Learning to Learn Engineering - A Learning Sciences Approach to Engineering Curriculum Design and Implementation

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***Abstract*—This is an Innovative Practice Full Paper. Engineering education research has often tended to focus on subject matter and effective pedagogy. Lacking is research illuminating the learning process itself and development of learning skills in engineering students. This paper presents a framework for engineering learner development that leverages processes allowing learners to learn more effectively, i.e., learning to learn engineering. Components include: engineering knowledge forms and levels; relationships between engineering knowledge and performance; risk factors; learner characteristics that produce working expertise; cultural shifts supporting learner development, and a model for the engineering learning process. Two case studies show how these components guide curricular implementation of learning to learn engineering.**

Keywords—learning to learn, curriculum, process education

I. Introduction

Research in engineering education has tended to focus on subject matter and effective methods in the classroom. Less developed is research relating to the learning process itself and development of learning skills in engineering students. This paper aims at expanding current engineering teaching and learning practices to include scholarship on learning to learn [1-4] as it applies to engineering. This can be accomplished by leveraging the developed body of knowledge on learning processes to allow learners of engineering to learn more effectively, i.e., *learning to learn engineering*. This developmental approach provides an innovative approach to realize the vision of the Engineer of 2020 [5], enhances engineering program's abilities to effectively address ABET assessment criteria, achieves *general education* outcomes, and increases retention and graduation rates.

The conceptual framework presented in Fig.1 illustrates how *learning to learn engineering* can be implemented. Students learning engineering enter with certain risk factors. These *risk factors* can be reduced or eliminated by building the characteristics of a quality engineering learner. Development of these characteristics is best supported through a *culture* of learning and growth in programs and classrooms. This cultural shift can be accomplished by applying the *engineering learning process methodology* to curriculum design. And finally, students will demonstrate improved *engineering knowledge* and improved *engineering performance* as a result of the learning to learn approach.

II. Premises

Fig. 1 is built upon a set of three key premises for *engineering knowledge* and *engineering performance*, located on the right side of the figure. The premises state that for high quality *engineering performance*, students need to be able to generalize their *engineering knowledge* across a variety of forms, and do so at a high level. Keeping these premises in

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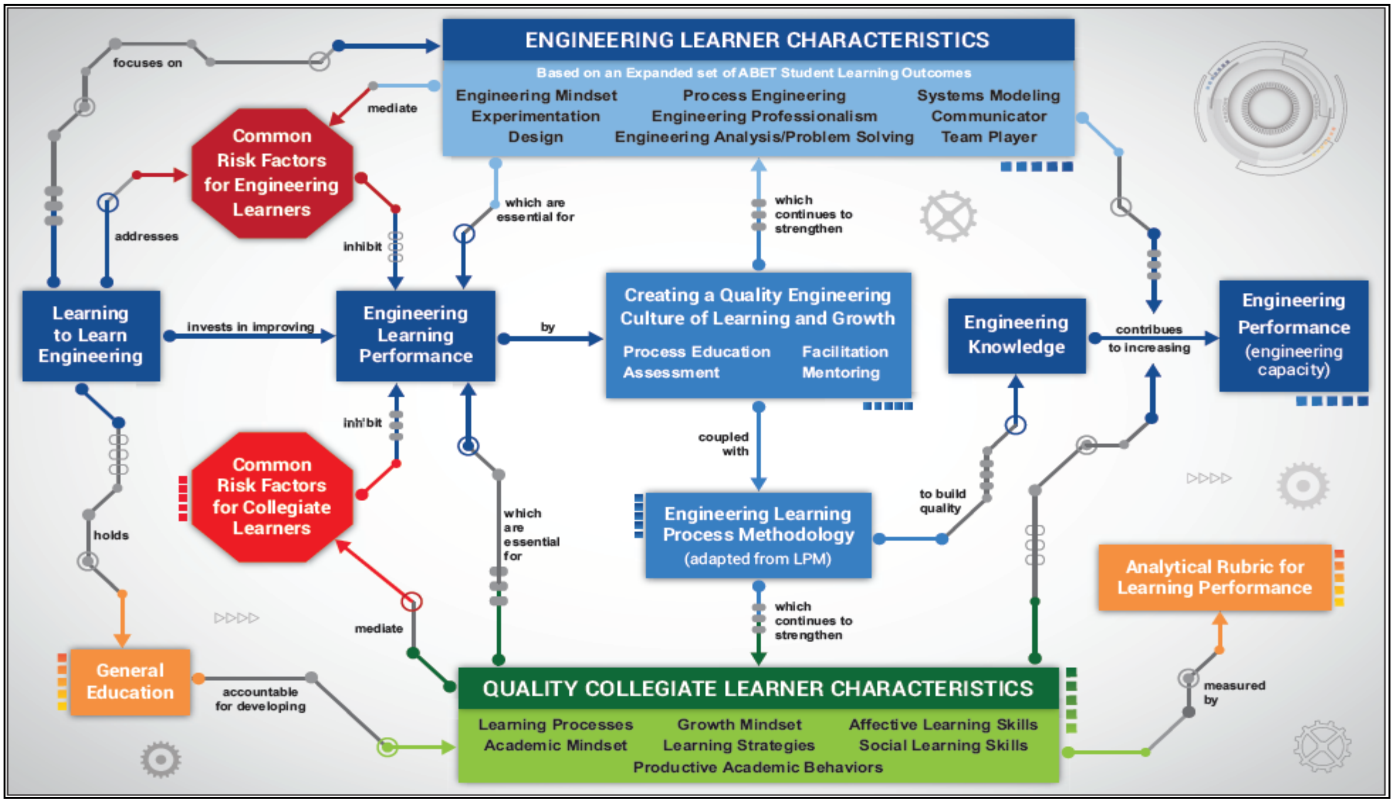

Fig. 1: Learning to Learn Engineering Conceptual Framework. Note: definitions of key terms may be found here (online glossary). These terms are shown in italics throughout the paper body.

mind throughout the curriculum design and delivery processes enhances implementation of *learning to learn engineering*.

A. Forms of Knowlegdge

Five forms of knowledge important to engineering practice are: concepts, processes, tools, contexts, and "ways-of-being" [6]. In particular, the 'process' and 'ways of being' areas are ones that are directly impacted by the *learning to learn* model/practices described later in the paper, with significant indirect impacts on knowledge acquisition under the 'concepts', 'contexts', and 'tools' areas. The alignment of these forms of knowledge with the *engineering learning process methodology* (described later in the paper) makes knowledge development more accessible for all levels of learners. Table I provides examples of forms of knowledge in engineering.

B. Levels of Engineering Knowledge

Bloom's taxonomy for cognitive educational learning objectives [7] aligns well with learner development necessary to attain working expertise in engineering graduates. Nygren created an approach for learners to elevate knowledge from level 1 to 3 that fits engineering well [8]. Generalized, transferable *engineering knowledge* (Nygren's level 4) is the ability, without external prompting, to transfer appropriate knowledge productively into engineering practice. Nygren describes the steps learners can use to produce generalized transferable knowledge as working expertise [9].

Nygren illustrates stages in the development of generalized transferable knowledge with his table, Levels of Knowledge Across Knowledge Forms, where comprehension and understanding are crucial stages in the learning process and prerequisites for being able to contextualize, generalize, and transfer knowledge.

TABLE I. EXAMPLE FORMS OF ENGINEERING KNOWLEDGE

Concepts	*Processes*	*Tools*	*Contexts*	*Ways of Being*
Equilibrium	Units Analysis	Machine Shop	Laboratory work	Validation
Conservation of Energy	Design	CAD	Engineering analysis	Prototyping
Ohm's Law	Scientific Methodology	Software Suite	Manufacturing	Taking things apart

III. RELATIONSHIP BETWEEN ENGINEERING LEARNING PERFORMANCE AND ENGINEERING KNOWLEDGE

Engineering knowledge at any given time is the result of the accumulated impact of engaging in engineering learning practices over a sustained period. *Engineering learning performance* is the driver of this accumulation of knowledge. To grow total *engineering knowledge*, one must pay attention to ways in which learning performance can be enhanced. We propose *learning to learn engineering* as the optimal mechanism whereby this learning performance increase can be accomplished. Below is a model adapted from kinematics that illustrates this approach. Within a time frame $t_1 \rightarrow t_2$ the total *engineering knowledge* gained, K, is the definite integral of the knowledge accumulation function (learning rate) over time. Here L_0 is the initial learning rate entering the performance period with L^2 representing a Learning to Learn function (similar to an acceleration) over that time period (assuming a continuous function). Analogous to the calculation of displacement, we can express this measure of engineering learning as:

$$K = \int_{t_1}^{t_2} dK = L_0 \int_{t_1}^{t_2} dt + L^2 \int_{t_1}^{t_2} t\, dt \qquad (1)$$

This perspective of improving performance aligns with the idea of Sharpening the Saw [10]. We provide this kinematics analogy simply as a heuristic to introduce the concept of ‘growth mindset’ which ameliorates the risk factor of ‘fixed mindset’ that appears later in this paper.

A. *Effective Learning Process is Necessary (but Not Sufficient) for Effective Problem Solving and Design*

A critical component of engineering problem solving and design is the use of generalized, transferable knowledge – the kind of knowledge produced by an effective learning process. Only recently have efforts been focused on the need for students to develop the ability to generalize knowledge so that it can be transferred as the bridge from application (level 3) to problem solving expertise (level 4) [11]. Because of these efforts, major advancements occurred in developing learner performance. The L^2 (Learning to Learn) function mentioned in the section above is characterized by certain aspects of the instructor and the learning environment. These additional mechanisms needed to supplement an effective learning process include strengthening classroom facilitation, constructive intervention, the use of active learning, learning activity design based on the *engineering learning process methodology*, integration of the classification of learning skills [12, 13], and the extensive use of formative assessment.

B. *The Role of Methodologies in Engineering Learning and Problem Solving*

A methodology is simply a set of procedures describing a process [14]. Methodologies can be used to identify which learning skills are most critical to implement in a learning process, to provide a powerful framework for both assessing performance and designing performance measures, and to help show differences or connections between different processes, especially processes dependent upon or closely related to each other (such as learning and problem solving). The use of methodologies in assessing a learner's *engineering performance* and providing feedback to develop their learning skills increases metacognition, increases learning rate, and contributes to the development of important engineering *learner characteristics*.

IV. ENGINEERING RISK FACTORS

A critical difficulty in building *engineering performance* is to effectively address the *risk factors* that engineering students enter college with [15, 16]. Horton identified 20 key *risk factors* common to many, if not most, incoming college students [17]. Twelve of these 20 *risk factors* most important for learning engineering are described in Table II.

TABLE II. RISK FACTORS FOR LEARNING ENGINEERING THAT ARE COMMON TO ALL DISCIPLINES

Lacks Self-Discipline: Easily distracted	**Does not Generalize**: Knowledge is situational
Afraid of Failure: Avoids challenges	**Negative Self Judgment**: Focuses on failures
Unmotivated: Disinterested in learning	**No Self–Efficacy**: Feels inadequate
Fixed Mindset: Believes can’t increase capability	**Teacher Pleaser**: Goal is grade not performance
Memorizes: Prefers algorithmic knowledge	**Unchallenged (bored)**: Lives in the comfort zone
Little Metacognition: Doesn’t understand learning	**Insecure Presenter**: Scared of public speaking

Several additional *risk factors* represent particularly common learning challenges in engineering, as well as other STEM disciplines. These *risk factors* have been identified by many efforts (for example, [18]) and are presented in Table III.

TABLE III. ADDITIONAL RISK FACTORS FOR LEARNING ENGINEERING

Risk Factor	Definition
Struggles with Mathematics:	Fails to comprehend the physical implications and functional behaviors that mathematical relationships imply.
Trouble Reading Engineering	Needs to be taught how to read and understand technical written information to augment their learning efficiency in class.
Fails to Manage Frustration/Anxiety	Unable to convert failure or negative feedback to learning; lets emotion interfere with accepting new challenges.
Minimal Problem-Solving Experience	Limited exposure to multifaceted, multivariable, multistep engineering problems solving strategies.
Isolated Learning	Fails to recognize the utility of working with others while learning.
Concrete Thinker	Misses important aspects of situations/environments by focusing on specifics and details.
Confused about Engineering Discipline	Fails to recognize educational and occupational differences between technicians and engineers.

V. Engineering Learner Characteristics

A. *Engineering Learning Characteristics that Increase Engineering Performance*

The expectations for an engineering learner span eight categories of performance, each with multiple characteristics, as shown in Table IV and adapted from [19]. These align with the Profile of a Quality Collegiate Learner (PQCL) [20], Profile of an Engineering Graduate [19], ABET criterion 3 [21], and the Engineer of 2020 [5]. Together, they illustrate that learners of engineering can reach far along the path to the Profile of a Professional Engineer [22]. Further, since engineering learning is a specific type of learning, it shares the same learning process characteristics derived from learning theory that are needed for *general education* and all disciplines. Therefore, we can advance students' *engineering performance* by making them better and faster learners of engineering, as described in equation 1. We do this by leveraging learning theory to address the special attributes associated with learning in engineering. Thus, by increasing learning rate, engineering performance is accelerated as well, propelling students even further along the path towards professional engineering performance levels.

B. *Measure of Engineering Learner Capacity*

Process Education research in the theory of performance, performance criteria and performance measures led to the idea that learner capacity can be defined and measured with an *analytical rubric for learning performance in engineering* [23, 24]. The measure builds on the Profile of a Quality Collegiate Learner [20], containing 50 aspects organized in 10 categories. The Profile of a Quality Engineering Learner (PQEL) builds on the PQCL by adding an additional 33 aspects across eight categories, summarized in Table IV. The *rubric* used to measure performance across these 83 aspects has five levels of learning performance, and contains descriptors for what that performance looks like at each level. The standard for a quality engineering graduate is level 5. Sets of descriptors are included for each category and for each of the aspects. An example of how the levels in the *rubric* apply to one of the 33 aspects (identifies problems) in one category (engineering analysis/problem solving) of the PQEL is shown in table V. Here, a survival learner may only identify problems already presented to them, while a pioneer learner may insightfully reveal critical issues to target for solution of the problem and gain consensus on those issues from their team or others.

TABLE IV. Profile of a Quality Engineering Learner

Engineering Mindset: The way of being of an engineer that differentiates the engineering profession from all other disciplines (PQCL: Confident, Leverages Failures, Persists) Aspects: Safety protector, solution producer, optimizer, tool user, innovator.
Engineering Professionalism: An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgements, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts. (PQCL: committed to success, manage frustrations, plans, works hard) Aspects: Client Advocate, Quality Specialist, Ethical Reasoner, Documenter, Project Leader
Engineering Analysis/Problem Solving: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. (PQCL: problem solving, use resources effectively, validate) Aspects: Data Analyst, Reverse Engineer, Analytical Thinker, Unit Analyst, Visualizer
Systems Modeling: An ability to synthesize a situation, environment or problem area by building a systems representation with effective mathematical modeling. Aspects: Mathematical Modeler, Systems Integrator, System Thinker, Simulator, Issue Clarifier, Dual Coder
Design: An ability to apply the engineering design process to produce solutions that meet specified needs with consideration for public health and safety, and global, cultural, social, environmental, economic, and other factors as appropriate to the discipline. Aspects: Decision Maker, Prototyper, Solution Reuser, Concept Developer, Specifier
Process Engineering: An ability to see details of how processes are used to produce products/results, correct errors, and eliminate waste in order to ensure consistent quality. Aspects: Algorithmic Thinker, Debugger, Operations Manager, Product Tester
Experimentation: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusions. Aspects: Scientist, Researcher, Technician
Additional ABET Student Learning Outcomes from Profile of a Quality Collegiate Learner Aspects: Communicator (from PQCL), Engineering Learning Performer (lifelong learning), Team Player (from PQCL)

TABLE V. Example Learning Performance Measures

Engineering Learner Characteristic		***Level 1***	***Level 2***	***Level 3***	***Level 4***	***Level 5***
		Trained: survival learners	**Learned: need- based learners**	**Learners: contained learners**	**Enhanced Learners: professional**	**Self-growers: pioneer learners**
Category	**Engineering Analysis/ Problem Solving**	**Formulaic problems**	**Complex exercises**	**Uses problem solving methodology**	**Real world problems**	**Within & interdisciplinary**
Aspect	Identifies problems	If others point it out	In obvious area of concern	In common situations	Reveals target issues	Gains consensus

VI. Needed Change in Engineering Culture

At the center of the learning to learn framework in Fig. 1 is the nature of the classroom and program *culture* in which engineering education is delivered. It is the responsibility of faculty to initiate and sustain high quality facilitation, mentoring, and assessment processes that underlie this concept, as described in section III.A above. Previous research has recommended cultural shifts towards professional engineering perspectives [5, 25]. In particular, process education research identified 14 aspects of cultural transformation that can dramatically shape educational outcomes [26].

Each aspect is defined, related mindsets are characterized, and high impact teaching/learning methods for moving towards emerging practices supporting learning to learn are outlined at www.transformation-of-education.com. Three aspects of engineering education *culture* that engineering faculty and students may find most challenging, but which can produce productive faculty and student attitudes about *learning to learn engineering*, are discussed next.

The most profound change surrounds ownership of learning [27, 28]. Students need to own the process for their own learning, rather than be directed step-by-step on what to do or what problem solutions they need to mimic. Robust student ownership is established by the way faculty deliver course materials, set expectations, and provide opportunities for students to demonstrate their performance. This involves a clear set of learning goals and instructions, accompanied by well-crafted performance criteria by which student performance can be monitored and assessed. As part of this process, students should be expected to demonstrate critical thinking in questions they ask, in how they contextualize new knowledge, and in generalizing their knowledge across new and complex learning situations.

Ownership of learning is strongly influenced by the faculty mindset behind course delivery. Delivery begins with selection of course readings, exercises, laboratories, etc. It continues with formal and informal learning activities developed using the principles of process education [29]. A key expectation is that students prepare before they come to class, guided through thoughtful instructional design that stimulates review of prior knowledge as well as construction of new foundational knowledge. Student preparation should be measured and preparatory performance should be regularly assessed. Individual and team-based readiness assessment tests are an effective way to ensure learning preparedness [30]. Pre-class preparation frees the instructor and the student to engage in higher level construction of understanding and application of knowledge during class time [31]. Instructional delivery that is student-centered and features active learning promotes a pattern of interaction that underscores mastery in learning and problem solving as well as just-in-time assessment and reflective practice.

During instructional delivery, control should be shared between faculty and students, with students actively engaged in determining how time is allocated for growing knowledge and skills as well as assessing outcomes. While the instructor will need to allocate some time for presentation of essential material, students need freedom to provide input how time is apportioned between individual thinking for understanding, collaborating on exercises, presenting solutions to each other, and contemplating better ways to approach learning as well as problem solving. A strong teaching practice for promoting student voice and control is a mid-term assessment following the first major exam or homework assignment [32, 33]. This helps to affirm course strengths, inventory potential course improvements, and crystalize other insights about *learning to learn engineering*.

Self-directed learning and growth does not emerge in a vacuum. In order to increase *engineering knowledge* and *engineering performance*, the *learning to learn* (L^2) function in eq. 1 is essential. It is cultivated by valuing student ownership of learning, facilitating enriching and engaging course experiences, taking time out to mentor students on points of personal development, and assessing time management as well as control of the learning environment. Successful learning outcomes involve trust and partnership between faculty and students. However, it is incumbent on faculty to take the first step in this journey. Here we have highlighted several factors about the *culture* of the classroom and relationships between students and faculty. It is only through effective delivery of the curriculum ("how to do it") that we can unleash the full potential of the curriculum design.

VII. The Engineering Learning Process Methodology

Engineering is a disciplined, creative process that involves both art and science. Learning engineering involves construction of fundamental *engineering knowledge*, developing necessary engineering and creative skills, experiencing engineering processes, and practicing the use of engineering tools to achieve desired objectives and produce expected results. The Learning Process Methodology (LPM), has a long history in Process Education literature [1, 34, 35], and is tightly connected to activity design for learning [36]. The stages and steps of the Engineering Learning Methodology can be illustrated as shown in Table VI.

The 15 steps of the *Engineering Learning Process Methodology* were evolved from the 14 steps of the Learning Process Methodology starting with the revised guidelines followed in the development of the two books addressing learning to learn within the field of mathematics [37, 38]. The learning to learn math experience and the latest research findings on learning to learn, including Improving Learning Performance [39] and Key Learner Characteristics for Academic Success [20], were used to create the *Engineering Learning Process Methodology*. This methodology takes on three perspectives - the design of the engineering experiences, the facilitation of the learning activities, and the learners constructing their *engineering knowledge* and skills. These elements, including the stages and steps from Table VI, should be a part of the mindset for program and course design as guidelines in design of the curriculum components and sequencing. These elements draw the student into the learning process, ensure that the learning activities develop the

TABLE VI. EXAMPLE LEARNING PROCESS METHODOLOGY

Step	Action	Correlate to LPM Step(s)
STAGE 1: PREPARING TO LEARN (normally before class)		
Step 1	Purpose	1: Why
Step 2	Discovery (exploration stage)	2: Orientation
Step 3	Expectations for the learning performance	4: Learning Objectives 5: Performance Criteria
Step 4	What do you already know?	3: Prerequisites
Step 5	Required engineering language (the precision of its terminology, symbolic representations, and notation)	6: Vocabulary
Step 6	Information needed before and during the learning experience (reading assignment)	7: Information
Step 7	Learning resources	7: Information and Resources
Step 8	Are you ready?	8: Plan
STAGE 2: ACTIVELY LEARNING (during and extending after class)		
Step 9 (during class)	Classroom Activity (Process Education/POGIL learning activity)	
	Why?	1: Why
	Learning objectives	4: Learning objectives
	Performance criteria	5: Performance criteria
	Additional critical information for the activity	7: Information
	Plan: lays out recommended sequence of tasks	8: Plan
	Models: critical examples to analyze	9: Models
	Critical Thinking Questions	10: Critical thinking questions
Step 10 (after class)	Demonstrate your understanding (may be started during class)	11: Transfer/application
Step 11	Hardest problem: generalizing the knowledge	11: Transfer/application
Step 12	Making it matter: problem solving	12: Problem solving
STAGE 3: IMPROVING THE PROCESS AND EXTENDING THE LEARNING		
Step 13	Identify and correct the errors	13: Self-Assessment (focus on content)
Step 14	Learning to learn engineering	13: Self-Assessment (focus on discipline process)
Step 15	Assess learning performance	13: Self-Assessment (focus on engineering learning process)

appropriate skills targeted for that experience, and allow the student to apply and reflect on these skills appropriately both within modules in a course and as they progress through the curriculum.

VIII. CASE STUDIES OF IMPLEMENTING LEARNING TO LEARN HAVE PRODUCED TRANSFORMATIONAL LEARNING

The scholarship and practice of learning to learn has advanced in summer Learning to Learn Camps over 20 years [40]. Students' learning and problem solving performances advanced remarkably as a result of the learning to learn camp experiences. Many of these Learning to Learn Camps became very STEM oriented with a greater focus on learning to learn math and engineering. These camps helped start the student transformation into a PQCEL to counteract these engineering *risk factors* in order to achieve success [41].

A. *STEM Learning to Learn Camps*

During the five years of the NSF funded STEM UP program (students with ACT scores 15-19) at Hinds Community College - Utica Campus, the Learning to Learn Camps evolved into a very strong implementation of learning to learn STEM [42]. While these Learning to Learn Algebra Camps continued to develop general *learner characteristics* of a quality collegiate learner, they also developed Engineering *learner characteristics* paramount for success in STEM. Over the five years, 60 percent of the annual cohorts transferred to 4-year STEM programs within 2 years. This grant has been renewed for another 5 years. Additionally, a pilot of 65 incoming "area of interest" students were brought through a *learning to learn engineering* Smart Grid Institute as a preparatory program before entering as freshmen. Examples of a few of the special *learner characteristics* developed include 1) embracing failure as part of learning, 2) seeking to know why something works, 3) validating their own learning, 4) communicating STEM, 5) increasing metacognition of their Engineering learning performance, 6) valuing productive struggle, 7) developing self-confidence by leveraging failures, 8) teaching others, 9) reading technical resources, and 10) building language and notation in Engineering. The outcomes of the students' mindsets and engineering learning skills can be reviewed online [41] for both programs.

B. *Course-Based Implementation of Learning to Learning Engineering*

Learning to learn can also be incorporated into any content course. For example, an Introduction to Engineering Course implemented the following approaches into the *culture* of the course through the use of extensive computer applications within the course to grow engineering *learner characteristics* [43]. Approximately one-third to one-half of class time in a three-credit, semester long course was devoted to learning to learn specific computer skills essential to engineering success. These skills were introduced using the computing tools MS-Word, MS-Excel, and MATLAB. *Learning to learn* using these engineering tools was completely integrated into the course through assignments targeting fundamental *engineering knowledge* and requiring important elements of real *engineering performance*.

Emphasis within the learning environment was placed on cooperative learning, frequent formative assessment feedback, integrative learning to merge computing and *engineering knowledge*, self-assessment, and generalizing knowledge across engineering, mathematics, and science contexts through the use of analytical problem-solving tasks and simple design projects. Engineering *learner characteristics* targeted in the course included: tool user, mathematical modeler, solution producer, prototyper, documenter, analytical thinker, unit analyst, team player, and communicator.

Results from the course included an 80% retention rate into the subsequent year with an engineering major, and high ratings for course effectiveness with comments such as these on course evaluations: "This should be a six credit class. The workload seems like it. Keep it up.", "Overall, it is very informative. The class was also very conducive to learning.", and "Most especially I am grateful that I can use the computer better now." [42].

IX. Conclusions

To realize the vision of the Engineer of 2020, enhance engineering program's abilities to effectively address ABET criteria, achieve student outcomes, and increase retention and graduation rates, a developmental approach for *learning to learn engineering* is presented. Founded on many learning to learn research efforts and practices, the presented approach along with a *learning to learn engineering* conceptual framework, risk factors, and *engineering learning process methodology* are discussed to guide program design and delivery, and to illustrate how learners of engineering can learn more effectively.

The paper, (1) offers premises that *engineering knowledge* has multiple forms, that knowledge can be developed through multiple levels, and that graduating engineers should be able to generalize and transfer knowledge to new engineering contexts; (2) describes the relationship between improved learning of *engineering knowledge* and improved *engineering performance* (3) summarizes *risk factors* confronting engineering students, (4) offers profiles describing what quality collegiate and quality engineering learners look like, (5) describes how a transformed engineering education *culture* supports this developmental approach (6) produces a model of the engineering learning process applicable for curriculum design and active learning, and (7) offers case studies demonstrating how these components tie together.

Future work includes the publishing of a textbook for a freshman engineering course that explicitly incorporates the *learning to learn engineering* process into each learning module, a comparative study of gains in engineering learning performance for several courses that uses a subset of aspects from the *analytical rubric for learning performance*, and the creation of a website with tools and resources based on learning sciences research for incorporating learning to learn into the curricular design process and implementing learning to learn processes within engineering curricula.

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