An Ontological Approach To STEM Literacy

Mansour Taherenzhadi[1], *Penny Billman*[2]

[1] College of Engineering and Engineering Technology, NIU, USA
[2] Outreach, Northern Illinois University, USA

tahernez@ceet.niu.edu[1]

Abstract

This paper presents of a new model to STEM literacy using an ontological approach. Utilizing a problem based learning environment, the proposed ontological approach utilizes an analysis by synthesis methodology. Analysis-Synthesis methodology enables the decomposition of the problem to its individual STEM components followed by subsequently integration in an attempt to arrive at a more refined characterization of the problem. In turn, the analysis-synthesis findings can be documented by students in the form of a web wiki. As a result of this ontological exercise, students will gain significant skills in mapping out the associated knowledge and concept domains of the problem. This mapping, also known as knowledge and concept inventory, is critical to engineering design and innovation. It will be shown that this ontological mapping is deeply rooted in Bloom taxonomy. Moreover, this mapping features convergent and divergent learning mechanisms which are critical to engineering design and innovation.

Introduction

Increasing quality and quantity of graduating engineering students is critical in maintaining US economic expansion and its competitiveness in the global market place. Lack of pervasive and meaningful early design presence in the engineering curriculum serves as a major contributing factor to low quality and quantity of graduating engineering students, resulting in (i) low retention; (ii) compromised ability to attract new students; and (iii) compromised ability to effectively practice in an industrial setting. These observations have also been exacerbated by [1]: (a) entering freshman students having less facility and depth; (b) presence of random gaps in students background ranging from mathematics to physics and to chemistry; (c) absence of laboratory skills for entering freshman students; (d) no tinkering skills; and (e) incongruent level of expectation between faculty and students.

Driven by ever changing demands of engineering practice, there has been significant interest to overhaul engineering education [2]-[8]. Consequently, in recent years, emphasis on team oriented open-ended projects has increased substantially. This is best evident from the Engineering Criteria 2000 (EC2000) of Accreditation Board for Engineering and Engineering Technology (ABET) [2], [8] in which places special significance on (i) insightful team design projects and (ii) learn and practice of project proposing, planning, and control. In addition, the NSF Foundation Coalition [9] has also identified team-driven class participation central to enhancing engineering education. In particular, it acknowledges that “students in team” approach leads to elevated academic performance and superior skills for the workplace.

The importance of introducing design experience early in students’ academic careers is supported by: (a) general observations relating to today’s entering college students; and (b) observations specific to entering engineering students. Many of today’s entering college students are consumer and entertainment oriented as shown by Taylor [22] and [26]. A combination of lack of self-direction and a need for instant gratification present barriers to persistence to degree completion. Intellectual disengagement results in boredom with traditional lectures, skepticism concerning the authority of experts and traditional ways of knowing, and reduced study time. Being technologically literate, many of today’s college-bound engineering students have little patience for low-tech teaching and learning. What is engaging to students is information directly related to “earning” goals.

Utilizing a cognitive science-based approach to learning in engineering education and employing a multi-disciplinary team of scientists, this paper puts forth a novel ontological characterization [53]-[54] of Concept Domain (CD) and

Knowledge Domain (KD) [55] towards advancing STEM literacy via early curricular integration of mentor-driven interdisciplinary team-based engineering designs with special emphasis on emerging technologies. Owing to the proposed ontological characterization of CD and KD, the underlying attempt is to synthesize a learner and teacher community in which sciences are viewed as a continuum or what is better known as convergent technologies [56]. Because of its underlying ontological construct, the proposed multi-layered model is steeped in a network centric setting, lending itself to: hierarchical student to students mentoring, service learning, and synthesis of concept maps to effect a graduating engineering student body which is meta-cognitively immersed in interdisciplinary aspects of engineering.

Improvement on Existing Practices and Background Information

Recent years have witnessed great deal of practices to overhaul engineering education **[57]** as to not only become more in tunes with industrial needs as dictated by global market pressures, but also to conform to the emerging demographics of entering engineering students manifesting increased dependency on **project based and** application-based learning. Owing to the fact that junior and senior years enjoy a comparatively high level of design coverage, these practices [1]-[12] by and large have put considerable emphasis on application and design-based integration of math, physics, chemistry, and social sciences to engineering courses primarily in freshman and sophomore years.

However, lacking in these practices is a unifying framework towards curricular integration of team-based interdisciplinary designs all the way from freshman to senior year in a network centric setting. Inter and intra departmental hierarchical mentoring towards completion of interdisciplinary design projects is the key element to fuel continuity of curricular integration in a holistic way without any modification of curricular content. In addition, service learning to the community **[59]-[60]**, ranging from addressing design needs of industry to meeting the needs of K-12 schools, is a natural resulting benefit. Moreover, owing to cognitive basis of the proposed scheme, student synthesized concept maps are critical in probing student minds to appreciate and assess the interconnectivity of interdisciplinary design concepts as students evolve through the program. Concept maps are utilized in a meta-cognitive attempt to help the student generate CD and KD ontologies. It is shown in [55] that it is the very bi-directional transformation between CD and KD which constitutes the design process.

Moreover, this paper brings about a soft-landing mechanism to team-based design projects as opposed to bursty and isolated design experience through the capstone-based senior design project which is widely and traditionally practiced by engineering programs nationwide. The novelty of the proposed approach lies in the fact that not only team-driven design projects **are** conducive in improving retention issues in early years, but also they are of significance for fostering and promoting interdisciplinary collaboration among the students and faculty alike. Above all, owing to proposed **ontological/**network centric nature of the proposed scheme, the interdisciplinary collaboration among students and faculty can be far extended across many institutions by appropriate web linkage of courses and their associated student mentor teams at various institutions **[58]**. This goes to underscore the far reaching impact of the proposed scheme at its full maturity.

In what follows background justification of the proposed scheme in relation to ontology of concept domain and knowledge domain (CK ontology), cognitive science of learning, interdisciplinary teams, mentoring, service learning, and concept maps is provided to establish the validity of the proposed innovative solution as a testable model for improvement on existing practices.

Ontology of Concept Domain (CD) and Knowledge Domain (KD)

According to Gruber [61], an ontology is the explicit formal specification of objects within a domain of interest in conjunction with their underlying relationships. Some applications of ontology can be found in [53] and [54]. Following rationales are cited in [53] as why one wants to perform ontology of a domain of interest to: (i) share common understanding of the structure of information among people or software agents; (ii) enable reuse of domain; (iii) make domain assumptions explicit; (iv) separate domain knowledge from the operational knowledge; and (v) analyze domain knowledge.

In relation to application of ontology in learning research, Chi and Slotta [62] have shown that pre-lecture ontological biasing of students would contribute to a higher understanding of course material and to what is known as "emergent process".

In this paper we are interested in ontology of two domains: Concept and Knowledge Domains. Without making any explicit references to ontology, Hatchuel and Weil [55] have formulated Concept-Knowledge (CK) design theory shown that bidirectional transformation between CD and KD is the key inherent process involved in synthesis of engineering design. It is stated that in contrast to KD, CD does not carry any logical status, i.e., false or true. It could be stated that CD basically corresponds to identifying key design concepts without being preoccupied about their logical validity. While transformation from CD to KD is referred to as the convergent thinking (from concept to logical question or conjunction), the converse transformation is what constitute divergent thinking (initiation of design reasoning or disjunction). In addition to bidirectional inter-domain transformations between CD and KD, we also have intra-domain transformations within CD and KD themselves as part of inherent sequencing involved in design process.

This paper merges CD and KD inter and intra transformations proposed in [55] with ontological constructs proposed in [53]-[54] and [61] to meta-cognitively formalize the design process for students and teachers. This merger of C-K design theory and ontology serves as the main contribution of this paper. Specifically, it is proposed for students and professors to establish ontology of CD and KD domains for each specific engineering course as it relates to engineering design from early freshman to senior years. Within the CEET, in freshman and sophomore years, the proposed CK ontology is applied to first semester freshman required "Introduction to Engineering" course along with elective "Engineering Connection Seminar" courses in second semester freshman and entire sophomore year. In addition, it is proposed to apply the proposed CK ontology to junior and senior level courses involving engineering design.

The proposed CK-ontology transforms student (or student team) generated concept maps (see Section b3.6) to CD and KD ontologies. The CD and KD ontologies disclose the underlying objects and relationship among each domain in a hierarchical fashion in an attempt to effect a formal blueprint of student (or student team) understanding of each specific course design content. As part of formalizing the design process, the student team then need to demonstrate an intra domain sequencing (intra-domain transformation) within the CD ontology which eventually converges to a node within the KD ontology. Once within the KD ontology, the student team then need to exhibit intra-domain sequencing within the KD domain with an eventual convergence to a node in the CD domain. This process is continued until all the design requirements for a given course project are met. As such, the proposed CK-ontology model provides a cognitive tunnel to student understanding of course material in relation to engineering design. This in turn enables us to further research on how student learn engineering. An example of intra and inter-domain transformation (in here is also referred to as sequencing) is given in [55].

Concept Maps

Concept mapping is an effective metacognitive tool in science of teaching and learning (Hartman, [49]). Concept maps also have been used extensively as an alternative assessment technique in science education (Shavelson, Lung, & Lewin, [50]). Novak and Gowin [36] claim that one of the most positive outcomes arising from the use of concept maps is "meta-learning." Students "learn how to learn" as they create concept maps to display and think about their conceptual understanding of subject-matter content. Concept maps are graphic representations of meaningful relationships between two or more concepts (Novack & Gowin [36]). Each relationship is represented by a proposition, which consists of two concept labels joined by a line and a word or two that make the relationship clear. The goal of concept mapping is to externally display internal knowledge structures (schemata).

Schemata are unconscious mental structures. Schemata set expectations for encountering new information. (Hartman [49]). Information that is consistent with a schema is assimilated into the schema. Information that conflicts with prior knowledge causes the existing schema to be accommodated (modified) so that new information can be incorporated into the schema (Piaget, [52]). Concept maps graphically depict these changes in thinking (Clarke, [51]). In addition, concept maps display misconceptions present in learners' schemata. Misconceptions are faulty ideas that are based on false or incomplete information, limited experience, incorrect generalizations or misinterpretations and are consistent with the student's basic understanding. Some misconceptions result from cultural myths or scientifically out-of-date information. Others may arise from vague, ambiguous, or discrepant information (Hartman, [49], p. 184). Once misconceptions are evident, teachers or mentors can assist the learner in clarifying and revising understanding of the concept being learned.

The structure of concept maps is consistent with three aspects of Ausubel's cognitive learning theory: hierarchical organization, progressive differentiation, and integrative reconciliation (Ausubel [34]). Concept maps are organized hierarchically in that more general and inclusive concepts and propositions are superordinate in the map to more specific concepts and propositions. Progressive differentiation indicates that when meaningful learning occurs, additional propositional links are added to the map. As long as meaningful learning is occurring, the concept map keeps evolving. Maps become more in-depth, and concepts become more differentiated. Integrative reconciliation is the process in which new relationships between concepts are discovered by the learner. Integrative reconciliation is indicated by drawing cross links from one concept to another on the map (Novak & Gowin [36]).

Concept mapping is particularly useful in assessing knowledge prior to instruction and in assessing changes in understanding as instruction proceeds (Clarke [51]; Novak & Gowin [36] Wholeben, 1994). Although concept maps are qualitative indicators of learners' knowledge structures, concept maps also can be scored numerically. The typical scoring algorithm includes awarding a specified number of points for (a) valid propositions, (b) the number of levels in the hierarchy, (c) cross links between segments of the map, and (d) specific examples or instances of the concept. Points are totaled with higher total points indicating more complex understand of the central concept (Novak & Gowin, 1984).

Concept maps will serve to assess (a) students' declarative and procedural knowledge of engineering concepts, (b) connections between declarative and procedural knowledge, (c) inclusion of content from courses prerequisite to the study of engineering, and (d) connections among intra- and inter-departmental knowledge bases. Using Novak and Gowin's (1984) scoring algorithm, the number of valid propositions, the number of hierarchical levels, and the number of valid examples or instances will assess declarative and procedural knowledge, as well as the inclusion of content from prerequisite courses.

Proposed Solution

The proposed solution is to synthesize a cognitively-driven educational model with a unifying formulation possessing the following salient elements: (i) CK-ontological-based linkages towards student collaboration on interdisciplinary team projects on emerging technologies; (ii) student to student hierarchical mentorship system towards collaboration on interdisciplinary projects ; (iii) student-driven service learning to middle schools , high schools, and industrial and business community; and (iv) student-generated concept maps to assess the degree and extent of student's understanding on interdisciplinary engineering designs.

Electronic portfolios, implemented using Live Text [64], have been used by engineering departments to document student learning outcomes at the program and course level [63]. Criterion 3 of the ABET Engineering Criteria 2000 [45] is the criterion most related to the proposed activities. Criterion 3 outcomes are: (3a) an ability to apply knowledge of mathematics, science, and engineering; (3b) an ability to design and conduct experiments, as well as analyze and interpret data; (3c) an ability to design a system, component, or process to meet desired needs; (3d) an ability to function on multi-disciplinary teams; (3e) an ability to identify, formulate, and solve engineering problems; (3f) an understanding of professional and ethical responsibility; (3g) an ability to communicate effectively; (3h) the broad education necessary to understand the impact of engineering solutions in a global and societal context; (3i) a recognition of the need for and ability to engage in lifelong learning; (3j) a knowledge of contemporary issues; and (3k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. The proposed network-based curricular integration in turn utilizes a hierarchical student-student mentoring to facilitate design process from inception to completion using electronic portfolios. The mentoring system allows for execution of design projects from a network centric approach, whereby a design project using CK ontology is decomposed into a set of suitable small components and consequently assigned to various teams of students belonging to various engineering courses. Whereas early small scale design conceptualization are relegated to freshman/sophomore students taking low level engineering courses, junior/senior students are charged with overseeing actual project formulation, implementation and execution with continuous dialog and active participation among the lower and higher level student teams. Moreover, Junior/Senior students serve as mentors to Freshman/Sophomore level students in a team-setting approach.

This paper echoes the goals of P-16 systems (Van de Water & Rainwater [16]) where education partners work together to improve links between interdependent parts of the system, especially transition points such as that between high school and college. An effective pipeline that plants the seeds of interest in engineering early, works with high school and community college teachers to assure appropriate preparation and student background for college study, promotes engaged learning for retention in a baccalaureate program, and prepares students for graduate level study.

References

01. "A new Undergraduate Curriculum," Department of Electrical and Computer Engineering, Carnegie Mellon, 1991
02. H.R. Coward, C.P. Ailes, and R. Bardon, "Progress of the engineering education coalitions," SRI Int., Arlington VA, Final Rep. Eng. Educ. Centers Division, NSF 2000.
03. C.W. Meyers, "Restructuring engineering education: A focus on change," NSF, Arlington, VA, Rep. NSF Workshop Eng. Educ. 1995.
04. "Criterion for accrediting engineering programs," ABET, Baltimore, MD, 2000
05. "Assessment white paper: A framework for the assessment of engineering education," Amer. Soc. Eng. Educ., 1996.
06. "How do you measure success? Designing effective processes for assessing engineering education," Amer. Soc. Eng. Educ., 1998.
07. Board Eng. Educ., Engineering Education: Designing an Adaptive System. Washington, DC: National Academy Press, 1995.
08. E. Dowell, E. Baum, and J. McTague, Engineering Education for a Changing World., Washington, D.C.: Amer. Soc. Eng. Edu., 1995.
09. http://72.14.203.104/search?q=cache:GxU94OZpOMEJ:fie.engrng.pitt.edu/fie97/papers/1078.pdf+NSF+Foundation+Coalition&hl=en&gl=us&ct=clnk&cd=5&client=netscape-pp
10. http://fie.engrng.pitt.edu/fie95/4d4/4d44/4d44.htm
11. http://fie.engrng.pitt.edu/fie95/4a1/4a12/4a12.htm
12. Dewey, J., Experience and education. New York: Macmillan. 1938/1963 .
13. Senge, P. M. et al. (1994). The fifth discipline: The art and practice of the learning organization. New York: Currency Doubleday.
14. Vygotsky, L.S. (1978). Mind in Society. Cambridge, MA: Harvard University Press.
15. Wolfe, P. (2001). Brain matters: Translating research into classroom practice. Alexandria, VA: Association for Supervision and Curriculum Development.
16. Van de Water, G. & Rainwater, T. (2003). What is P-16? http://www.ecs.org/clearinghouse/24/28/2428.htm
17. http://www.servicelearning.org/resources/quick_guides/eng_ed/
18. http://epics.ecn.purdue.edu/about/papers/IJEE1549.pdf
19. Sheskin, D. J. (2004). Parametric and nonparametric statistical procedures (3rd ed.). New York: Chapman & Hall/CRC
20. Cook, T. D., Campbell, D. T., Shadish, W. R., & Shadish, W. (2001). Experimental and quasi-experimental designs for generalized causal inference (2nd ed.). Boston: Houghton Mifflin
21. Huberman, M., & Huberman, A. M. (1994). Qualitative data analysis (2nd ed.). Thousand Oaks, CA: SAGE.
22. M. Taylor, Generation NeXt: Today's postmodern student—meeting, teaching, and serving. "A collection of papers on self-study and institutional improvement: Vol. 2. Becoming a learning focused organization: The learning environment," Chicago: The Higher Learning Commission (2005).
23. M. Taylor, Generation NeXt comes to college: 2006 updates and emerging issues. "A collection of papers on self-study and institutional improvement: Vol. 2. The future-focused organization: Focusing on the needs and expectations of constituents." Chicago: The Higher Learning Commission (2006).
24. J. Piaget, "The psychology of the child," New York: Basic Books (1972)
25. H. A. Simon and C. A. Kaplan, Foundations of cognitive science, "Foundations of cognitive science," M. I. Posner (ed.) Cambridge, MA: The MIT Press (1989).

26. J. R. Anderson, “Cognitive psychology and its implications,” New York: W. H. Freeman and Company (1980).
27. J. R. Anderson, “The architecture of cognition,” Cambridge, MA: Harvard University Press (1983).
28. A. E. Lawson, “The neurological basis of learning, development and discovery: Implications for science and mathematics instruction,” Dordrecht, The Netherlands: Kluwer Academic Publishers (2003).
29. R. J. Seidel, K. C. Perencevich, and A. L. Kett, “From principles of learning to strategies for instruction: Empirically based ingredients to guide instructional development,” New York: Springer (2005).
30. A. Newell, P. S. Rosenbloom, and J. E. Laird, Symbolic architectures for cognition, “Foundations of cognitive science,” M. I. Posner (ed.) Cambridge, MA: The MIT Press (1989).
31. E. D. Gagné, “The cognitive psychology of school learning,” Boston: Little, Brown, and Company (1985).
32. A. S. Elstein, What goes around comes around: Return of the hypothetico-deductive strategy. “Teaching & Learning in Medicine,” 6, 1994, pp. 121-123.
33. P. A. Kirschner, J. Sweller, and R. E. Clark, Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. “Educational Psychologist,” 41(2), 2006, pp. 75-86.
34. D. P. Ausubel, (1968). “Educational psychology: A cognitive view,” New York: Holt, Rinehart, and Winston, Inc (1968).
35. NSTA, “National Science Education Standards,” National Research Council (1996). http://www.nsta.org/standards.
36. J. D. Novak and D. B. Gowin, “Learning how to learn,” New York: Cambridge University Press (1984).
37. J. R. Anderson and G. H. Bower, “Human associative memory,” Washington, DC: Winston (1973).
38. R. Calfee, Cognitive psychology and educational practice, “Review of research in education,” Vol. 9, Washington, DC: American Educational Research Association (1981).
39. J. E. Ormrod, “Human learning: Theories, principles, and educational applications,” New York: Merrill Publishing Company (1990).
40. J. S. Bruner, From communication to language: A psychological perspective, “Cognition,” 3, 1975, pp. 255-287.
41. B. Rogoff, “Apprenticeship in thinking: Cognitive development in social context,” New York, NY: Oxford University Press (1990).
42. L. B. Resnick, A. Lesgold, and M. W. Hall, Technology and the new culture of learning: Tools for educational professionals, “Cognition, education, and communication technology,” P. Gärdenfors and P. Johansson (eds.) Mahwah, NJ: Lawrence Erlbaum Associates (2005).
43. J. S. Russell, Mentoring in engineering, “Leadership and Management in Engineering,” January, 2006, pp. 34-37.
44. B. Jacoby and Associates, “Service-learning in higher education: Concepts and practices,” San Francisco: Jossey-Bass (1996).
45. ABET, “Criteria for Accrediting Engineering Programs,” The Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology (1999). http://www.abet.org/eac/eac.htm
46. J. S. Eyler, D. E. Giles, Jr., C. M. Stenson, and C. J. Gray, “At a glance: What we know about the effects of service-learning on college students, faculty, institutions, an communities, 1993-2000: Third edition. (2001). http://www.compact.org/resources/downloads/aag.pdf
47. E. Tsang (ed.) “Projects that matter: Concepts and models for service-learning in engineering. Washington, DC: AAHE (2000).
48. E. J. Coyle, L. H. Jamieson, and W. C. Oakes, EPICS: Engineering projects in community service, “International Journal of Engineering Education,” 21, (2006) pp. 1-12.
49. H. J. Hartman, Metacogniton in science-teaching and learning, “Metacognition in learning and instruction: Theory, research, and practice.” H. J. Hartman (ed.), Dordrecht, The Netherlands: Kluwer Academic Publishers (2001).
50. R. J. Shavelson, H, Lung, and B. Lewin, “On concept maps as potential “Authentic” assessments in science,” Washington, DC: National Center for Research on Evaluation, Standards, and Student Testing (1993).
51. J. H. Clarke, “Patterns of thinking: Integrating learning skills in content teaching,” Boston: Allyn and Bacon

(1990).
52. J. Piaget, “The construction of reality in the child,” New York: Basic (1954).
53. http://protege.stanford.edu/publications/ontology_development/ontology101-noy-mcguinness.html
54. http://www.dfki.uni-kl.de/~aabecker/Freiburg/Final/Templeton/ontpaper.html
55. http://www.cgs.ensmp.fr/publications/sitearticleconception1/HatchuelLeMassonWeil2004DesSocindusappliCKtheoryverB3-versionenvoyee2.pdf
56. M.C. Rocco and W.S. Bainbridge, “Converging Technology for Improving Human Performance Nanotechnology, Biotechnology, Information Technology and Cognitive Science,” NSF/DOC sponsored report.
57. National Science Foundation, Systemic Engineering Education Reform: An Action Agenda, NSF98-27, www.n.fgo-v/cgi-bin/getpub? rrs/9S27, 1997.
58. Gay, G., and Lentini, M., “Use of Communication Resources in a Networked Collaborative Design Environment,” Journal of Computer-Mediated Communication, VoL 1, No. 1, 1995. ww’w.asc;~sc.org/jcmc/wl1/ i.csuel/IMG..JCMC/ResourceUse.html.
59. KoIb, D.A., Experiential Learning: Experience as the Sour-ce of LianaingandDr’velopment, Englewood Cliffs, NJ.: Prentice-Flail, 1984.
60. Whitheck, C., Ethics in Engineering Practice and Research, New York, N.Y.: Cambridge University Press, 1998.
61. Gruber, T.R. (1993). A Translation Approach to Portable Ontology Specification. Knowledge Acquisition 5: 199-220.
62. http://www.pitt.edu/~chi/SlottaChiCogIns2006final.pdf
63. R. M. Felder and R. Brent, “Designing and teaching courses to satisfy the ABET engineering criteria,” Journal of Engineering Education, 92(1), 7-25, 2003.
64. http://www.livetext.com/college/portfolios.html
65. [Knowles, M. S. “The modern practice of adult education: From pedagogy to andragogy.” Chicago: Follett Publishing Company (1980).
66. Jarvis, P. “Adult education and lifelong learning: Theory and practice (3rd ed.).” London: RoutledgeFalmer (2002).
67. Bonk, C. J., and Kim, K. A., Extending sociocultural theory to adult learning, “Adult learning and development: Perspectives from educational psychology,” M. C. Smith and T. Pourchot (eds.) Mahwah, NJ: Lawrence Erlbaum Associates (1998).
68. Vygotsky, L. S. “Thought and Language (revised).” Cambridge, MA.: MIT Press (1986).