THE GOALS OF ENGINEERING EDUCATION: A RATIONALE FOR A UNIVERSAL DOCUMENT BASED ON THE CDIO SYLLABUS AND THE TAXONOMY OF ENGINEERING COMPETENCIES

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Abstracts
Among statements about educational goals found in the engineering literature, two – the CDIO Syllabus and the Taxonomy of Engineering Competencies – stand out in regard to range and level of detail. The two statements have been formulated independently and each presents a different perspective on the goals of engineering education. This paper takes advantage of the unique opportunity afforded by having two well-worked but different perspectives on the goals of engineering education. A comparison of the two statements reveals their respective strengths and weaknesses, provides mutual endorsement of their comprehensiveness and quality, and gives deeper insight into the dynamics and difficulties associated with the formulation of statements about the goals of engineering education. In addition, it develops a rationale for the formulation of a universal document on the goals of engineering education, discusses the merits and limitations of such a document and makes some recommendations about how it might be compiled.

Keywords: Engineering education, learning outcomes, CDIO, educational goals

Introduction

In the literature there are many documents and statements that, in one way or another, attempt to describe the goals of engineering education. There are numerous reports from surveys of the opinions of practicing engineers [1], [2], [3], [4], [5], there are statements that are more theoretically based [6], and there are statements of required learning outcomes in documents formulated by bodies responsible for the accreditation of engineering programs (see web sites given at the end of the reference list).

Two recent initiatives in engineering education have each produced a detailed statement of goals for engineering undergraduate education. These statements are the "Taxonomy of Engineering Competencies (which will be referred to as "the Taxonomy") and the CDIO Syllabus (which will be referred to simply as "the Syllabus"). This paper examines and compares the two statements in some detail with the following objectives in mind.

- To better understand the goals of engineering education and how these can be formulated.
- To explore the consolidation of the two statements into a single more universal document.
- To examine the Syllabus and Taxonomy as exemplars to better understand the merits and limitations of a universal document and how such a document could be formulated.

The CDIO Syllabus

Background to the Syllabus

The following information was extracted from the CDIO website (www.cdio.org), from a CDIO symposium in Pretoria (in 2005) and, more particularly, from the papers by Crawley [7] and Bankel et al [1].

CDIO (Conceive-Design-Implement-Operate) is a collaborative reform initiative that is actively seeking to "shape the future of engineering education". The driving force behind the CDIO initiative is to address "how universities can continue to provide quality education in technical fundamentals while simultaneously imparting a sense of engineering professionalism." More particularly, the concern is to close the gap between engineering education and engineering practice. This gap is the result of a shift that occurred in the middle of the last century in the way that engineering was taught [7], [8]. The shift was characterized by the increasing prominence given to engineering science in engineering education as compared with the more traditional emphasis on practical engineering [8]. Today, the teaching staff in engineering schools tends to be more strongly rooted in engineering science and research and less strongly rooted in a wide background of industrial experience [7], [8].

The foundational premise on which the CDIO initiative is built is the conviction that design is at the heart of what it is "to engineer" [7]. This conviction is encapsulated in the CDIO vision statement: "Every graduating engineer should be able to 'Conceive-Design-Implement-Operate' complex value-added engineering systems in a modern team-based environment". Accordingly, the reform strategy involves (a) expanding the design modules that exist in all engineering curricula, (b) ensuring that many of these have the strong practical dimension that accompanies actually building what has been designed, and (c) reorganizing the design part of the curriculum so that students participate in several major team-based, design-and-build projects during the course of their undergraduate career.

In an effort to support the design focus and to further close the gap between engineering education and practice, the CDIO initiative re-evaluated the goals of engineering education from the perspective of modern engineering practice and developed a generic syllabus (the CDIO Syllabus) that used design (or, more accurately, CDIO) as its chief organizing principle. As a statement of the goals of engineering education, the Syllabus became the foundation for the curriculum redesign component of the reform initiative. The other components are 'pedagogic improvement', continuous assessment, and the provision of learning-space for design-and-build projects [1].

The Syllabus and how it was developed

The Syllabus was developed as a collaborative effort between a range of engineering schools (aerospace, mechanical and electronics engineering) at MIT and three Swedish universities over a three year period based on work involving focus groups, surveys, workshops, and peer reviews [7]. It has been worked out to four – sometimes five – levels of detail. It is presented in Appendix 1 to the third level of detail. Appendix 2 gives examples of fourth and fifth level detail. The full Syllabus is found on www.cdio.org.

The Syllabus details the many, inter-related processes, knowledge, skills and attributes involved in engineering a technical system or product from its conception, through design, construction and implementation, through its operation and eventual life-end and disposal. It also details the external, societal, enterprise and business contexts in which such engineering is conducted and the personal, inter-personal and professional skills needed for competent performance of the relevant engineering tasks and processes.

As can be seen from Appendices 1 and 2, the Syllabus takes the form of an extended, structured bullet list of brief statements each describing an aspect of engineering practice. The structure invites additions and deletions. Indeed, the first major category – Technical Knowledge and Reasoning – is empty, having only three subcategories that distinguish between basic, core and advanced technical knowledge and reasoning. Implementation of the Syllabus requires the addition of the relevant particulars.

Preliminary evaluation of the Syllabus

In regard to validity and reliability, the specific content and structure in the Syllabus seems solid. It was formulated by senior academics at four leading universities in wide consultation with alumni and leading engineering professionals through a careful, three-year process of design and development. During its formulation, consideration was given to published data but only two references are cited. The primary data used was gathered from surveys based on drafts of the Syllabus. Remarkable agreement between respondent opinions was obtained (at the second level of detail) with the responses to very few items showing differences that were statistically different [7]. A correlation exercise showed that all the required learning outcomes in ABET's EC2000 document were included in the Syllabus and that the Syllabus was considerably more detailed.

In regard to comprehensiveness, 277 academics, practicing engineers and industry leaders, and 164 students responded to the survey [7]. This is not a large number of respondents but, as will be shown indirectly, the findings from these surveys are consistent with the results from larger surveys.

The Taxonomy of Engineering Competencies

Background to the Taxonomy

Research and restructuring efforts at the University of the Witwatersrand in South Africa have produced a generalized statement about needed graduate competencies that takes the form of a Taxonomy of Engineering Competencies [6]. The driving force behind this work was the concern to deal more effectively with high rates of student attrition in South African institutions of engineering education by paying more careful attention to the dynamics of student development and learning.

High attrition rates and academic underperformance among entrants to engineering education are global problems that have prompted a range of responses [9], [10], [11], [12]. In South Africa, the most common response in the past has been to provide 'add-on' academic development measures of various kinds either prior to or in parallel to the mainstream educational programs [9], [13]. Currently, there is a move away from this approach and more attention is being given to the redesign of mainstream courses in the first year as well as to broader reform and re-structuring of the mainstream program as a whole [13], [14], [15].

The initiative behind the Taxonomy identified and addressed two related issues as underlying the problem of high attrition rates in the South African context. The first had to do with the nature and dynamics of the obstacles to learning that were occurring in the first year program. This was a teaching and learning issue. The second was a curriculum design issue that had to do with the challenge posed when there is among the students a wide diversity in the kind of learners they are and in their educational and social backgrounds, maturity, preferred language, experience and expectations. Strong evidence supported the contention that if these two challenges are not met in a satisfactory way, teaching and learning is bound to be affected adversely, and retention, pass rates and student competency levels will be lower than they could be [6]. A further likely consequence of not properly resolving these issues at the first year level is the knock-on effect on subsequent years of study: students entering each year of study will not be as well prepared as they could be. This scenario is typical of situations around the world where the diversity of the student intake has broadened as a result of, for example, massification policies [16].

At the heart of the restructuring effort was the conviction that a new way should be found to address the teaching, learning and diversity issues [17]. The foundational premise on which the research/restructuring effort was based was that, instead of thinking about language, learning, organizational and related non-technical skills as academic development issues, they should be regarded as issues of 'academic competency' and that development of these competencies should be seen as the first stage in developing critically important non-technical professional competencies.

It was in this context that the Taxonomy was developed. The rationale for its formulation was that a solid description of what constituted a competent engineer was needed as a framework to conceive and design how the degree program would facilitate the development of the non-technical aspects of the academic/professional competencies of its students. It was considered important to contextualize and anchor the planning of the developmental pathways of students in a clearly articulated understanding of engineering practice and its constituent competencies.

The Taxonomy and how it was developed

The Taxonomy was developed independently from the Syllabus on the basis of findings from a literature search [6]. In the first place, the search looked at statements of required learning outcomes found in the documentation published by national bodies responsible for the accreditation of engineering programs in Australia, Canada, New Zealand, South Africa, the UK and the USA[1]. Secondly, it looked at published opinion surveys of practicing engineers in regard to the competencies graduate engineers should possess (surveys similar to those undertaken in the development of the CDIO syllabus). Thirdly, descriptions of the nature of engineering work found in the literature were noted and generic models of the major components of work and work proficiency, and of the determinants of competency were consulted. Fourthly, the literature search looked at the findings of a large body of research in human resource management that had been compiled into a competency dictionary and into generalized competency models for different job types. Woollacott [6] describes how the findings of the literature search were consolidated into the Taxonomy of Engineering Competencies. The Taxonomy itself is presented in Appendices 3A and 3B.

Where the Syllabus focuses on design and what it is "to engineer", the Taxonomy focuses on "engineering work" and the competencies and dispositions[2] needed to do it well. This approach draws attention to the different kinds of work activities an engineer may be called to engage in. Distinctions are made between engineering-specific activity and non-engineering-specific activity. Attention is also given to the range of contexts in which these two types of activity are integrated for the achievement of the goals of the enterprise in which an engineer is working. The Taxonomy describes the knowledge, skills and dispositions needed for the competent performance of these activities.

[1] See web sites given at the end of the reference list.
[2] 'Dispositions' is used here as a composite term that includes attributes, attitudes, traits, interests, orientations and motivations.

Preliminary evaluation of the Taxonomy

The comprehensiveness, reliability and validity of the Taxonomy rest on the range and quality of the references consulted and on the quality of the theory and research evidence that were utilized in its formulation. In regard to sources, the references cited in the originating paper [6] show that a wide range of literature was consulted – significantly more than is reported for the Syllabus. In regard to theory and research evidence, three particular features of the Taxonomy give weight to the claim that it is comprehensive in its coverage of the issues it addressed. These features are:-

- The organization of its first level detail was based directly on a well-respected model of generic work [18]. The model claims to comprehensively describe the components of any type of job – a claim that has significant support in the field of industrial psychology [19]. (An augmented version of the Campbell model is presented in Appendix 4.) Organizing the Taxonomy around the categories in this model therefore provides a theory-supported claim that no aspect of work has been overlooked.
- The Taxonomy's strong emphasis on dispositions is derived from another Campbell model (Appendix 5) that claims to comprehensively describe the generic determinants of competency [18]. Again the claim is well supported [19]. The significance of 'dispositions' is that it incorporates personal, affective traits and attributes along with motivation and shows their importance to competent performance of any job and the way that these influence how a person's knowledge and skills are actually marshaled and brought to bear in the performance of his/her work. The comprehensiveness and reliability of the description of the relevant dispositions rests on the surveys of opinion of practicing engineers that were consulted and on the feature of the Taxonomy's formulation described next.
- The seventh category in the Taxonomy – Advanced Dispositions – was extracted from a competency model for technical professionals [20]. The model is derived from the consolidation of over 20 years work in over 20 countries and is based on many hundreds of rigorously structured personal interviews by trained industrial psychologists with ordinary and superior performers in a range of technical (and other types of) jobs. The research was carefully structured to identify the characteristic behaviors that distinguished superior from ordinary performers. The reliability and comprehensiveness of these insights rests on the extensive range of the data collected and on the degree of rigor with which the research was conducted and the data analyzed.

Comparative evaluation of the Syllabus and the Taxonomy

Level of Detail

Earlier, the Syllabus and Taxonomy were shown to be compilations of education goals that are more comprehensive and detailed than other compilations found in the engineering education literature. In regard to the range of the content, the Syllabus includes and describes more fully all the items in the Taxonomy except for a few which are discussed shortly. Table 1 shows that the Syllabus is significantly more detailed than the Taxonomy: it contains more third-level subcategories and some fifth level detail. Some appreciation of the extent and nature of the extra detail can be gained by comparing the fourth and fifth level content of the Syllabus shown in Appendix 2 with the equivalent content in the Taxonomy (Appendix 3).

One of the strengths of the Taxonomy relative to the Syllabus is its rootedness in theory and the literature. Noting this and the observation that the Syllabus incorporates most of the Taxonomy's content gives further endorsement to the comprehensiveness, reliability and validity of the Syllabus.

Table 1: Comparison of the Extent of Detail

	Number of categories and the level at which detail is elaborated				
Level of Detail	1st Level	2nd Level	3rd Level	4th Level	5th Level
CDIO Syllabus	4	17	74	Detail (ODFC[b])	Detail (NDFC[a])
Taxonomy of Engineering Competencies	7	25	54	Detail (NDFC[a])	–

[a] NDFC = no division into further categories
[b] ODFC = Occasional division into further categories

Format

The formats of the two statements are quite different. The bullet-list approach which invites the addition or deletion of items gives the Syllabus the functionality of a working document. Because goals are broken down to 4 or 5 levels of detail and are communicated by means of brief, clear statements, the Syllabus is conducive to easy translation into learning outcomes. The format of the Taxonomy, on the other hand, is more compact and descriptive making it less functional as a working document but very functional as a descriptive document. Considering these observations and the earlier comments about detail, it appears that any consolidation of the two goal statements should be based on the Syllabus after modifications that have considered how it differs from the Taxonomy.

Rationale

In essence, the Syllabus addresses what it is “to engineer” while the Taxonomy addresses what it is “to work as an engineer”. The difference is subtle but is significant because it gives a different perspective on the goals of engineering education.

The Taxonomy presents a broad view of engineering work that distinguishes between three types of engineering-specific work (engineering analysis, design and investigation) and the integration of engineering specific work into contexts where engineering is only one part of more broadly based work activity. More specifically, it portrays engineers working in jobs that may include (and sometimes focus narrowly on) analysis, design, testing, development, maintenance, selling, research, line management, project management, consulting, teaching or entrepreneurial endeavor.

In contrast, the Syllabus focuses on the knowledge, skills and attributes needed for performing the various engineering processes associated with the life-cycle of an engineering system or product. This focus does incorporate most of the elements that the Taxonomy indicates are necessary to perform the wide range of engineering work. However, in its focus on what it is ‘to engineer’, the Syllabus does not give as good a sense of the breadth of engineering work and is less successful than the Taxonomy in presenting the wide range of dispositions needed to be a competent engineer. The strong design focus also slants the way teamwork and operating are portrayed. Teamwork is presented primarily from the perspective of design teams and ‘operating’ from the perspective of the operation of design products. In both cases, the perspectives under-represent the multi-disciplinary associations that characterize, in particular, production environments such as mining operations and chemical or metallurgical processing plants.

More positively, the Syllabus' focus on design and what it is "to engineer" has some distinct advantages. Firstly, it provides a more coherent statement of goals: the different elements of the overall design process are more logically and sequentially connected than are the different types of engineering work. Secondly, design has long been recognized and entrenched as an effective vehicle for integrating and bringing cohesion to an engineering curriculum. Thirdly, the Syllabus has been tested and adopted by a number of quality schools around the world.

To conclude this discussion it appears that the rationale of the Syllabus works and communicates and that any shortcomings with regard to under-representation of the variety of engineering work could be accommodated by adding relevant statements to the appropriate sections of the Syllabus.

Methodology and Reform Initiative

Reflection on the origin of the goals statements reveals two significant points.

- Both the Syllabus and the Taxonomy are products of reform initiatives and, in both cases, the initiatives were prompted by a conviction that the prevailing engineering curriculum was not properly 'responsive' in some way. The initiative behind the Syllabus was concerned that curricula were not properly addressing engineering practice while the initiative behind the Taxonomy was concerned that the prevailing curriculum was not properly developing among a diverse student intake important academic/professional competencies. These observations suggest that reform trends and concerns may inherently be responding to educational goals which may be very significant but have been subtly overlooked or inadequately understood.
- Both the reform concern and the methodology used to formulate goal statements can introduce bias. Earlier, it was shown that bias was introduced by the particular rationale selected to organize the goal statements. Bias can also be introduced by the methodology used in the formulation of the goals statement. For example, surveys which solicit a rating on a list of specified goals will not capture goals that are not included in the list. Surveys will be less rigorous or penetrating than face-to-face interviews by trained industrial psychologists. In addition, theory and the literature can provide insights that both the survey and the interview methodologies might miss.

The conclusion to be reached from these observations is that in order to capture as wide a perspective as possible on the goals of engineering education, the methodology used should be multi-dimensional and should include surveys, consultation of theory and literature, and an interrogation of prevailing reform trends and concerns.

Engineering Practice

The CDIO initiative is very directly concerned about engineering practice and the Taxonomy is an attempt to identify the competencies that engineering practice embodies. However, in both cases, the term 'practice' is used rather loosely. To tighten up what is meant by the term it is helpful to consider the following insights from situated learning theory [21], [22], [23]. Practice is social activity in a 'community of practice'. To become a competent engineer involves becoming a competent participant in such a community through a socialization or enculturation process [14], [21], and by becoming competent in the engineering discourse that is characteristic of that community. Engineering discourse includes specific engineering knowledge and skills but also, very importantly, less tangible factors such as particular values and vocabulary, ways of thinking and doing, and the "well-defined roles, the implicit relations, the tacit conventions, the subtle cues, the untold rules of thumb, the recognizable intuitions, the specific perceptions, the well-tuned sensitivities, the embodied understandings, the underlying assumptions, the shared worldviews" [22]. It is interesting to note that the CDIO's tactic of having students design, build and implement systems or products in a team-based environment is fully consistent with the perspectives of situated learning theory that, for effective pedagogy, students should participate in authentic engineering activity and engage with the associated discourse.

These brief remarks are sufficient to make the point that there is more to 'engineering practice' than is addressed by either the Syllabus or the Taxonomy and that situated learning theory presents a different and important perspective not only on the nature of learning but also on the nature of engineering practice and what is involved in becoming a competent engineer. Further explorations in this direction are likely to reveal additional goals for engineering education [14]. In particular, two topics should be included in the Syllabus – the nature of engineering and scientific knowledge and the issue of knowledge management in communities of practice [22].

A Universal Document?

Engineering practice is not static. Not only is new technology being developed all the time, but there are shifts in emphasis, in the kinds of demands placed on engineers and, therefore, in how graduate engineers need to be educated. Instances of such shifts and reform movements in engineering education have been mentioned in the paper. Consequently, the need from time to time to modify an existing curriculum or to develop a new one should be recognized to be a permanent feature of engineering education. As this study has shown, such modification or development requires a careful articulation of educational goals and that it is far from straight forward to identify and communicate these accurately and clearly. Accordingly, it would be very attractive to have available a 'trusted universal document' – a relevant statement of goals that can be trusted to be up to date, to have been compiled in a rigorous way from a wide range of perspectives, and to have been subjected, in an ongoing way, to global scrutiny.

The Syllabus is explicitly intended to be a universal document. (Note, for example, the titles of the papers by Berggren et al [24] and Crawley [7]: respectively "CDIO: an international initiative for reforming engineering education"; "Creating the CDIO Syllabus: a universal template for engineering education".) How well the Syllabus functions as a universal document has, in effect, been tested in this study by comparing it to the Taxonomy – a virtually unknown document that has been rigorously but independently formulated. The comparison has given a solid endorsement to the quality of the Syllabus but has also revealed some bias and a few shortcomings. Some of these are easily addressed by making appropriate additions to the Syllabus while others suggest that a more extensive re-evaluation of the Syllabus should be contemplated. However, before making recommendations in regard to updating or revising the Syllabus or about the consolidation of the Syllabus and Taxonomy into a single document, further discussion is required about the form which a universal statement on the goals of engineering education should take.

The role that a statement of goals plays in the design and delivery of an engineering curriculum can be understood by reflecting on the steps that Crawley and others [1], [7] suggest should be taken to implement a curriculum based on the CDIO Syllabus. Explicitly and implicitly, they suggest the following:-

- Modify the generic statement of the educational goals by adding or deleting topics as needed.

- Survey stakeholders to elicit their opinion on the importance of each educational topic in the modified goals statement and the degree of proficiency they believe graduates should possess in regard to each topic.
- Examine and rationalize the survey data obtained and set appropriate proficiency levels for each goal/topic. Translate the goals into appropriate learning outcomes.
- Use these learning outcomes along with the detail in the Syllabus to contemplate how the targeted knowledge, skills and attributes might be developed in students.
- Design the curriculum structure and content, educational strategies, learning environment and assessment strategies accordingly.
- Plan, prepare and deliver lessons and assessments accordingly.

What is clear from these recommendations is that a statement of educational goals can and should inform the design and delivery of an educational program at many points. More specifically, such a statement must fulfill two general functions – to facilitate the definition and articulation of required learning outcomes for specific engineering programs, and to inform and enrich each stage in the design and delivery of an engineering curriculum.

It is helpful to reflect on how the Syllabus and Taxonomy each fulfills these two general functions. The Syllabus fulfills the first by presenting a generic syllabus for engineering education that is designed for easy modification and translation into specific learning outcomes. It fulfills the second general function by providing extensive detail in the long list of curriculum items. The format of the detail, however, does not appear to lend itself to as holistic an appreciation of engineering practice as does the Taxonomy. On the other hand, the Taxonomy is a classification of desired engineering competencies. Its compact format is not conducive to direct translation into learning outcomes but does function well as a 'big-picture', descriptive document of what is involved in working as an engineer. It would seem, therefore, that both the Syllabus and the Taxonomy each fulfills one of the general functions well and the other less well.

Three implications flow from these observations. The first is a general one: a universal document on the goals of engineering education must pay careful attention to how the document satisfies the two general functions of generating learning outcomes and of providing a useful descriptive reference for curriculum design and delivery. The second implication is that this kind of careful attention must be given to any update or revision of the Syllabus or to any attempt at a consolidation of the Syllabus and Taxonomy into a single document. The third implication is that a re-evaluation of the Syllabus is called for – even if only to examine the extent to which it fulfills both of the general functions just described.

Conclusions and Recommendations

Having two independently-formulated perspectives on the goals of engineering education has proved to be very powerful. It has enabled a comparison that has reveal their respective strengths and weaknesses and has provided mutual endorsement of their comprehensiveness and quality. More generally, it has given a deeper insight into the dynamics and difficulties associated with the formulation of statements about the goals of engineering education. In addition, it has indicated that, in order to capture as wide a perspective as possible on these goals, the methodology used should be multi-dimensional and should include surveys, consultation of theory and literature, and an interrogation of prevailing reform trends and concerns.

In regard to modifications to the CDIO Syllabus, the following recommendations are made.

- Add those items in the Taxonomy that are covered less well or not at all in the Syllabus (items 12, 24, 34-36, 38, 41, 44-48, 52-53 in Appendices 3A and 3B).
- Re-evaluate items in the Syllabus that are expressed differently in the Taxonomy (items 14, 29, 33, 40, 42-43, 49, and 54 in Appendices 3A and 3B).
- Expand the sections on life-long learning to include a broader consideration of learning issues in general. The goals here should include an appreciation of the nature of engineering and scientific knowledge and of knowledge management in communities of engineering practice.
- Pay more attention to dispositional issues. The Taxonomy has highlighted the need to pay particular attention to developing or reinforcing in students the dispositions that are appropriate for the competent performance of engineering work. The importance of this issue is a subject that is easily overlooked when the student intake has a fairly homogeneous profile and is reasonably sophisticated in technical and scientific knowledge.
- Pay more attention to issues arising from multi-cultural contexts and globalization and the social appropriateness of technological solutions in cross-cultural settings.
- Incorporate goals concerning the appreciation of the range and nature of engineering work.

In regard to recommendations about a universal document on the goals of engineering, only procedural recommendations seem appropriate at this point: more specific recommendations would probably be premature until after the suggested modifications to the Syllabus have been given due consideration. The procedural recommendations are as follows:-

- Base efforts to develop an improved universal document on the current CDIO Syllabus. Its quality has been endorsed by this study, it is already widely accepted and established as a universal document, and it is more extensive and detailed than the Taxonomy.
- Accept that revision of the Syllabus is needed: the recommendations for modification given above should be given due consideration.
- Give careful attention to how the Syllabus can function better as a descriptive reference that informs the design and delivery of engineering curricula. In this regard, it would seem prudent to incorporate in some way the perspective and possibly some of the formatting features of the Taxonomy. This could add richness and breadth to the revised document.

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Professional Engineering Bodies: Web sites for outcome statements in accreditation documents
Accreditation Board for Engineering and Technology, Unites States, www.abet.org
Canadian Council of Professional Engineers, www.ccpe.ca
Engineering Council of South Africa, www.ecsa.co.za
Engineering Professors Council, United Kingdom, www.engprofc.ac.uk
Institution of Engineers, Australia, www.ieaust.org.au
Institution of Professional Engineers, New Zealand, www.ipenz.org.nz

Biographical Information
Laurie Woollacott has been a senior lecturer at the University of the Witwatersrand, Johannesburg since 2000. He has eight years experience in the mineral processing industry. His current scholarly and teaching interests are engineering education and, in particular, the issues associated with high attrition rates among first year students.

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APPENDIX 1: The CDIO Syllabus (Condensed) [1]

1 TECHNICAL KNOWLEDGE AND REASONING
1.1 KNOWLEDGE OF UNDERLYING SCIENCE
1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE
1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES
2.1 ENGINEERING REASONING AND PROBLEM SOLVING
2.1.1 Problem Identification and Framing
2.1.2 Modelling
2.1.3 Estimation and Qualitative Analysis
2.1.4 Analysis With Uncertainty
2.1.5 Closing the Problem

2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY
2.2.1 Principles of Research and Inquiry
2.2.2 Experimental Inquiry
2.2.3 Survey of Print and Electronic Literature
2.2.4 Hypothesis Test, and Defence

2.3 SYSTEM THINKING
2.3.1 Thinking Holistically
2.3.2 Emergence and Interactions in Systems
2.3.3 Prioritisation and Focus
2.3.4 Trade-offs and Balance

2.4 PERSONAL SKILLS AND ATTITUDES
2.4.1 Initiative and Willingness to Take Risks
2.4.2 Perseverance, and Flexibility
2.4.3 Creative Thinking
2.4.4 Critical Thinking
2.4.5 Personal Inventory
2.4.6 Curiosity and Lifelong Learning
2.4.7 Time and Resource Management

2.5 PROFESSIONAL SKILLS AND ATTITUDES
2.5.1 Professional Ethics, Integrity, Responsibility and Accountability
2.5.2 Professional Behaviour
2.5.3 Proactively Planning for One's Career
2.5.4 Staying Current on World of Engineer

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION
3.1 MULTI-DISCIPLINARY TEAMWORK
3.1.1 Form Effective Teams
3.1.2 Team Operation
3.1.3 Team Growth and Evolution
3.1.4 Leadership
3.1.5 Technical Teaming

3.2 COMMUNICATIONS
3.2.1 Communications Strategy
3.2.2 Communications Structure
3.2.3 Written Communication

3.3 COMMUNICATIONS IN FOREIGN LANGUAGES
3.3.1 English
3.3.2 Languages of Regional Industrial Nations
3.3.3 Other Languages

4 CONCEIVING, DESIGNING, IMPLEMENTING, AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT
4.1 EXTERNAL AND SOCIETTAL CONTEXT
4.1.1 Roles and Responsibility of Engineers
4.1.2 Understand the Impact of Engineering
4.1.3 Understand How Engineering Is Regulated
4.1.4 Knowledge of Historical and Cultural Context
4.1.5 Knowledge of Contemporary Issues and Values
4.1.6 Developing a Global Perspective

4.2 ENTERPRISE AND BUSINESS CONTEXT
4.2.1 Appreciating Different Enterprise Cultures
4.2.2 Enterprise Strategy, Goals, and Planning
4.2.3 Technical Entrepreneurship
4..2.4 Work successfully in Organizations

4.3 CONCEIVING AND ENGINEERING SYSTEMS
4.3.1 Setting System Goals and Requirements
4.3.2 Defining Function, Concept and Architecture
4.3.3 Modelling of System and Insuring Goals Can Be Met
4.3.4 Project Management

4.4 DESIGNING
4.4.1 The Design Process
4.4.2 The Design Process Phasing and Approaches
4.4.3 Utilization of Knowledge in Design
4.4.4 Disciplinary Design
4.4.5 Multidisciplinary Design
4.4.6 Multi-Objective Design (DFX)

4.5 IMPLEMENTING
4.5.1 Designing and Modelling of the Implementation Process
4.5.2 Hardware Manufacturing Process
4.5.3 Software Implementing Process
4.5.4 Hardware Software Integration
4.5.5 Test, Verification, Validation, and Certification
4.5.6 Managing Implementation

4.6 OPERATING
4.6.1 Modelling, Designing and Optimising Operations
4.6.2 Training and Operations
4.6.3 Supporting the System Lifecycle
4.6.4 System improvement and Evolution
4.6.5 Disposal and Life-End Issues
4.6.6 Operations Management

APPENDIX 2: Examples of 4th and 5th Level Detail in the CDIO Syllabus
(Extracted from the CDIO Website www.cdio.org.)

Example of 4th Level Detail

2.4 PERSONAL SKILLS AND ATTITUDES

2.4.1 INITIATIVE AND WILLINGNESS TO TAKE RISKS
- The needs and opportunities for initiative
- The potential benefits and risks of an action
- The methods and timing of project initiation
- Leadership in new endeavours, with a bias for appropriate action
- Definitive action, delivery of results and reporting on actions

2.4.2 PERSEVERANCE AND FLEXIBILITY
- Self-confidence, enthusiasm, and passion
- The importance of hard work, intensity and attention to detail
- Adaptation to change
- A willingness and ability to work independently
- A willingness to work with others, and to consider and embrace various viewpoints
- An acceptable of criticism and positive response
- The balance between personal and professional life

2.4.3 CREATIVE THINKING
- Conceptualization and abstraction
- Synthesis and generalization
- The process of invention
- The role of creativity in art, science, the humanities and technology

2.4.4 CRITICAL THINKING
- The statement of the problem
- Logical arguments and solutions
- Supporting evidence
- Contradictory perspectives, theories and facts
- Logical fallacies
- Hypotheses and conclusions

2.4.5 AWARENESS OF ONE'S PERSONAL KNOWLEDGE, SKILLS AND ATTITUDES
- One's skills, interests, strengths, weakness
- The extent of one's abilities, and one's responsibility for self-improvement to overcome important weaknesses
- The importance of both depth and breath of knowledge

2.4.6 CURIOSITY AND LIFELONG LEARNING
- The motivation for continued self-education
- The skills of self-education
- One's own learning style
- Developing relationships with mentors

2.4.7 TIME AND RESOURCE MANAGEMENT
- Task prioritization
- The importance and/or urgency of tasks
- Efficient execution of tasks

Example of 4th + 5th Level Detail

3.2 COMMUNICATIONS

3.2.1 COMMUNICATIONS STRATEGY
- The communication situation
  - Communications objectives
  - The needs and character of the audience
  - The communication context
- A communications strategy
  - The appropriate combination of media
  - A communication style (proposing, reviewing, collaborating, documenting, teaching)
  - The content and organization

3.2.2 COMMUNICATION STRUCTURE
- Logical, persuasive arguments
  - The appropriate structure and relationship amongst ideas
  - Relevant, credible, accurate, supporting evidence
  - Conciseness, crispness, precision and clarity of language
  - Rhetorical factors (e.g. audience bias)
- Cross-disciplinary cross-cultural communications

3.2.3 WRITTEN COMMUNICATION
- Writing with coherence and flow
- Writing with correct spelling, punctuation and grammar
- Formatting the document
- Technical writing
- Various written styles (informal, formal memos, reports, etc)

3.2.4 ELECTRONIC/MULTIMEDIA COMMUNICATION
- Preparing electronic presentations
- The norms associated with the use of e-mail, voice mail, and videoconferencing
- Various electronic styles (charts, web, etc)

3.2.5 GRAPHICAL COMMUNICATION
- Sketching and drawing
- Construction of table, graphs and charts
- Formal technical drawings and renderings

3.2.6 ORAL PRESENTATION AND INTER-PERSONAL COMMUNICATIONS
- Preparing presentations and supporting media with appropriate language, style, timing and flow
- Appropriate nonverbal communications (gesture, eye contact, poise)
- Answering questions effectively

APPENDIX 3A: A Taxonomy of Engineering Competency (Part1) [6]

1st Level Categories	2nd Level Categories	Competency: An Ability to … (3rd Level Categories and 4th Level Detail)
A) Engineering-Specific Work	General Engineering Work	1) Perform the different aspects of any engineering work or task namely initiating and planning the work/task, acquiring the resources needed, performing sub-tasks and evaluating and synthesizing results.
		2) Use appropriate engineering and computer methods, skills and tools and properly assess, analyze and interpret the results they yield.
		3) Evaluate effectiveness, productivity, profitability, quality, service, impact or implications of any aspect of work done or planned and a disposition to do so.
		4) Arrange, sort, retrieve and properly assess data, knowledge and ideas.
	Specialist Engineering Work	5) Perform **analytical work** to solve existing and anticipated engineering problems and model relevant systems by (a) applying knowledge of mathematics and the natural, engineering and computational sciences, and (b) identifying, assessing, formulating and solving convergent and divergent engineering problems in a creative and innovative way.
		6) Perform **design work** by converting concepts and information into detailed plans and specifications for the development, manufacture or operation of systems, processes, products or components that meet desired needs.
		7) Plan and perform **investigations** to (a) **test** that a design or product meets specifications, (b) **develop** products, components, systems or processes, or (c) **search for new knowledge** that can be applied for the advancement of engineering practice.
	Engineering Mixed with Other Work	8) Integrate specialist engineering work appropriately with work relating to core functions of an enterprise, management, administration, supervision, projects, sales, consulting, entrepreneurship or teaching in order to achieve the broader aims of the business enterprise or stated objectives in the different generic settings of engineering work. These are analysis, design, testing, development, maintenance, selling, research, line management, project management, consulting, teaching and entrepreneurial endeavor [25].
B) Non-Engineering-Specific Work	General	9) Perform tasks and execute behaviors not specific to one's particular job.
		10) Manage one's personal work effectively to ensure that all aspects are properly coordinated, are progressing in a satisfactory manner and that problems that arise are identified and are dealt with appropriately.
		11) Support and help peers and facilitate group functioning by being a good model, keeping the group directed and reinforcing participation by other group members.
		12) Ensure that the resources and capacity to do good work are maintained, sustained, and, where necessary, developed further.
	Supervision, Leadership	13) Influence the performance of subordinates through interpersonal interaction and influence, modeling, goal-setting, coaching and providing reinforcement.
		14) Function as a supervisor in the 'line production' activities of the enterprise at the appropriate designated position in the supervision hierarchy.
	Management, Administration	15) Articulate goals for a unit/enterprise, organize people or resources to achieve these, monitor progress, help solve problems or overcome crises that stand in the way, control expenditures, represent the unit in dealing with other units or clients.
		16) Manage a project and ensure that it is completed successfully, on time and within budget.
C) Communication		17) Effectively exchange, transmit and express – verbally, graphically and in writing – knowledge and ideas to achieve set objectives when communicating with colleagues, peers, clients, superiors, subordinates, engineering audiences and the larger community.
D) Inter-personal Interactions		18) Interact effectively and positively with colleagues, clients, superiors, subordinates, engineering audiences and the larger community.
		19) Function effectively on multi-disciplinary teams through personal contributions and interactions with others that enhance their contributions.
E) Dispositions	See Table 3B	

APPENDIX 3B: A Taxonomy of Engineering Competency (Part 2)

1st Level Categories	2nd Level Categories	Ability, Disposition or Understanding (3rd Level Categories and 4th Level Detail)
E1) Personal Dispositions	General	20) Agreeable personal style, characteristics and self-management including maturity, initiative, enthusiasm, poise, appearance, values, goals, outlook and motivation.
		21) Disposed to consistent commitment to all job tasks, to working at a high level of intensity and the willingness to keep working under adverse circumstances and to expend extra effort when required.
		22) Disposed to taking responsibility within own limits of competence.
		23) Interest and knowledge in contemporary issues.
	Discipline	24) Disposed to maintaining personal disciplines and avoiding negative behaviors.
		25) Being critically aware of the need to act professionally and ethically.
		26) Being critically aware of the impact of engineering activity in a global/social setting.
E2) Adaptive Dispositions	Self-Development	27) Disposed to improving personal competencies in general.
		28) Understands nature/importance of effective learning skills and is able to apply them.
		29) Able to assess one's own performance effectively and accurately.
		30) Disposed to improving critical knowledge, skills and dispositions in an effort to sustain or improve one's reputation and advancement prospects.
	Life-long Learning	31) Understands the requirement to maintain continued competence.
		32) Able to and disposed to engage in independent and interdependent life-long learning through well developed learning skills.
	Change Management	33) Able to manage the impact of change effectively and flexibly, and to engage in new learning in coping with change.
E3) Advanced Dispositions (Extracted from the Competency Dictionary and Generalized Competency Model for "technical professionals". [20])	Achievement Orientation	34) Works to meet required standards but also creates own measures of excellence.
		35) Disposed to improve performance or improve morale, revenues or customer satisfaction by making specific changes in the system or in own work methods.
		36) Sets and acts to reach challenging goals for self and others*.
		37) Innovates.
	Impact and Influence	38) Gives presentations tailored to audience, calculates the impact of own actions/words and adapts presentations or discussion to appeal to the interest and level of others.
		39) Shows concern with professional reputation.
	Conceptual Thinking	40) Recognizes key actions and underlying problems by observing discrepancies, trends and inter-relationships, crucial differences, past discrepancies.
		41) Able to condense large amounts of information in a useful manner.
		42) Makes connections and patterns by pulling together ideas, issues and observations into a single concept and identifies key issues in complex situations.
	Analytical Thinking	43) Anticipates obstacles, breaks problem apart systematically, makes logical conclusions, sees consequences and implications.
	Initiative	44) Persists in problem solving when things do not go smoothly. Exceeds job description. Addresses problems before asked to. Creates opportunities.
	Self-Confidence	45) Expresses confidence in own judgement. Sees self as a causal agent, prime mover.
		46) Seeks challenges and independence, welcomes challenging assignments, seeks additional responsibility, states own position clearly and confidently.
	Interpersonal Understanding	47) Understands attitudes, interests, needs of others and is good at discerning the unspoken thoughts, concerns or feelings of others.
	Concern for Order	48) Seeks clarity of roles and information, checks quality of work/information, keeps records and an organised workplace, monitors data, projects and the work of others.
	Information Seeking	49) Asks questions, personally investigates, digs deeper, calls or contacts others, does research, uses own ongoing systems, involves others.
	Teamwork and Cooperation	50) Genuinely values others' input and expertise and is willing to learn from others.
		51) Empowers others, encourages those who perform well and gives them credit.
	Expertise	52) Applies technical knowledge to achieve additional impact, goes beyond simply answering a question and helps resolve others' technical problems.
		53) Exhibits active curiosity to discover new things, makes major efforts to acquire new skills and knowledge, and to maintain an extensive network of relevant contacts.
	Service Orientation	54) Seeks information about the real, underlying needs of the client, beyond those expressed initially, and matches these to available (or customised) products or services.

* Meaning there is a "50-50 chance of achieving the goal – it is a definite stretch, but not unrealistic or impossible" [20].

APPENDIX 4: The Components of Any Job

(Extracted from Campbell et al [18] except for item 9.)

	Component	Description
1	Job-specific tasks	Performance of the core substantive or technical tasks that is central to the job. Job-specific performance behaviors that distinguish the substantive content of one job from another.
2	Non-job-specific tasks	Performing tasks or executing performance behaviors which are not specific to one's particular job – eg, an engineer doing administration or sitting on the safety committee.
3	Written or oral communication	Proficiency in writing or speaking (independent of the correctness of the subject matter).
4	Demonstrating effort	Consistent commitment to all job tasks, to working at a high level of intensity and the willingness to keep working under adverse circumstances and to expend extra effort when required.
5	Maintaining personal discipline	The degree to which negative behaviors – such as alcohol abuse and absenteeism – are avoided.
6	Facilitating peer and team performance	Supporting and helping peers and facilitating group functioning by being a good model, keeping the group goal-directed, and reinforcing participation by other group members.
7	Supervision and leadership	Influencing the performance of subordinates through inter-personal interaction and influence, modeling, goal setting, coaching, and providing reinforcement. Similar to (6) but supervisory leadership involves different performance behaviors than peer leadership.
8	Management and administration	Involves processes additional to those in (7) such as articulating goals for a production unit or enterprise, organizing people or resources to achieve these, monitoring progress, helping to solve problems or overcome crises that stand in the way of goal accomplishment, controlling expenditures, obtaining additional resources and representing the unit in dealing with other units.
9	Adaptive performance (Not in Campbell's Model)	'Ease of learning new tasks, confidence in approaching new tasks, flexibility and capacity to cope with change,'[26] 'capacity to engage with new learning in coping with change,'[27], 'developing oneself' [19].

APPENDIX 5: The Components of Competency and Job Performance

(Extracted from Campbell et al [18] and Williams [19].)

Performance Determinants	Declarative Knowledge (*DK*)	Procedural Knowledge and Skill (*PKS*)	Motivation (*M*)
Sub Categories (of performance determinants)	Facts Principles Goals Self-knowledge	Cognitive skill Psychomotor skill Physical skill Self-management skill Interpersonal skill	Choices about whether to perform, the level of effort, the degree of persistence.
Antecedents or Predictors (of performance determinants)	(ability, personality, interests), (education, training, experience), (interactions between aptitude and prior learning experience*)	(ability, personality, interests), (education, training, practice, experience), (interactions between aptitude and prior learning experience*)	Depends on which motivational theory is used.
Performance Component, PC_i	$PC_i = f\,[\,DK \times PKS \times M)$ where i = 1,2, … k are performance components		
Overall Performance, *P*	Performance, *P*, is some combination or accumulation of performance components such as that suggested below. $P = \prod_i PC_i$ (This is illustrative only. It is not from Campbell.)		

* 'Prior learning experience' refers to prior education, training, experience.