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The Historical Roots of the Field of Engineering Systems: Results from an In-class Assignment

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Abstract. *The field of Engineering Systems (ES) is quite young but there are intellectual roots that go far back in time. At least that is the working hypothesis in an integrative capstone assignment given in the first doctoral subject for incoming ES PhD students at MIT. The assignment has been given for four years (2008-2011) and involves pairs of students researching the intellectual connections between a specific historical root and a specific modern ES method. This paper describes the faculty and student perspectives on the assignment, including the perceived learning outcomes, and insights gained into the roots of Engineering Systems. Some overall observations include:*

•Interconnections among almost all selected topics (whether labeled roots or modern methods) are apparent. Each topic has an extensive time period of unfolding which gives rise to overlap and complex interactions among the topics;

•Herbert Simon's work appears most pivotal in the roots of Engineering Systems. Jay Forrester, John von Neumann, Norbert Weiner and Joseph Schumpeter are also identified along with others as having a significant impact;

•The faculty always learn something about the field from what the students find even when topics are repeated; and,

•The assignment is a valuable – but not perfect – vehicle for learning about Engineering Systems and for launching budding researchers' efforts in the field.

Keywords. *historical roots, Engineering Systems, methodologies, knowledge relationships, citation analysis, engineering pedagogy*

1 Introduction

In the initial, required, Engineering Systems doctoral seminar at the Massachusetts Institute of Technology (MIT) (see (Massachusetts Institute of Technology, 2012) and (Roberts et al., 2009) for thorough course descriptions), the two overarching learning objectives are:

1. Increasing student knowledge of the field;
2. Increasing student understanding of research in Engineering Systems.

Over the past four years, an assignment in this course – dubbed "Historical Roots" – evolved into one of the major tools for accomplishing both learning objectives. This paper describes the assignment, its evolution and its role in the course. Perhaps more importantly, the paper also attempts to use the assignment submissions over the past four years to explore, in a preliminary way, the historical roots of the new but vibrant field of Engineering Systems (which is only one name – that used at MIT – for the field that seeks to comprehend complex socio-technical systems). This paper thus begins to explore both the content of and suitable pedagogy for the intellectual foundations of the field, and the relationships among these foundations.

The paper is structured as follows: the assignment and student submissions are described in Section 2. Section 3 describes the sources of the observations provided in this paper, which are based on the faculty's reflections on the assignment and their review of the submitted materials. Student feedback was also solicited through the use of a web survey. A quantitative summary of the survey data is presented in Section 4 and integrated results are detailed in Section 5. Overall discussion of the results follows in Section 6.

2 Historical Roots Assignment

The Historical Roots assignment requires each student team to prepare a 5,000 word report and later give a 25 minute in-class presentation[1]. Each student team selects both a "historical root" *and* a "modern methodology." The assignment further requires[2] that each team explore forward in time from their historical root and backward in time from the modern methodology using careful historical analysis of the literature, citation analysis and other methods to explore the complex web of work which precedes current Engineering Systems practice and research. The historical development of these interrelated fields is explored deeply in each submission[3]. Over the past four years, students have chosen the historical roots/modern methodology pairs shown in Table 1.

[1] The presentations were not part of the assignment in 2008 but were from 2009-2011.
[2] The full detailed assignment is available (see Massachusetts Institute of Technology, 2012).
[3] Two example submissions have been posted by the student authors (Santen and Wood, 2008; Cameron and Pertuze, 2009) and are worth examination by the interested reader.

Table 1: Root and Methodology pairs (on same line) for all 24 papers submitted from 2008-2011. Topics shaded in grey have been selected more than once.

Year	Historical Root	Methodology
2011	Impact of Technology on the Economy	Technological Dynamics
	Cybernetics and Control Theory	Strategy
	Sociobiology	Modern Network Analysis
2010	Complexity Theory	Social Networks
	Organizational Theory	Real Options Analysis
	Equilibrium Economic Analysis	Benefit Cost Analysis for Project Evaluation
	(Historical) Network Analysis	Social Networks
	Sociobiology	Agent Based Modeling
2009	Cybernetics and Control Theory	System Dynamics
	Operations Research	Stochastic Optimization
	Negotiation	Consensus Building
	Equilibrium Economic Analysis	Operations Research Network Analysis
	Impact of Technology on the Economy	Stakeholder Analysis
	(Historical) Network Analysis	Modern Network Analysis
	Supervisory Control	Decision Making Under Uncertainty
2008	Scientific Management	Real Options Analysis
	Scientific Management	Strategy Development
	Game Theory	Decision Analysis
	Decision Theory	Decision Making Under Uncertainty
	(Historical) System Dynamics	Agent Based Modeling
	Systems Engineering	Multi-Attribute Tradespace Exploration
	(Historical) Network Analysis	Social Networks
	Impact of Technology on the Economy	Strategy
	Decision Theory	Agent Based Modeling

In most instances, the root and method were chosen by the students with the expectation that a direct link could be found between them. Even though a number of roots and a number of methodologies were studied more than once, in only one instance was the same pairing chosen. Hence, virtually all of the 24 reports submitted represent unique endeavors.

3 Methodology

The lead author generated the insights described in Section 5 by reviewing the 24 student submissions and the associated faculty-provided feedback; these represent the faculty perspectives on the assignment. The student perspective was sought through a web survey described herein.

3.1 Student Web Survey

The authors used SurveyMonkey (https://www.surveymonkey.com/) to develop an online 16-question multiple-choice/Likert scale/open-ended response survey. The 47 students who have completed the Historical Roots assignment in the MIT Engineering Systems doctoral seminar were invited to participate by email over a period of two weeks in January 2012. The survey response rate was ~75% (i.e., 35 responses out of 47), with most respondents completing the survey in 15-30 minutes.

The survey sought to gather information in the following categories:

- General attitude toward and retrospective feedback regarding the assignment;
- Recall of insights, ideas, skills and methodologies gleaned from the assignment and their influence on students' subsequent doctoral research activities; and
- Evaluations of the role of the assignment in Engineering Systems cohort and community building.

To complement the multiple-choice responses, 12 of 16 questions allowed for elaboration and open-ended comments, providing a qualitative source to search for common themes in the students' perspectives. One author coded the 160 qualitative responses obtained, with codes and results described in Section 4.

To improve clarity and to minimize fatigue and bias, the authors consulted four student pre-testers and two MIT survey methodology experts.

To the extent of the authors' ability, the final survey instrument was designed to guard against acquiescence bias (Dillman et al., 2009), and social acceptability bias. Steps within the survey included: careful question wording; and the option to gracefully opt-out of individual questions, the whole survey, and the qualitative responses. These biases were further mitigated through measures to preserve respondent anonymity. Specifically, raw responses were available only to the student co-authors, and were anonymized before they were analyzed; the results were aggregated before they were shared with the professorial co-authors. The responses may still be subject to such biases, however, the nature of the comments themselves – seemingly frank and sometimes critical – provides some measure of confidence.

Another potential bias is a variation in the respondents' ability to recall the pertinent details. Given that the respondents completed this assignment between several months and several years prior to this study, a systematic bias is also possible for students of earlier years (e.g., 2008-2009). To accommodate lack of recall, survey questions included "do not recall" response options and allowed the respondent to skip questions, where appropriate. By way of reminder, the invitation to participate included a list of roots and methodologies chosen by each student pair (see anonymous list in Table 1), but no other efforts were made to aid respondents' recall.

Another potential temporal bias arises from the minor inter-annual differences in the Historical Roots assignment details (see Section 2), though none were deemed important enough to necessitate separate survey instruments for separate years. Instead, results were analyzed by year as well as in aggregate to identify temporal variations (see Section 4).

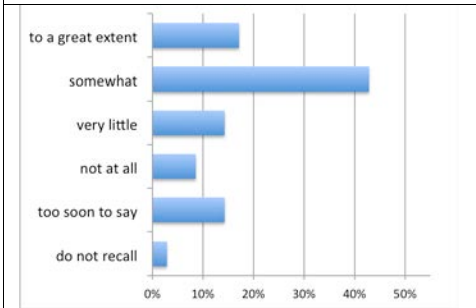
4 Survey Results

The main survey results are briefly introduced here and later referenced in Section 5. The multiple-choice responses are summarized in Table 2, Figure 1 and Figure 2. They indicate a generally positive attitude toward the assignment and a recollection of useful skills and insights, though these understandably diminish with the time elapsed since completion of the assignment (see Figure 2).

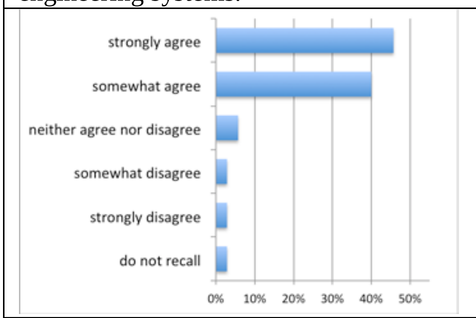
Table 2: Survey responses (*from Questions 3–6*) indicate a positive impact of the Historical Roots assignment on development of student knowledge and, to a lesser extent, direct contributions to research.

	X = ideas or insights	X = skills or methodologies
Can you remember any new [X] to which you were exposed through your Historical Roots assignment? *[If you answered Yes, please describe them here]*	80% replied Yes	82% replied Yes
Have you used any [X] from this assignment in your subsequent research? *[If so, which ones?]*	49% replied Yes	33% replied Yes

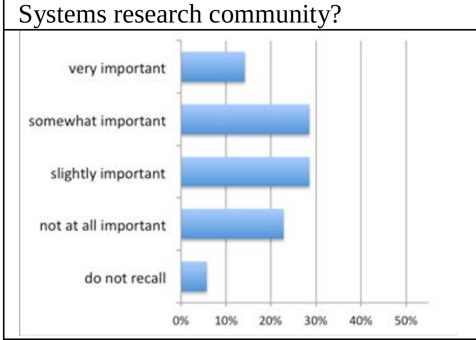
8. Did your experience with the ESD.83 Historical Roots assignment encourage you to explore more deeply the historical roots of your subsequent doctoral research?



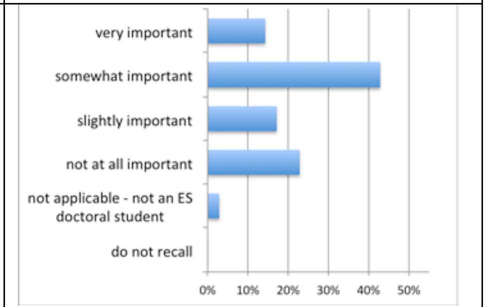
9. Rate your level of agreement with the following statement: "From listening to my classmates presentations of their Historical Roots assignment, I learned a lot about the breadth and depth of engineering systems."



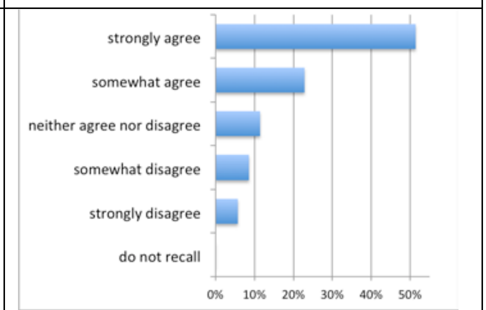
10. How important was the Historical Roots assignment to helping you feel like a part of the emerging Engineering Systems research community?



11. How important was the Historical Roots assignment to helping you feel a sense of community with your year's cohort of doctoral students?



12. Rate your level of agreement with the following statement: "Overall, the Historical Roots Assignment was the worth the time I devoted to it."



13. Rate your level of agreement with the following statement: "I was glad to work with a partner on the Historical Roots assignment."

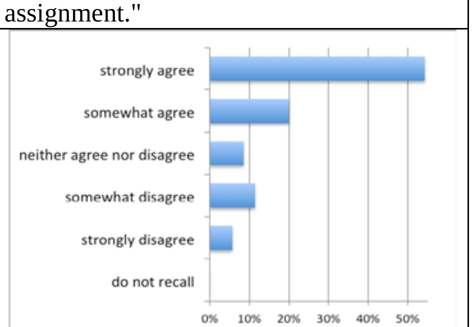


Figure 1: The survey results indicate generally positive responses to the learning and social aspects of the Historical Roots assignment.

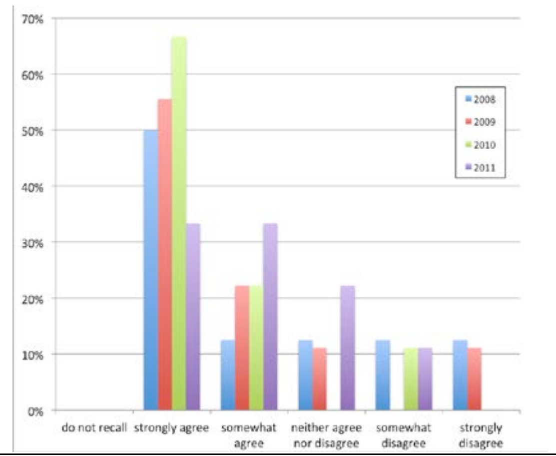
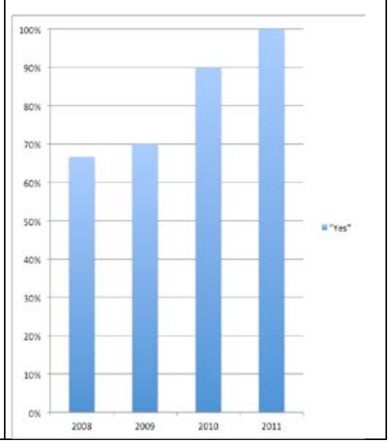
12. Rate your level of agreement with the following statement: "Overall, the Historical Roots Assignment was the worth the time I devoted to it."	3. Can you remember any new ideas or insights to which you were exposed through your Historical Roots assignment?
	

Figure 2: Responses suggest that more recent classes have a slightly more positive recollection of the Historical Roots assignment *(Q12)*, while monotonically declining recall of new ideas or insights suggests a possible recollection bias *(Q3)*.

In their open-ended responses, students described gaining insights into the roots of Engineering Systems, increasing their knowledge of the field, and increasing their understanding of research in the field. The major themes found included (number of mentions in parentheses): the interrelation of fields (13); the historical development of Engineering Systems (9), including the importance of key scholars (6); learning about concepts (22), methods (23), and fields (6) related to Engineering Systems; and the development of scholarly skills (25) such as literature searches (20).

5 Integrated Observations and Findings

This section summarizes the faculty and student perspectives in two broad categories: 1) development and interrelation of fields underlying Engineering Systems; and, 2) pedagogy, value and limitations of the assignment in developing future scholars in Engineering Systems. Broadly speaking, the first section introduces some of the specific findings and meta-results from the assignments, and the second provides the student perspective on their learning.

5.1 Development and Interrelations of Fields Underlying Engineering Systems

The development and interrelation of fields is a pervasive theme throughout the submitted assignments and is clearly evidenced in many of the open-ended survey comments. The importance of the development and interrelations of the fields underlying Engineering Systems is embodied in several survey responses below[4]:

- “The fact that many of today's challenges were actually being discussed back as early in the 1960s;”
- “Establishing a new discipline (e.g. [Engineering Systems]) requires knowing history and using it in a different way;”
- “Science is a very personality driven process, with major advancements centered around specific individuals.”

Relationships Among Fields Underlying Engineering Systems. The submissions’ greatest focus is on the relationships among different fields. Some selected examples from the papers that explore these relationships are:

1. A submission containing detailed expositions of the relationships among developers of linear programming, non-linear programming, integer programming, combinatorial optimization, stochastic programming and Monte Carlo methods;
2. A submission demonstrating that the tension between cost-benefit analysis and economic theory that continues even today had its beginnings in the 1930s (Samuelson, 1938);
3. Submissions demonstrating a strong link of sociobiology to modern network analysis (Nowak, 2006) and to agent based modeling (Axelrod and Hamilton,1981);
4. A submission identifying Homans (Homans, 1951) as the first to use matrix realignment in identifying social groups in Social Network Analysis;
5. Numerous submissions demonstrating that particular roots have direct impact on numerous modern methods – for one example, OR can be shown to have influenced stochastic optimization, strategy development, dynamic programming, and network theory among other methods of relevance to Engineering Systems.

The assignments frequently produce novel observations, including the discovery of “deep roots” of a field, surprising inter-relationships, and apparently deliberate ignoring of closely related work, among others.

“Deep roots” are those that originate in centuries past. One example is a submission tracing modern social network analysis back to a stochastic model of social networks developed in 1875 by Francis Galton. A second deep root was illustrated in a submission chronicling the evolution of cost–benefit analysis in 18th century France and its use in the early 19th century by Thomas Jefferson’s Secretary of the Treasury, Albert Gallatin.

Surprising inter-relationships were those that created unexpected linkages between fields, often through convoluted pathways, individual scholars or unique works. A

[4] Note that typographical errors in student responses have been corrected when presented here. When they have been edited (either for anonymity or clarity), this is indicated by square brackets.

submission demonstrating a strong linkage between cybernetics and business strategy by emphasizing, among others, the work of Maruyama (Maruyama, 1963) and Boyd (Boyd, 1987) is an example. A second surprising inter-relationship is identified in a submission demonstrating a strong connection between scientific management (Taylor, 1911) and strategy development (Porter, 1980; Mintzberg, 1990) via the conduits of OR, organizational theory and industrial psychology. In addition to these direct and indirect links, the papers often demonstrate substantial conceptual linkages in novel ways; for example: between a “Engineering Systems framing paper” by Joel Moses (Moses, 2004) and the work of Schumpeter (Schumpeter 1936; Schumpeter 1976); and, another submission demonstrating the links from negotiation to game theory, decision-making and social psychology (Osinga, 2007). Another interesting if not surprising example is the influence of cybernetics on social sciences, evidenced by convincing quotations from scholars like Phillips (Phillips, 1954) and Simon (Simon, 1957; Simon, 1962).

The concept of “apparently deliberate ignoring” refers to a lack of citation or collaboration where it would be expected. One submission showed the total absence of references between four leaders of system dynamics and five leaders of cybernetics despite their evolution in close proximity. A quote from the open-ended survey results reflects on this unexpected finding, “I was exposed to the complicated relationship (or lack thereof) between Norbert Weiner and Jay Forrester. Despite largely the same subject material, their lack of collaboration is unusual.”

In addition to those noted in individual submissions, some interrelations between fields became clear only during the session dedicated to student presentations. Reading and listening to each assignment gave both students and professors a wider appreciation of the breadth of Engineering Systems and the complex interlinking of its underlying fields. This element of student learning is evidenced by their responses to survey Question #9 (see Figure 1), in which 86% indicated that they learned a lot from listening to their classmates’ presentations.

The Importance of Historical Context in the Development of Fields. Several students noted the importance of historical context in shaping the development of concepts and fields. For example, in their class presentation, one group noted how Euler’s publication in Latin may have slowed the diffusion of his foundational contributions to graph theory. Another student noted, “how different concepts are shaped and forged depending on the historical context (e.g. the birth of Operations Research as a consequence of WWII).”

Apart from “apparently deliberate ignoring,” the papers also describe how concepts can be lost in time, or discovered separately by distinct groups of scholars. Many submission delineate differences in approaches from different disciplines and frequently find evidence of lost or delayed conceptual connections (a specific example arises between de Solla Price’s original work in power laws (see (de Solla Price, 1965)) and independent “rediscovery” later by researchers from outside of the social networks field). This shows that careful cross-disciplinary literature search is not always practiced as widely as would be desirable.

The Importance of Key Individuals to the Development of Engineering Systems. An important common theme among the assignments was the prominent role of certain scholars. As one respondent put it, "Every methodology and root analyzed had not only common themes, but common actors in their past." Collectively, the assignments point to substantial intellectual legacies in multiple fields by the likes of Jay Forrester and John Von Neumann. The authors were surprised by the evidence – in the papers and from the survey – of the singular influence of Herbert Simon among these historical roots.

In response to the survey (Question 7), students named a maximum of three important early contributors to Engineering Systems as a field. Figure 3 depicts the top five contributors mentioned: Herbert Simon, Jay Forrester, John Von Neumann, Norbert Wiener, and Joseph Schumpeter. Others mentioned include (those with multiple mentions are noted in parentheses): R. Ackoff (3), P. Anderson, G. Dantzig, I. de la Sola Pool, L. Euler (2), J. Holland (2), H. Kahn, D. Kahneman, J. Little, M. Maier, B. Mandelbroit, J. March, A. Marshall, S. Milgram, P. Morse, K. Popper, H. Raiffa (3), E. Rechtin, P. Romer, L.J. Savage, C. Shannon, C.P. Snow, R. Solow, F. Taylor, A. Tversky, and L. von Bertalanffy. The breadth of fields represented by this group of scholars attests to the broad foundations of Engineering Systems.

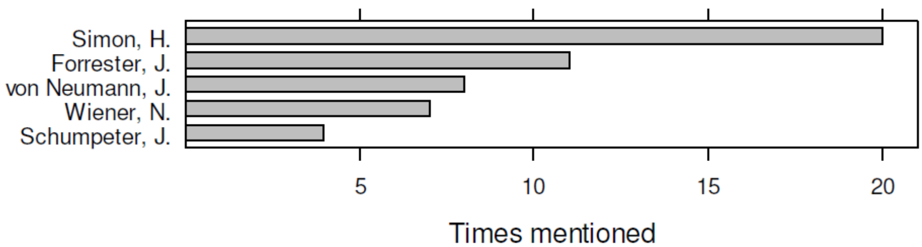


Figure 3: Seminal Engineering Systems contributors most cited by survey respondents.

5.2 Pedagogy: Value and Limitation of the Assignment

From the findings described above, the assignment appears to provide, from the faculty's perspective, a valuable vehicle for meeting the two overarching objectives of the course: increasing knowledge of Engineering Systems; and increasing understanding of research in this field. This section employs the survey results to illuminate the student perspective on the relevance of the assignment to the two learning objectives, its potential limitations, and its reported value.

With respect to the course objectives, that of learning about the field was clearly met. The majority of the qualitative survey responses pertained in some way to learning about Engineering Systems. Specifically, the assignment taught them about Engineering Systems as a field, its boundaries, and its breadth. As one student put it, "I really appreciated the time we devoted to learning more about the history of [Engineering Systems] since I believe it added color and depth to my understanding of the field." Fifty-five open-ended responses describe specific insights about concepts and methods related to their chosen fields or to Engineering Systems more generally. One survey respondent said in this regard, “It was great. I learned a lot about my root and methodology and […] I also learned about various other areas of thought from reading my classmates papers and listening to their presentations.”

Students also grew as Engineering Systems scholars, and developed specific research skills. Again, many of these pertained to specific Engineering Systems methods, but fundamental skills in literature search and citation analysis proved to be an important learning outcome. That the students developed these skills is clear from their submissions and was also cited by 71% survey respondents. Some students gained broader insights into academic research, e.g., “By encouraging us to look at the linkages among different strains in research, I gained new insights to the notion of research as a career and an industry. […] the main takeaway was learning about the processes by which we have arrived at a new field, and the innovations necessary to be able to think critically about the massive sociotechnical systems with which we are concerned.” Others, however, were pleased to learn specifically about their own area of research, e.g., “The assignment provided a great grounding in ES, an opportunity to dig into the literature of one of my areas of research [...].”

Not all students were so fortunate as to learn material that applied directly to their dissertation research. Some students noted this as a limitation of the assignment. At this early stage in their doctoral program, it can prove challenging for each student to choose a relevant root or method. Table 2 in Section 4 gives quantitative evidence relative to this issue. While 80+% of the respondents remembered new insights, ideas, skills or methodologies they learned from the assignment, only 30-50% used them in subsequent research. Two quotes from the open-ended survey input highlight this discrepancy:

- “Not applicable to my research, but history and context for the methods one uses generally is a good thing.”
- “The skills gained in performing literature searches and citation analyses were useful. The exercise of research, writing and presentation were good practice. Not “strongly agree” because the content of the paper was quite tangential to my research.”

Related to these responses were indications in six open-ended comments about the (possibly excessive) time commitment needed to complete the assignment. Perhaps conversely, two other students critiqued the level of depth of study afforded by the assignment’s format. The remaining critiques cited the limitations of citation analysis and suggested improvements to the assignment wording (e.g., the level of guidance). There were several strong objections to the use of assigned partners, but the majority of students were pleased to work in pairs (> 70%).

Despite these limitations, the majority of students found the assignment to be worthwhile overall (>70%), as shown by their responses to Question 12 (see Figure 1). In the words of the students:

- “Most valuable assignment I have completed in the doctoral program thus far. It was very time-consuming, but helped to frame what [Engineering Systems] actually is and from where it has emerged.”

- "I really think this was an excellent assignment. It was a great way to explore the key methodologies in engineering systems and their roots. I really learned a lot."

Figure 4 summarizes the author and student perspectives of the learning benefits realized by students through their completion of the Historical Roots assignment.

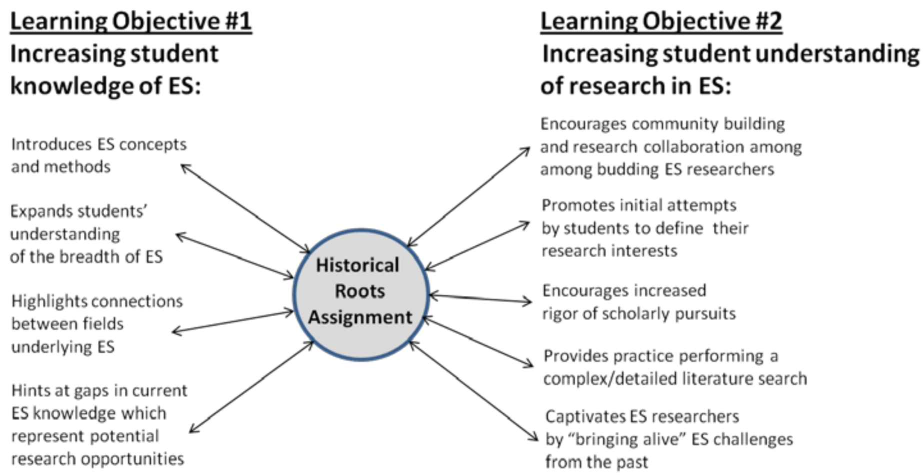


Figure 4: Summary of key pedagogical benefits conferred by the Historical Roots assignment

6 Discussion

Re-examining the student submissions to the Historical Roots assignment and surveying the students who completed the assignment produced a broadly consistent set of observations. Specifically, Engineering Systems roots and methodologies are intertwined in a complex fashion and arise from a wide variety of disciplines and fields. Nonetheless, several key individuals have published work which has profoundly shaped the field. In particular, the work of Herbert Simon is most notable. Having had an outsized impact on this field is consistent with Simon's tendency to cross-over strongly between technical disciplines, such as computer science and artificial intelligence, and social sciences, such as economics and social psychology, not to mention his impact on organizational theory and engineering design. Other highly cited contributors to the roots of engineering systems including von Neumann, Wiener, Forrester and Schumpeter also exhibited particularly wide-ranging intellectual pursuits and interests.

The interdisciplinary nature of Engineering Systems imparts the advantage of insight derived from disciplines in the natural sciences, engineering, social sciences and business. Consequently, however, it is difficult to isolate the impacts of these disciplines on the overall field. The origins of Engineering Systems are deep and varied, with each root bringing the intellectual imprints of its source discipline. As one might expect, it is often difficult to accurately untangle and definitively establish a clear relationship between a particular root and a modern methodology. This is not a critical problem except to budding scholars attempting to learn enough about this field to become practicing and viable researchers. One key challenge for the development of Engineering Systems as a vibrant discipline may revolve around the need to educate researchers just starting out in the field. The evidence reviewed in this paper, and summarized in Figure 4, indicates that the "Historical Roots" assignment discussed herein can serve as a highly useful – but imperfect – tool for meeting this crucial challenge.

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