principles, learning differences, characteristics of our university's students, success story case examples, setting up T&L communities, etc.?

How large are the differences among research universities in their emphasis on teaching and learning? We intend to explore this question. An article in the Atlanta Journal & Constitution (Oct. 17, 2004, pgs. C1-C4) about history professor Patrick Allitt of Emory University notes that he recently served as the Arthur Blank Professor of Teaching, teaching colleagues how to improve their teaching. He is now director of the Center for Teaching and Curriculum, whose mission is to improve teaching on campus. We suspect that our contrast of Research University vs. PUI is more of a continuum across both types, with varying degrees of resource commitment and emphasis on teaching and learning. Furthermore, are there ways to transfer research knowledge directly to learners?

The National Survey of Student Engagement [] 2004 Report Overview – Table 5 compares student responses to this extensive survey by type of universities (using Carnegie classes). Of note, undergraduate research with a faculty member on average engages 20% of the students at research universities. This is very comparable to the level of involvement at other college types, ranging from 17 to 20%, except that Baccalaureate – Liberal Arts colleges (PUI's) are considerably higher, 33%. Is this a research university resource that could be tapped more effectively?

Does the presence of a College of Education on campus helps transfer Types I and III research knowledge? We are aware of the speculation that such knowledge and those who generate it are held in low esteem by many STEM disciplinary faculty.

In reviewing literature, we have been impressed by the work of the National Center for Research to Improve Postsecondary Teaching and Learning. One of their publications that integrated many other writings pointed toward active learning, sharpening expectations about student learning, and so forth. It also summed up three influential reports as focusing on the desirability of "liberal education" with a core curriculum emphasizing the humanities.[49] How do such educational aims mesh with STEM? One could serve up a litany of "on the other hands" – integrative learning vs. individualized choice, disciplinary rigor vs. educational breadth.

If the emergence of Federal research funding has contributed significantly to the emphasis on research over teaching, agencies such as NSF could alter the balance by insisting that educational impact objectives be set forth and then assessed for each research project. It would be worthwhile to evaluate how well these objectives are being fulfilled.

Would diminution of the role of tenure affect the effort expended upon teaching? As one young faculty member attending a National Academies conference to stimulate frontier research noted to one of us, he further perceives pressure to obtain research funding as distinct from doing research.

A special concern is whether research university reward systems impede generation of STEM disciplinary pedagogical research knowledge.[50]

Is "innovation" a helpful concept in considering STEM university education? We think so in that it offers a different slant in prompting focus on change processes. However, as per the contrast between Figures 2 and 3, we recognize that a simple one-to-one transfer of concepts from studies of science and technology innovation processes is not valid. Innovation in public health may provide a richer analogy.

[49] Stark, J.S., and Lowther, M.A., *Designing the Learning Plan: A Review of Research and Theory Related to College Curricula*, National Center for Research to Improve Postsecondary Teaching and Learning, University of Michigan, 1986.

[50] http://www.aarweb.org/profession/vtlc/articles/Carnegie02.asp includes an article by Huber and Cox on impediments to the "scholarship of teaching".

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