AC 2010-796: THE ENGINEER: A TREE OR A PRODUCT?

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The Engineering Paradigm: a Tree or a System?

Abstract

This paper offers a new metaphor for the engineering graduate, and links this metaphor to the design and implementation of engineering education. The paper discusses current practice in Canadian engineering schools of teaching a range of Engineering Science and Engineering Design courses each as distinct stand-alone topics, and refers to existing literature on engineering education likened to a manufacturing process or network.

In the contemporary models of engineering education, each step in the education of an engineer is illustrated as flow through boxes in a process diagram. The students are thus likened to "raw material" passing through the system. The boxes are relatively static. In this view, the "design" expertise has traditionally taken a minor role compared with the engineering science expertise. The author proposes that this is not the only way to view the "product" of an engineering educational system.

The proposed metaphor presents the individual student as a whole entity, and compares each unique graduate professional to a tree in a forest. In this metaphor, an engineer "tree" can have an infinite variety of branches and leaves, while still retaining a core trunk of design and project management expertise which distinguishes them as an engineer. While the paradigm may sound fanciful, the author uses an example course plan from the Canadian experience to illustrate how this different paradigm can be more receptive to student interests, and to industry needs yet still support the foundations of the profession. The proposed paradigm shows that, in accordance with the role of engineers in industry, the ability of design, project management and teamwork are central, while the specific technical specialities are supporting "branches".

Introduction

It is an ongoing enterprise to continue to improve teaching models for young engineers, and to adapt those models to best fit the demographics of our students. All faculty teaching in the first few years of an engineering program understand how important it is to speak in terms that the students understand, and to encourage them. Its always a struggle for faculty, especially those of us the same age as our students parents, to keep our examples, and our language relevant to our teenage students. Thus, we need to continue to update. However, have we successfully updated the model in which we work? In effect, have we been thinking of our students in the same way that our own professors thought of us. Perhaps we need to look at a view of what we do, and the conceptual framework between us, our students, and our system differently.

A research study by Scott and Yates [1] identified a number of successful young engineers in Australia, as defined by their supervisors in industry. Many of these graduates were interviewed, and a collection of over 40 factors related to their successful work performance were identified.

Using these factors, a larger number of recent graduate engineers were given questionnaires to rank the quality of their educational experience. They ranked many "people skills" and organizational skills as crucial to success, most of which were not part of their learning in an engineering undergraduate program. As a result of this, many authors have argued for more teaching of the "soft skills" in engineering. Studies like this continue to fuel the see-saw between highly "scientific" engineering education and highly "social". Ultimately, the argument comes down to the question of which side of the balance is sacrificed in favour of the other.

The "structural" design of most engineering programs in Canada is, in accordance with the Canadian Engineering Accreditation Board guidelines [2], based on separate distinct courses. Each course in a student's degree program has a weight in "academic units" (AU's) which roughly correspond to faculty contact hours for each course per week semester. Comparing this accreditation standard with current educational literature, there is a sense that the "traditional" engineering program is heavy on lecture based courses [3 4]. This is in contrast with new models that incorporate Project-Based Learning (PBL) using a variety of approaches [5-8]. Many of the authors present motivation for moving away from Lecture Based Learning (LBL) based on pedagogical principles [9 10], or professional results [1, 11].

In contrast to this, a program designed following an inquiry-based PBL system modelled on the classic example developed by the medical school at McMaster University [12 13] would have no equivalent to the separate course-by-course grocery list. In this alternate model, students do not see distinct courses, but centre their study on problems. In such a program, the student teams have only one "course" per semester, and they have daily contact with their problem group and a faculty member or guide. Since the early 1970's, this PBL approach has been successful in medical education at many institutions. There are very few engineering programs that have fully implemented a similar model. Are we hampered from adopting more PBL teaching models in Engineering programs because of our fundamental conceptual model of what is an engineering education, and, ultimately, what is an engineer?

The System Paradigm

Within the existing structure at most engineering schools, students recognize that each course carries equal weight towards their degree, and each course gives them an independent grade that is equal in value towards their degree and for scholarships. Thus, it is logical that the content of these courses is equal and largely stand-alone, from the student viewpoint. The specific teaching style, whether LBL, PBL, or something else in each course is a separate matter from the structural layout of the engineering education program. In programs where there are one or two PBL courses, students are still encouraged to see these as separate and distinct from the rest of the lecture-based courses.

Engineers are comfortable with systems or logic diagrams to map out interactions between components in complex problems. In papers by [4, 14-16] design engineering models of engineering education are shown as system diagrams. In all the models, there is a logical starting point where the raw materials (students) enter, travel through the process, and emerge as output at the other side of the page. The same conceptual view is used for a piping network, or electrical grid in our profession. The underlying paradigm assumes the education of a student is a network of discrete teaching blocks through which the prospective engineer must pass. We are thinking of the students in this approach as objects that we must do things "to" before they are acceptable engineers. It's hard to reconcile this with the "student centred approach" that is promoted by the recruitment offices at many modern universities. Likewise, this implicit concept of students as a bulk raw material and our structure of courses as the manufacturing process neglects the reality of their peer-to-peer learning, and their various interconnected communities as having a role in their eventual graduation as junior engineers.

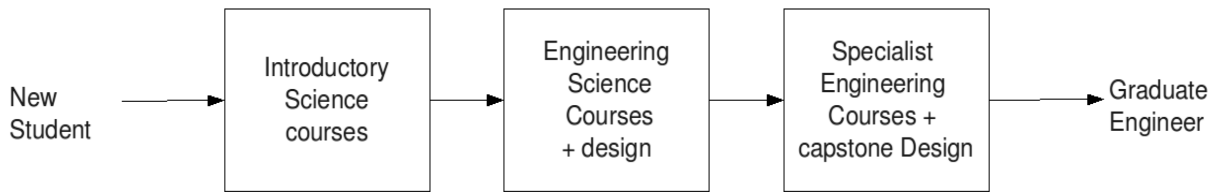

figure 1: The linear system model of engineering education. The student is likened to a material flow through a process leading to the desired "engineer" graduate.

The model of an education based on this approach is represented in Figure 1. The student, after completing high school, enters the University system and follows through taking discrete courses as represented by the blocks. Each block follows the preceding one in a succession until the complete diagram is filled. We, the faculty determine what blocks must be filled, while the student has only limited say in the model. In effect, the system is an open-loop one with no feedback to control the output.

Implicit in this picture of education is that there is one allowable pathways from the input to the output. Drawing an analogy to a piping system, the pipes between process vessels do not cross, or interconnect without a valve, or gate. The purpose of these valves in a piping system is to keep the material in different paths separate, unless the operator/program director deems it acceptable to comingle the streams. Professors, as plant designers and operators in this analogy, decide which process vessels are used (courses), and the choice of process determines the nature of the end product. Thus, in many engineering programs, just as in many plant process systems, the path from input (high school) to the output (qualified graduate) is quite separate for the different streams (i.e. mechanical engineering stream, versus the electrical engineering, versus biological engineering).

In this conceptual model of the education of young engineers, the decision of which process stream the students enter would, in their minds, have a huge impact on their careers. Students spend a great deal of time and suffer sleepless nights deciding which stream to enter, not knowing at the start what they will end up looking like at the end, nor what sort of career opportunities they will have when they graduate. Unfortunately, a student has very little understanding of the engineering profession, let alone the different disciplines in the months before they enter an engineering program, and cannot be expected to make an informed choice from high school before they even enter their first engineering classroom. In addition, the network model gives them little ability to change their direction or chart a different network once they are inside the process of becoming an engineer.

In Atlantic Canada, a long-standing affiliated University system has existed between Dalhousie University (Halifax, NS), Acadia University (Wolfville, NS), NS Agricultural College (Truro, NS), Saint Mary's University (Halifax, NS), Cape Breton University (Sydney, NS), St. Francis Xavier (Antigonish, NS), and University of Prince Edward Island (Charlottetown, PEI). In the program, students enter any one of the seven partner schools, and study the first two years towards their engineering degree in the largely liberal-arts and science campuses, then move to Dalhousie's Sexton Campus (formerly a separate engineering university, the Technical University of Nova Scotia) in Halifax to complete the final years in distinct engineering disciplines.

Students at each of the partner schools are faced with a selection of courses that are common, and very few discipline-specific courses in the first two years. The model prior to 2010 could be represented by a course plan example in Table 1. The example shows a course plan for either mechanical or civil engineering in the first 2 years. In either case, the majority of courses are common, and a few are unique to the student's discipline.

Table 1: compared course selections

Civil	Mechanical
Year 1	
Calculus 1	Calculus 1
Physics 1	Physics 1
Chemistry 1	Chemistry 1
Engineering Communications	Engineering Communications
Academic Writing	Academic Writing
Calculus 2	Calculus 2
Physics 2	Physics 2
Chemistry 2	Chemistry 2
Statics	Statics
Computer Programming	Computer Programming
Elective	Elective
Year 2	
Calculus 3	Calculus 3
Statistics	Statistics
Engineering Ethics	Engineering Ethics
Material Science	Material Science
Geology	Electric circuits 1
Calculus 4	Calculus 4
Design 1	Design 1
Strength of Materials	Strength of Materials
Electric Circuits	Engineering finance
Economics	Electric circuits 2
Geology 2	Electronic Physics 1

After a number of years advising students for course selection, its seems there is a population of engineering students who compare and contrast the selection in table 1 to try and second-guess the accredited path. It is sometimes difficult to justify why, for example, a course in Statics in the second semester of first year has engineering communications as a pre-requisite. Why would a student intending to pursue mechanical engineering with a stress analysis emphasis, for example, need to take 4 courses in electric theory in their first two years? Despite a great deal of hand-waving and motherhood arguments, in reality, the pre-requisite path is laid out by the need to ensure all students get all the required courses for accreditation, and may have nothing to do with the interests of the student, nor with the job market for the graduates. In this sense, we treat students genuinely as a common feedstock for our rigid system.

The Tree paradigm

What if we shake off the concept of our students and graduates as the "product", and our University as a process? Perhaps it will help to view our students as complete and whole individuals rather than as a continuous raw material feeding our system? The engineering profession is ultimately the creation of combined effort and skills of all of the practitioners, not a block diagram.

What if we consider the analogy of a forest to represent our profession? Forests contain a large variety of tree species. When I walk beneath a locust, or a maple, or a hemlock, I recognize each of them as individual trees, while still appreciating that they collectively make a forest. Each individual may have very different bark, and leaves, and may be very different in size from the average, but there is little argument of what constitutes a "tree". Even the difference between saplings and adult trees is not enough to confuse our identification of an individual as a "tree". I propose that the modern engineer could be more usefully pictured as a "tree" than as the product of a processing network. In the same way as we know a tree when we see it, despite differences between individuals, we know an engineer when we "see" one. Figure 2 shows a pictorial model.

The roots

As we all know, the engineering profession is not isolated from society. It has evolved from the need in society to take natural philosophy (in the classical sense, including science and humanities) and turn the understanding and knowledge of the world into creation of useful things for humanity. In the analogy, we can start with considering the roots of an engineer to be the fundamental understanding of natural sciences and social sciences. Thus, all engineering programs have a fundamental component of study in mathematics, physics, chemistry, economics, psychology, and others.

Many programs already recognize this need for solid foundation in the basic sciences, as does the CEAB in their accreditation requirements for engineering degree programs [2]. Unfortunately, there is pressure in some programs to reduce the degree requirements for engineering, and this has lead to the elimination of requirements for basic introductory science courses in favour of engineer-specific courses in chemistry, physics, or math. Many programs no longer even have engineering students interact with students in other academic disciplines by virtue of these engineering-specialization courses from the first year university and onward. However, the richer, and more varied are the soil and roots of the tree, and the stronger and taller will the tree grow. Taking the course plan from Table 1, Table 2 highlights the "root courses" in black. These courses are common to all engineering disciplines.

The trunk

Probably the main feature that we see of trees in a forest or field is the trunk. It is the most clearly "tree-like" feature. Many academic authors define an engineer by his or her expertise in design, project and team management [8, 15-18]. It is this skill and expertise that makes us important in business and society, for we can apply this core strength to any problem. Thus, the essential features of an engineer, the core or "trunk" rests in our skill in these tasks.

While engineering education has evolved over decades into more and more technical specialization, it is common to see engineers educated in one discipline of engineering spend their entire careers practising in another. What of the courses they took as undergraduate engineering students were retained or used by them in practice? Ironically, the essential elements of this main trunk are not explicitly taught in our engineering schools. This point has certainly not been lost on other authors [3, 4] In most programs, the skills of project management and leadership are incorporated as side-lines to existing science or engineering design courses.

Taking the example shown in Table 1, Table 2 illustrates the "trunk" courses that are essential to every engineer as core skills/theory in grey. These courses include design, project management, safety engineering. The courses address what are found in professional practice to be the basis of an engineer's daily practice in most industries. It can be that any of these courses are taught from the viewpoint of any discipline, and yet an engineer practising in one field will still have no difficulty appreciating the similarity in the content in any other discipline.

The lower branches

For a tree to grow, and to provide protection and shade in the forest, it needs to draw energy from photosynthesis. The lower branches of a tree are large, and have grown from the saplings first few branches. For the engineer, these lower branches are the first few common "engineering science" type areas of knowledge. We typically have engineering mechanics, electric circuits, strength of materials, and other type fundamental courses. Just like the difference between roots and branches of a tree, the engineering science fundamentals are not the same as fundamental science courses, but both are necessary for a successful engineer. Most engineers, regardless of discipline, can look to fundamental engineering science type studies which gave them their first ability to analyse a problem, and offer a design solution, but which built on a foundation of basic sciences. In the same way, these lower branches support and nourish the "design core" of the trunk of our engineer.

While all engineers may not need, for example, electric circuit theory at a higher level, its arguable that all should have some basic exposure to the theory. These "lower branch" courses are shown also in Table 2 in white cells.

The higher branches

As the tree grows, it needs more than just the first few branches to provide nourishment. The most successful tree in a forest is one that can grow above the rest, and put out branches above the canopy of its competitors. In the same way, an engineer cannot depend on a common set of fundamental engineering science disciplines for success. We need a wide range of more rarefied skills and science from which to draw. These are the "competitive edge" of an engineer, and it makes sense that the suite of knowledge for each young engineer should be suited to a niche that will allow him or her to prosper. These might be machine design, programmable logic controller design, or stress analysis, to name a few. The important feature is that no two engineers should try to fill exactly the same niche. Every individual can benefit from very different branches of learning at this higher level. In addition, as a tree grows, it must put out new upper branches to accommodate the growth. The engineer must continually add branches of knowledge as he or she grows in their professional life. Table 2 indicates these higher courses simply as "elective".

Table 2: The course plan according to the Tree model

Civil	Mechanical
Year 1	
Calculus 1	Calculus 1
Physics 1	Physics 1
Chemistry 1	Chemistry 1
Engineering Communications	Engineering Communications
Academic Writing	Academic Writing
Calculus 2	Calculus 2
Physics 2	Physics 2
Chemistry 2	Chemistry 2
Statics	Statics
Computer Programming	Computer Programming
Elective	Elective
Year 2	
Calculus 3	Calculus 3
Statistics	Statistics
Engineering Ethics	Engineering Ethics
Material Science	Material Science
Geology	Electric circuits 1
Calculus 4	Calculus 4
Design 1	Design 1
Strength of Materials	Strength of Materials
Electric Circuits	Engineering finance
Economics	Electric circuits 2
Geology 2	Electronic Physics 1
Year 3	
Differential Equations	Differential Equations
Linear Algebra	Linear Algebra
Thermodynamics	Thermodynamics
Fluid Mechanics	Fluid Mechanics
Project Management	Project Management
Dynamics	Dynamics
Design 2	Design 2
Safety Engineering	Safety Engineering
Measurements	Measurements
Engineering Finance	Electromagnetism
Elective	System Dynamics
Elective	Elective
Year 4	
Structural analysis	Machine design
Fluids 2	Dynamics 2
Reinforced concrete	Fluids 2
Construction management	Thermodynamics2
Environmental eng.	Heat Transfer
Design 3	IC engines
Design Project	Design project
Elective	Design Project
Elective	Elective
Elective	Elective
Elective	Elective

While these “upper branches” may be courses taught in an undergraduate program, in most cases they will be added to later in the engineer's career, and they should be the most adaptable to personal choice, job market considerations, and interests.

The complete tree

A picture of the complete, successful engineer is one with a healthy and deep system of roots in the basic sciences and humanities, with a solid, straight core trunk of team skills including the ability to lead design and project management, with healthy lower branches of understanding in the fundamental engineering sciences, and with a set of upper branches that permit him or her to take advantage of the surrounding conditions by being unique and responsive to the social environment.

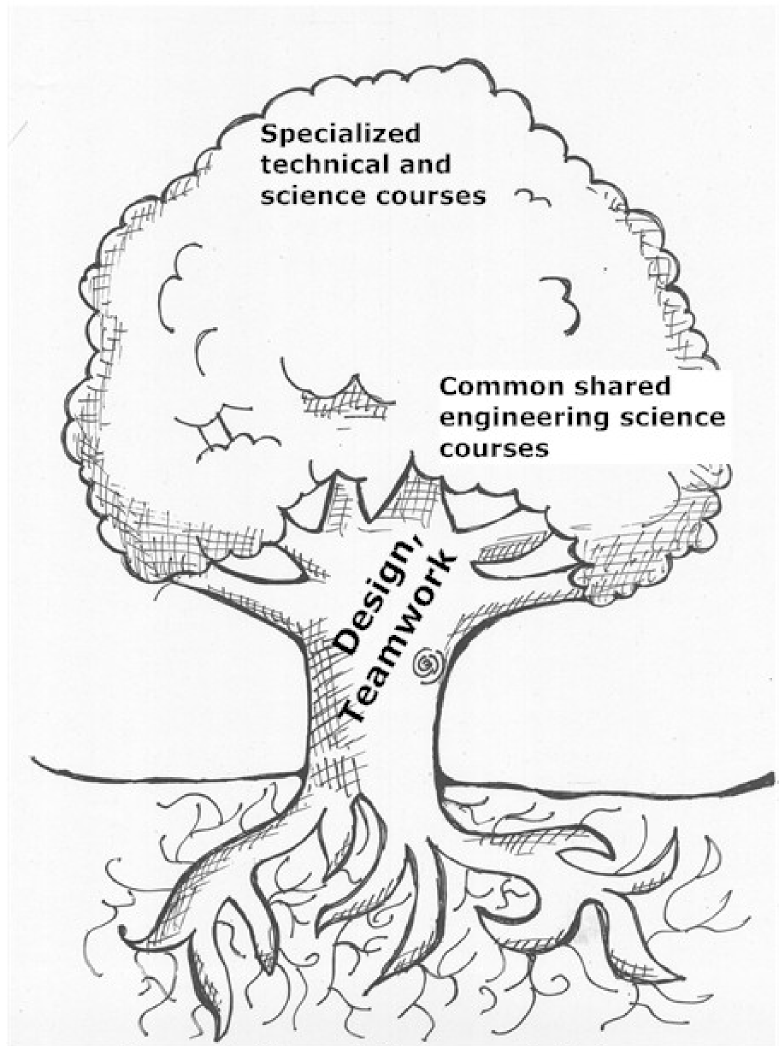

figure 2: This concept of the engineer likened to a tree with its roots in the basic sciences, a core of design and project management and fed by branches in different engineering specialist fields

Application of the model

The value for proposition of a new paradigm for the engineer is to give guidance on the design of the education of young professionals. What can we do with a picture of an engineer where the central feature is a solid core of teamwork, project management, and design fed by branches of engineering sciences and built on roots in fundamental natural philosophy? This image can be used to design an engineering program.

First and foremost, this model reinvigorates the importance of an engineer gaining a foundation of basic sciences. The theoretical courses which are being sacrificed in some programs in favour of only engineering courses goes against this concept. We can recognize that successful engineers need to start with basic chemistry, basic physics, basic biology, and basic philosophy and psychology. Other core fields of knowledge may be added, but these topics become the language and fundamentals of all that we do after.

Once we have accepted the importance of the knowledge that lies "beneath the surface", we look to the core of the tree. Engineers must have as the central part of their education a fundamental understanding and ability in design. As part of this, they need to excel in management of people, and in management of time and resources. All of the aspects that we collectively think of as "design" must be the central theme through an engineering education. It is simply not sufficient to assume that students will learn this on their own, or as a sideline in other courses. They need to have a clear progression of teaching and learning in these core topics.

Finally, the branches that comprise the engineering science topics are important, but their role in the paradigm is one of support for the core, not a replacement for the core. In table 2, the only significant differences between the disciplines is in the "upper branch" courses, predominantly seen in the later years of the student's progress. Thus, it is appropriate to look at building a degree program that has relative inflexibility in course progression in the early years, and much more open choices for students in the later years.

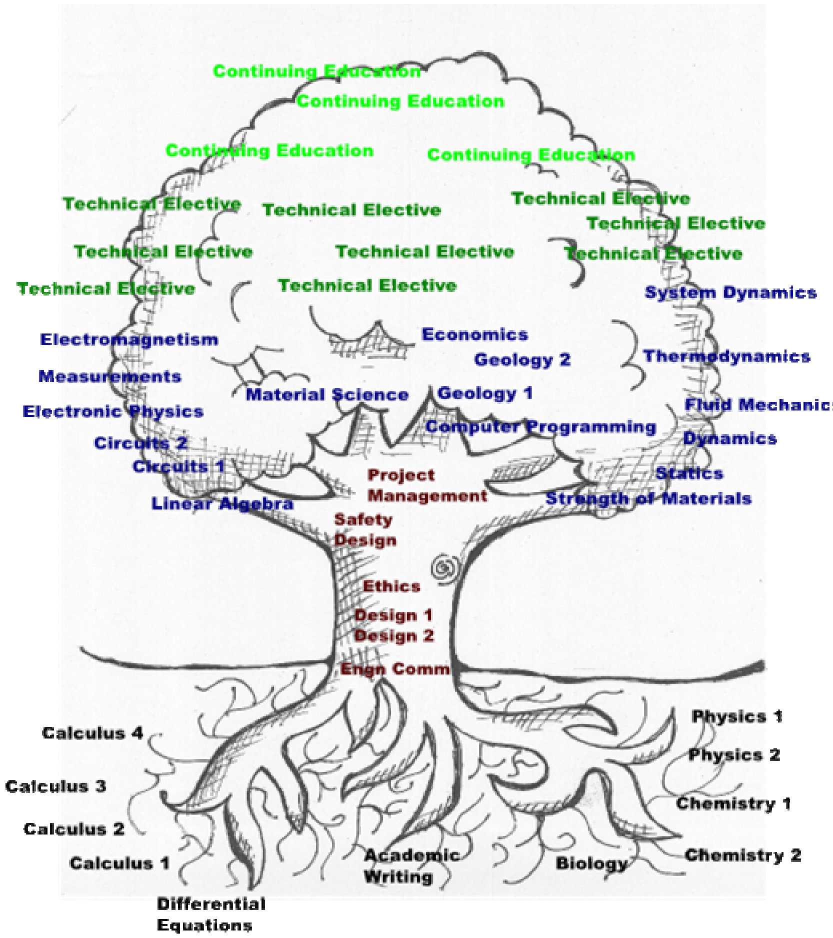

figure 3: The engineer-tree showing courses organized according to their role in the engineer's development

This picture should emphasize that engineering programs can permit more scope for adapting to immediate needs in industry for graduates with a specific set of "upper branches" of knowledge. For instance, is it essential that all mechanical engineers take a course in IC engines, or could a mechanical engineer replace that with a course in concrete structures if he/she felt the course had more interest, or would afford different job opportunities? The recognition that an engineering student can be given a wider set of choices in the "upper branches" while identifying those essential "root" and "trunk" courses that are not negotiable is a key to developing an adaptable, yet responsive engineering program. Ultimately, this will yield an education program that is responsive, and potentially encourages students with a broader base of knowledge than has been our tradition in engineering.

The most important impact of the new paradigm could be to shed new light on our concept of the distinct engineering disciplines. In essence, there need be no distinction between an electrical or mechanical engineer other than the technical areas in which they have a knowledge base, in effect, the upper branches of the tree. For a student to graduate, rather than force them to take a suite of ES courses that may have nothing to do with their particular career aspirations, we should focus on offering courses that support a student's interests and aspirations. These also must support the needs of industry and government for the junior engineers coming in to their employ.

Conclusions

Eder [16], and others [8, 14, 17, 19] have described the function of engineers, and expressed a view that the current engineering-science based curriculum does not serve the graduates well. Despite the fact that the vast majority of engineers in practice today were trained in a Lecture-Based Learning (LBL) model, it is difficult to find literature expressing a view that LBL is the best model for educating engineers. While this paper does not attempt to defend the status quo, it is an attempt to propose a conceptual framework for the engineering graduate.

Engineering programs are typically some of the most tightly packed undergraduate degrees in Canadian Universities, and are filled with a great number of required courses, giving students few options for exploring their personal lines of interest. In a four-year degree program, there is no room to put additional course requirements on students without moving to a longer degree program. What is to be cut in order to make room? Figure 3 can give some guidance to decide on educational priorities.

In particular, this conceptual paradigm becomes fundamentally student-centred. The paradigm leads to some practical conclusions, including:

- A renewed commitment to educating young engineers with a broad and comprehensive natural science and philosophical background. The tree is only as strong as the roots from which it grows;

- Opportunity for young engineers to choose advanced engineering science courses that may be outside of the traditional mechanical-civil-electrical engineering curricula based on their own interests and career aspirations. Not every tree is the same shape, with the same branches;

- A renewed willingness to offering specific courses at the higher level that are responsive to current and changing needs of industry. Trees must adapt to their environment throughout their long lives;

- A new emphasis on specifically teaching creativity, design, project management, team work, and leadership as core skills rather than relying upon students to pick these skills up as needed. The most important "tree-like" feature is the trunk.

References

1 G. Scott and K. W. Yates. (2002, 12). Using successful graduates to improve the quality of undergraduate engineering programmes. *European Journal of Engineering Education 27(4),* pp. 363.

2 Canadian Engineering Accreditation Board. (2008, Accreditation criteria and procedures. Canadian Council of Professional Engineers,

3 C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer. (2005, January 2005). Engineering design thinking, teaching, and learning. *J. Eng. Edu 21(1),* pp. 103.

4 C. Baillie. (2007, 08). Education development within engineering. *European Journal of Engineering Education 32(4),* pp. 421-428. Available:
5 E. F. Crawley, D. R. Brodeur and D. H. Soderholm. (2008, 04). The education of future aeronautical engineers: Conceiving, designing, implementing and operating. *Journal of Science Education & Technology 17(2),* pp. 138-151.

6 N. E. Cagiltay. (2008, 08). Using learning styles theory in engineering education. *European Journal of Engineering Education 33(4),* pp. 415-424.

7 A. B. De Magalhães, M. Estima and B. Almada-Lobo. (2007, 12). PUKHA: A new pedagogical experience. *European Journal of Engineering Education 32(6),* pp. 711-719.

8 J. R. Mihelcic, K. G. Paterson, L. D. Phillips, Q. Zhang, D. W. Watkins, B. D. Barkdoll, V. J. Fuchs, L. M. Fry and D. R. Hokanson1. (2008, 12). Educating engineers in the sustainable futures model with a global perspective. *Civil Engineering & Environmental Systems 25(4),* pp. 255-263.

9 S. Tornkvist. (1998, 03). Creativity: Can it be taught? the case of engineering.. *European Journal of Engineering Education 23(1),* pp. 5.

10 J. Pritchard and C. Baillie. (2006, 10). How can engineering education contribute to a sustainable future? *European Journal of Engineering Education 31(5),* pp. 555-565.

11 G. Ranson. (2003, 01). Beyond ‘Gender differences’: A canadian study of Women’s and Men’s careers in engineering. *Gender, Work & Organization 10(1),* pp. 22-41.

12 V. R. Neufeld and H. S. Barrows. (1974, 11). The "McMaster philosophy": An approach to medical education. *J. Med. Educ. 49(11),* pp. 1040-1050.

13 S. Mennin, P. Gordan, G. Majoor and H. A. S. Osman. (2003, 03). Position paper on problem-based learning. *Education for Health: Change in Learning & Practice 16(1),* pp. 98.

14 S. Toral, M. Martínez-Torres, F. Barrero, S. Gallardo and M. Durán. (2007, 10). An electronic engineering curriculum design based on concept-mapping techniques. *International Journal of Technology & Design Education 17(3),* pp. 341-356.

15 O. Rompelman and E. De Graaff. (2006, 05). The engineering of engineering education: Curriculum development from a designer's point of view 1. *European Journal of Engineering Education 31(2),* pp. 215-226. 16 W. E. Eder and V. Hubka. (2005, 02). Curriculum, pedagogics and didactics for design education. *J. Eng. Des. 16(1),* pp. 45-61.

17 M. Harris and R. Cullen. (2009, 06). A model for curricular revision: The case of engineering. *Innovative Higher Education 34(1),* pp. 51-63.

18 K. W. Jablokow. (2007, Engineers as problem-solving leaders : Embracing the humanities. *IEEE Technology & Society Magazine 26(4),* pp. 29-35.

19 M. Savin-Baden. (2008, 04). Problem-based learning in electronic engineering: Locating legends or promising problems? *Int J Electr Eng Educ 45(2),* pp. 96-204.