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Deconstructing Engineering Education Programmes: The DEEP Project to reform the mechanical engineering curriculum

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The goal of the Deconstructing Engineering Education Programmes project is to revise the mechanical engineering undergraduate curriculum to make the discipline more able to attract and retain a diverse community of students. The project seeks to reduce and reorder the prerequisite structure linking courses to offer greater flexibility for students. This paper describes the methods used to study the prerequisites and the resulting proposed curriculum revision. The process involved dissecting each course into topics at roughly the level of a line in a syllabus, editing the list of topics, associating prerequisites and successors to each topic and then using a genetic algorithm to produce clusters of topics. The new curriculum, which consists of 12 clusters, each of which could be a full year course, is quite different from the traditional curriculum.

Keywords: engineering education; mechanical engineering

1. Introduction

This paper describes the results of a project known as deconstructing engineering education programmes (DEEP) to review and revise the standard undergraduate curriculum in mechanical engineering (ME) to make it more able to attract and retain a diverse community of students

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without sacrificing technical rigor. The methods developed are neither specific to a diversity-gains motivation nor to engineering. They could be applied to any degree programme that has a ladder structure.

The DEEP project team includes eight universities: California State University at Los Angeles; the University of Washington; Michigan State University; Howard University; Tuskegee University; Smith College; Stevens Institute of Technology; Johns Hopkins University. Individually and institutionally, the team is intentionally very broad. The institutions included two historically black colleges, an Hispanic-serving university, the first women's college in the US to offer a full engineering degree, three large public institutions, a medium-sized private school and a technological university. Team members are diverse – European and American women and men from a variety of race/ethnicities. For each institution, an ME professor became a team participant. Additionally, the project team included three experts on engineering education and diversity. All are included as authors.

It is important to find a means of broadening the attractiveness of engineering programmes. The world has become a more global marketplace and students who graduate in engineering must increasingly be comfortable with cultural diversity. This is far easier to achieve if the student body is diverse. Also, because the design function requires the development of a wide range of technical solutions to problems with constraints, it is useful to have engineers (and engineering students) with a diverse range of experiences. It is also important to broaden the access of under-represented groups and women to engineering because this generally ensures relatively high-paying professional opportunities. Additionally, there are concerns about how to increase the number of technically trained people, a problem that could be resolved if engineering education were more in demand by women and under-represented groups. Currently, the graduating classes in the US are between 18 and 21% female and under-represented groups are about two-thirds of this size (National Science Foundation 2009). Female graduates in engineering in the UK were 9.5% of the total in 2005/2006 (UK Resource Centre for Women in Science, Engineering and Technology 2006). Females in European countries have been typically around 20% of the total engineering student body (Daudt and Salgado 2006).

Recent efforts to attract and retain women and under-represented minorities have stalled and even reversed. For example, although women are 52% of the college age population in the US and are now the majority of students attending colleges and universities, between 1998 and 2007 women received between 18.5% and 20.5% of undergraduate engineering degrees, with the smallest percentage occurring in 2007. During that same time period the percentage of under-represented males (URM) earning bachelor degrees in engineering ranged from 11.3 to 12.3, with the highest fraction occurring in 2007. For URM in mechanical engineering, the key issue is retention. For 2006, 15.5% of the first year ME students in the US were URM but only 12.5% of second year students were URM and 11.6% of third year students. To put these percentages in context, in 2006, 32.9% of 18–24 year olds in the United States were under-represented minorities (National Science Foundation 2009). Further, among the large engineering disciplines, ME is now the least diverse in the US and much of Europe. For this reason, it was decided to focus on ME in this study.

There have been significant developments in ME curricula in the last decade including the introduction of mechatronics (Alciatore and Histand 2001, Lin 2001, Geddam 2003, Smaili and Chehade 2005) and the consolidation of design teaching (Lamancusa 2006) culminating in a capstone activity (Downey and Lucena 2003, Kadlowec *et al.* 2007) and more recently the connection to cornerstone programmes. However, ME has been slow to initiate curriculum reform compared to other engineering disciplines, such as bioengineering (Abu-Faraj 2008), civil engineering (Bernold 2005, Cheah *et al.* 2005, Galloway 2007, Nehdi and Rehan 2007), environmental engineering (Haghighi 2005) and materials engineering (Kim 1999, Flemings and Cahn 2000). In ME there is relatively little curriculum discussion despite the lack of alignment to the expectations and needs of the profession and industry (Sorby*et al.* 1999, Tryggvason and Apelian 2006, Sheppard *et al.* 2009) and its relative unattractiveness to students.

In Europe, the Bologna Declaration of 1999, signed by 29 countries, formalised an action plan to ensure greater convergence of the European educational systems (Confederation of EU Rectors' Conferences and the Association of European Universities 2000). Much of the ME curricular work since that time has focused on changes that respond to the accords (Fernandes Teixeira *et al.* 2007, Olabi 2007, Edan *et al.* 2008).

The DEEP project is premised on the assumption that the curriculum content and sequencing of a degree programme affects its ability to attract and retain students, i.e. that student choice is predicated in part upon the passion they have for the topics presented. Engineering is at a distinct disadvantage compared to most other college and university programmes because there are fewer secondary school courses that introduce engineering concepts and most courses for first year engineering students cater to those who have already chosen to pursue an engineering degree.

The hypothesis of DEEP is that ME programmes will be better able to attract and retain a diverse community if:

- greater linkages between fundamental concepts and applications and between technical and nontechnical subjects are developed;
- there is greater focus on the impact of engineering on the real-world human experience;
- the curriculum structure has shorter critical path lengths.

The traditional ME curriculum focuses on fundamental concepts that are reinforced using applications. Further, applications tend to focus on a few products, such as automobiles, aircraft and engines, which traditionally have greatest appeal to non-minority male students. A recent report by Sheppard *et al.* (2009) reviews the literature on teaching and learning in engineering and advocates a major shift in pedagogy to teaching applications and allowing fundamental concepts to emerge through their consideration. This transformation is already underway in Europe, where problem-based learning approaches in engineering are growing (Sahin 2010, Ahern 2010, Bell *et al.* 2010). It is clear that the current stock of applications is limited and does not have broad appeal to a diverse community. It is, for example, well-documented that women are more interested than their male peers in engineering products related to greening the environment or improving quality of life (Margolis and Fisher 2002, Fromm 2003). A more diverse set of applications should be available and better tied to fundamental concepts. Further, both concepts and applications should provide opportunities to relate the required technical content to non-technical material so that courses outside of science and engineering can be viewed as useful reinforcements of understanding rather than simply a necessity of a degree programme.

The DEEP project has developed lesson plans for topical applications with broad appeal (Campbell *et al.* 2008, Patterson *et al.* 2009) and three sets of lesson plans are currently available (Patterson 2008, 2009, 2010). Piloting some of the applications in existing courses has produced results generally in line with existing research literature (Campbell *et al.* 2008). Compared to almost identical courses, either without applications or with traditional applications, significant changes in student and instructor perceptions of the class were found. Almost all students felt hands-on laboratory and classroom-based applications increased their interest in ME and that increased interest was very highly correlated with their ratings of their learning. Students also rated their learning of concepts covered by the applications higher than did other students in the same courses taught by the same instructor without those applications. There were no differences in the groups' ratings of their learning of other concepts. Similarly, faculty teaching courses with new applications reacted positively.

Engineering programmes have arguably the longest critical path lengths in the curriculum. For instance, it is normal to require a course on dynamics prior to a course on system dynamics and control. Dynamics, in turn, requires kinematics and mechanics of solids, which lists introduction to materials as a prerequisite, and so on. Hence, students cannot make a decision to enter an ME programme late unless they are willing to stay beyond the normal time for graduation. Further, a student who fails a single course may find himself or herself needing to stay longer than anticipated because not all courses may be offered every term. Thus, most engineering programmes can be characterised as having a single entry point and a large number of exit points (although only one is considered successful). While increasing degree programme flexibility does not directly make a programme more attractive to under-represented student groups, it can have an impact by facilitating a decision to switch into engineering after arriving at university. This is particularly important as students from groups under-represented in engineering are less likely to be advised to consider an engineering degree programme.

2. Methods

Testing DEEP's hypothesis requires addressing the educational equivalent of a mathematically stiff system. It is necessary to consider the entire curriculum if one is to reduce critical path lengths. These critical paths are established by prerequisite relationships, where a particular topic is thought to be understandable only if one holds prior specific knowledge of related topics. Defining and examining these topical relationships requires a level of detail far finer than course titles offer. Hence, the problem involves consideration of a large-scale system at a fine detail level.

DEEP involved three sequential steps, described below, and a fourth independent task of developing new applications (previously described). The three sequential tasks were intended to produce a full, new curriculum including all of the required topics (where topic here refers to a concept at roughly the granularity of a line in a syllabus for a course), linked to the prerequisite/successor structure and aimed at minimising critical path lengths. The approach did not presume that existing courses or curriculum structures needed to be preserved. Since this is a reordering of the topics in the curriculum rather than a change of content, the results should meet accreditation requirements.

The sequence for curriculum development was: define the topics required for a ME undergraduate degree; associate with each topic prerequisites for understanding, applications to which they might relate, number of hours of class time to dedicate to the topic and non-technical material that could be brought into the conversation; use the topic relationships to generate a curriculum map from start to finish with topic clusters that could constitute courses.

2.1. *Defining the topics*

The first step was to define the technical topics to be included by dissecting the syllabi for required courses for an ME undergraduate degree in the eight partnering institutions represented in the DEEP team and MIT (whose syllabi are available on the web).

Syllabi for each of the technical courses required for an ME degree were obtained and a set of topics covered in each course generated from the syllabi. A single alphabetised list of 2149 topics was generated.

Next the topics list was edited to remove duplicates. The topics list at this point posed a number of challenges. First, the definitions of some topics were not clear so definitions were sought prior to determining whether they were unique. For example, the topic 'anti-differentiation' once defined, was a duplicate of 'integration'. Second, it was necessary to determine the appropriate level of granularity in the topics list. For instance, most ME curricula offer a course on thermodynamics so the syllabi from these courses would include topics in thermodynamics. However, a capstone design course might also list thermodynamics as a topic. The question is whether 'thermodynamics' should be a topic, given that subtopics of it are already included. It was decided to eliminate the large topic headings. Third, it was determined how similar topics must be in order to be collapsed into a single topic. For instance, 'normal modes' and 'modal analysis' are not identical, but it was decided that they were close enough to combine into a single topic.

Next, the list was edited again to eliminate topics that did not need to be required for future ME students, add topics that were necessary in the future but not currently in the curriculum and eliminate topics that should be covered prior to post secondary education. This produced a final list of 833 topics.

The data were examined to answer the question, what is the extent of similarity in the nine ME programmes spanned by the research (Jarosz and Busch-Vishniac 2006). Of the nearly 1000 topics, only 70 were present in the majority of the universities, suggesting that programmes are not very similar. The small number of overlapping topics suggests that the body of knowledge universally accepted as necessary for a ME undergraduate degree is able to be fitted into a four-year programme.

2.2. *Defining Inter-topic relationships*

The next step was to define the relationships between the topics. Three pieces of information were sought for each topic: topics that are prerequisites for understanding, successor topics leading immediately from this topic and the minimum number of hours necessary to teach the topic. The predecessor/successor relationships defined the curriculum map while the class time needed for each topic made it possible to assemble clusters within the map, which define courses of appropriate length.

The typical engineering curriculum lists prerequisite and co-requisite relationships between courses. The reasons for these relationships include a natural progression of technical material, a desire for efficient use of resources and a sense that certain concepts require greater maturity for understanding. DEEP accepted only prerequisites for understanding as appropriate grounds for defining prerequisite/successor relationships.

The team defined prerequisite/successor relationships by brute force. Team members went through the topic list topic-by-topic and noted, for each, immediate prerequisite topics and immediate successor topics found elsewhere in the list. Results were combined into a single set of prerequisite and successor relationships by including all suggested predecessor and successor topics.

Although it was not appreciated at the time, work was duplicated and contradictions were potentially introduced by listing both prerequisites and successors. Logically, if A is a prerequisite for B, then B is a successor of A. In order to avoid introducing logical inconsistencies, the team worked solely with the prerequisite relationships to generate the curriculum map.

Defining inter-topic relationships was straightforward, but the relationship database produced caused a number of problems. The most difficult problem to overcome was the unintentional creation of loops – i.e. A is a prerequisite of B, and B is a prerequisite of A. The initial relationship database had a large number of loops, some of which were small (two-topic loops as in the example) and some of which were large (20 or more topics). The loops were caused by variations in deciding whether an application should follow (succeed) a fundamental concept or motivate (precede) it and the tendency to link topics that were related but might not necessarily be sequential.

The relationship database issues were resolved by using a single person to review the relationships, eliminating those that seemed illogical or that linked similar topics that did not have a true prerequisite/successor relationship. The bias of this single reviewer is unlikely to have had a significant impact, as the fundamental concepts and application topics were closely linked and thus likely to be clustered together in the curriculum map in any event.

2.3. *Generating the curriculum map*

The single most difficult step in this work was the generation of a map of the entire required curriculum. This was done using a genetic algorithm approach applied to the inter-topic relationship database.

A major step in the restructuring of the ME undergraduate curriculum was to put the topics into a best set of clusters. Best was defined as having the clusters populated with topics with numerous intra-cluster prerequisite relationships and minimal inter-cluster (cross-cluster) links. The reduction of cross-cluster links was key to increasing the flexibility in cluster timing in the curriculum.

While defining clusters with minimal links was the major goal, cluster size, in terms of instructional hours, was also a concern. Cluster instructional hours (the sum of the number of hours to teach each topic in a cluster) had to be relatively consistent across clusters and to be a reasonable fit to the current academic semester/quarter system. An optimisation process involving genetic algorithms was used to develop clusters, curricular maps of topics, which could then be turned into courses.

A genetic algorithm is a computer simulation in which a population of abstract representations of candidate solutions (members) to an optimisation problem evolves toward better solutions.[1] The process begins by selecting a population size, say 100 members. The 100 members that are all possible solutions are generated. In this optimisation, a member was defined when all of its topics were assigned to clusters. Each member of the population was scored and ranked by the number of cross-cluster links, with fewer links being better. If a topic was an orphan, having neither prerequisites nor successors, it was dropped. (Altogether, 30 such topics were dropped – each arguably another phrasing for a retained topic.)

Once the members were ranked, a subset of the worst solutions was discarded. The remaining members with the lowest number of links were kept and used to generate new solutions based on:

- mutation: taking one member of the population and generating a new member by taking some of the topics, cloning them and putting them in different clusters;
- breeding: taking two members of the retained population, selecting an arbitrary spot to break them and then recombining the pieces across the two members to form a new member.

The new and retained old members were then ranked, the worst solutions discarded and the process repeated tens of thousands of times.

There were several methods used to assign topics to a starting cluster, including randomly assigning topics to a cluster and taking terminal nodes, nodes with no successors and walking the dependency chain backwards. The team started using terminal nodes, then did random clustering and ended up doing a combination of both.

Several different limits for total cluster instructional hours were also examined. For the results presented here, 84 hours was selected as a target corresponding to three hours per week multiplied by the 28 weeks in a typical school year. Each cluster would thus correspond to a full-year course.

3. Results

3.1. *Curriculum structure into clusters*

After hundreds of runs and tens of thousands of generations of solution sets, 17 clusters were generated. Running the optimisation process reduced the number of cross-cluster links from 988 to 345; 159 of these involved a topic in one cluster being a prerequisite to a topic in another cluster and 186 involved a topic in one cluster being a successor to a topic in another cluster.

Five of the clusters generated in this solution were very small, including only 12 unique topics totally. The 12 topics were assigned to the larger 12 clusters based on 'best fit'. This reduced the number of cross-cluster dependencies to 334 (158 prerequisite and 176 successor cross-topic links). In Table 1 the 12 clusters are labelled A to L and each is described by the numbers of topics and 'lecture' hours it contains. Also provided is the length (number of topics) in the longest prerequisite chain in the cluster, the number of neophyte topics and the number of terminal topics.

The 12 clusters in the curriculum map cover all 833 topics, with cluster instructional times ranging from 52 to 115 hours and a mean cluster length of 91 hours. Durations for eight of the clusters ranged from 82 to 96 hours with a median of 93 hours. While the cluster mean hours exceeds the target of 84, the times per topic are not precise, so the addition of topic hours in a cluster produces only a rough approximation. If the new curriculum were required to fit into the traditional course timetable, the low hour clusters might correspond to roughly four hours per week for one semester (52–65 hours) and the high hour clusters to a full year course, meeting either three or four hours per week. (A full list of the clusters with the cluster instructional hours and the topics included in each cluster may be found at digitalcommons.mcmaster.ca/mech_eng_coll/.)

The curriculum structure traditionally is shown via a map of courses. Each row shows a term with three to five courses and the number of rows indicates the number of terms needed to fulfil the programme. Typically, there are prerequisite links from one term's courses to the next, creating a long set of prerequisites that must be followed from the first to the last term in the programme. The solution that was found still links the major clusters (by linking some topics in the clusters) in spite of attempts to decouple the clusters as much as possible. What this shows is that the topics required for a typical ME degree programme naturally evolve into prerequisite chains, making it very difficult to decouple topics into independent clusters. One solution to this problem, presumably the one currently employed, is to repeat the coverage of certain topics in multiple courses. This is referred to as cloning topics and the clusters include 47 cloned topics; 44 of these were included in two clusters and three topics ('complex numbers', 'electric current' and 'sum and average of random samples') were included in three clusters. Cloning topics is equivalent to breaking a cross-cluster link and replacing it by repeating a topic in multiple clusters. Where significant numbers of repeated topics from one cluster would need to be placed in another cluster, this suggests the two clusters should be related instead by a prerequisite relationship.

Table 2 is a matrix of cross-cluster dependencies. Each row shows the number of prerequisite relationships from topics in one cluster to each of the others. Each column shows the complementary relationship – the number of cross-cluster prerequisite links for topics in a given cluster.

Table 1. Cluster characteristics.

Cluster	Number of topics	Number of hours	Length of longest prerequisite chain (in topics)	Number of neophyte topics	Number of terminal topics
A	98	96.25	11	8	49
B	69	84	12	10	19
C	91	115	12	6	41
D	65	85	5	9	24
E	72	105	6	3	39
F	75	82.25	6	5	31
G	41	52.5	3	12	17
H	75	95	17	3	25
I	76	93.75	8	8	42
J	74	107	9	8	31
K	79	85	7	16	33
L	67	93.5	9	11	27

Table 2. Cross-cluster linkages.

Cluster	A	B	C	D	E	F	G	H	I	J	K	L	Successors
A	X	3	3	2	1	1	0	11	2	3	2	0	28
B	12	X	2	2	3	2	0	5	5	2	0	4	37
C	5	2	X	11	14	9	3	11	3	0	3	8	69
D	0	0	3	X	2	0	0	1	3	0	0	2	11
E	7	1	7	2	X	5	1	3	5	5	2	2	40
F	5	2	5	1	5	X	0	0	8	4	0	1	31
G	0	0	2	2	0	0	X	0	5	0	1	1	11
H	15	3	13	3	5	2	0	X	0	0	0	3	44
I	1	1	3	0	1	2	0	1	X	2	1	2	14
J	1	1	0	4	6	0	0	1	0	X	1	1	15
K	0	0	1	0	4	0	0	2	1	5	X	0	13
L	1	1	4	1	0	2	2	1	3	2	4	X	21
Prereqs	47	14	43	28	41	23	6	36	35	23	14	24	

Prereqs = prerequisites.

Table 2 shows how clusters of topics depend upon one another. This determines the order in which students might be exposed to the clusters/courses. For example, consider clusters G–K by focusing on the square subportion of Table 2 near the lower right corner. Cluster G has a total of six prerequisites for other members of the cluster G–K subset; cluster H, 0; cluster I, four; cluster J, two; cluster K, seven. Similarly, cluster G has 0 successors in the cluster G–K subset; cluster H, four; cluster I, six; cluster J, seven; cluster K, three. This means that clusters G–K are largely independent of one another so there is greater flexibility as to where they can be placed in the curriculum. Complete decoupling of the elements of this particular subset of clusters would require cloning a relatively small number of topics. By contrast, two clusters, A and C, show a significant number of cross-cluster links.

It is useful to consider Table 2 together with a choice of a maximum number of cross-cluster links. By setting a maximum for the number of permissible cross-cluster links, and thus cloned topics, one sees a cluster prerequisite structure emerge. For instance, if it is posited that any two clusters related by 10 or more prerequisites should result in the clusters having a prerequisite relationship then: A precedes H, B precedes A, H precedes A, C precedes D, C precedes E, C precedes H and H precedes C. This structure suggests that clusters A, C and H are true co-requisites as the cross-cluster links say that they must precede and follow one another. Further, cluster B should come before A, C and H. Clusters E and F should come later. All other cluster positions in the sequence would remain flexible as long as up to nine topics were cloned into any cluster to decouple it from any other.

Repeating this exercise with the cross-cluster links maximum set to eight adds one more relationship between clusters: C precedes F. Reducing the maximum allowable cross-cluster links to seven adds two new cluster relationships: C precedes L and F precedes I. Thus, at this maximum four levels of clusters have been hit: the earliest includes B, the next level has A, C and H, the next has F and the last has I. Clusters D, E and L each occur in the third or fourth levels. Clusters G, J and K remain unspecified and could thus appear at any level.

One could continue this process with the maximum cross-cluster links stepped progressively lower. As the maximum is lowered, the cluster sequence becomes more specified, but it would be illogical to produce a different but no less rigid curriculum than the existing one. Further, as the number of cross-cluster links permitted to define cluster prerequisites continues to decrease, there is a growing number of co-requisite clusters that clump with clusters A, C and H. At a maximum of six cross-cluster links, cluster E becomes co-requisite with A, C and H. At a maximum of four cross-cluster links, J and F are additional co-requisites with A, C and H.

Based on this analysis, it makes sense to set the maximum cross-cluster links to seven or more. For someone entering ME as a first year student, the choice of seven provides the scheduling flexibility to create a four-year degree programme with time for some non-engineering material each year. In this scenario, students would see clusters K, J and B in the first year; A, C and H in the second year; D, E and F in the third year and G, I and L in the fourth year. However, choosing seven cross-cluster links as the maximum also means that a student cannot enter the ME programme in the second year and complete the degree programme without a fifth year at the academic institution. By going to eight cross-cluster links as the maximum, one could use the four-year, three cluster per year curriculum as the norm, but a student entering a year late would have the flexibility needed to complete the degree programme in three engineering-intensive years rather than four.

3.2. *Cluster characterisation*

The most important result of this work is that the clusters produced by minimising cross-cluster links do not produce traditional courses. The clusters tend to mix the topics from technical sub disciplines.

Table 3 shows a high-level description of the topics in the various clusters, using the terminology of today's curriculum structure. What drives the mixture of topics in any cluster is common prerequisites. Further, fundamental topics often listed as prerequisites, such as mathematical concepts, tend to be placed immediately prior to the first topic that requires their knowledge, creating a sort of 'just-in-time' learning scenario and linking topics not normally put together in the traditional curriculum. As an example, cluster B links (with intervening topics) 'work and energy' to 'curvilinear kinematics' and to the 'first law of thermodynamics'. Thus, in this cluster, kinematics and thermodynamics are seen to have something in common. This mixing of subdisciplines presents a huge change from the current curriculum. This result also confirms the

Table 3. The distribution of traditional course topics into clusters.

	A	B	C	D	E	F	G	H	I	J	K	L
Mathematics*	X		X	X	X	X	X					X
Physics*					X							
Chemistry*				X	X	X						
Scientific computing		X						X			X	X
Statics								X	X			
Electrical engineering concepts		X		X		X	X		X		X	
Prob./Stats.												X
Graphics		X		X					X	X		
Material Science	X	X		X	X	X				X		
Mechanics of solids				X	X				X			X
Dynamics		X	X		X				X			
Thermodynamics	X	X										
Heat transfer	X											
Fluid mechanics	X		X					X	X			X
Manufacturing							X			X		
Machine design		X			X		X					
System dynamics	X		X			X			X		X	
Design		X						X		X		X
Economics											X	

*Traditional courses generally are not taught within a Mechanical Engineering Department. Further, there are multiple mathematics courses that are here lumped into a single row.

starting premise, that it would not be possible to reduce critical path lengths without considering all topics in the curriculum simultaneously.

The massive rearrangement of topics in this optimised curriculum map poses interesting challenges. It suggests that it might be very difficult to pilot just one or two of the clusters to study faculty and student reaction since one could not easily identify a course to replace with the pilot course. Further, it would be difficult to find appropriate text books for these new courses. Also, there is a significant question of whether faculty members would be willing to develop and teach the curricular material required by the new clusters. This is a critical question for the future. To develop the new courses would require faculty to teach beyond their identified subdiscipline. While this might lead to a cultural transformation of mechanical engineering, it could also meet with stiff resistance.

The new courses also introduce an interesting set of questions. Does student learning of concepts improve with topics rearranged to reflect common prerequisites? The current curriculum structure tends to create silos of knowledge in established subdisciplines. Would this new structure eliminate silos and encourage students to understand the similarities in topics? If not, then is the new curriculum a sufficient improvement over the current curriculum to justify the enormous logistical challenge of developing an entirely new degree programme set of courses?

Some of the clusters are long and thin while others are short and thick. Long clusters can have a sequence of as many as 12 levels of topics from the beginning of the cluster to its end. The cluster length is driven by the topic prerequisite structure, with long clusters indicating that the cluster includes one or more long prerequisite chain. Such a lengthy chain of topics does not pose the same sort of problem as a long chain of courses and reflects the success of the optimisation in taking the longest chains of topics and embedding them into a single cluster. This transfers the problem of critical paths between courses to a critical path within a single course.

One can conceive of a cluster as a series of topic sequence chains that tend to intersect by having some topic or topics in common between chains. In a traditional class, topics tend to build linearly with each new topic relying on understanding of the earlier material. In the clusters, one would achieve this by teaching the topics along a given prerequisite sequence, then repeatedly returning to a branch-point topic to continue along a different prerequisite sequence until topics in the cluster were exhausted. This would produce the necessary repetition required in most learning theories.

Cluster B shown in Figure 1 is a short, thin cluster. The lines connecting topics show prerequisites within the cluster. The cross-cluster prerequisites have been suppressed. Cluster B has 12 levels of topics from left to right. The thickness of any level varies from two to 14 items, with each level representing 2 to 20.5 hours of instruction. In this cluster, there are 10 topics, which are neophytes appearing on levels 1–8. Because they do not have prerequisites listed, they occur at the level prior to the first topic that lists them as a prerequisite.

Cluster B also has 19 terminal node topics and these appear in levels 2–12. Terminal node topics are the most sophisticated topics in the undergraduate curriculum. However, a significant number of the terminal node topics occur in early levels in a cluster, either because a successor relationship has been missed (the team's error) or because they are the culmination of a relatively short sequence of topics. Because they represent endpoints, it is the terminal node topics that are the most reasonable to consider when seeking to reduce the required content topics in the curriculum. The question is: why is this topic required if it will not be used after this exposure?

By contrast, Figure 2 shows a short thick cluster, cluster F, which has six levels varying from two to 25 topics and from 1.5 to 28.5 hours of instruction. Cluster F has five neophyte topics, all of which are in level 1 except for 'electric current', which is level 3. There are 31 terminal nodes appearing in levels 2–6.

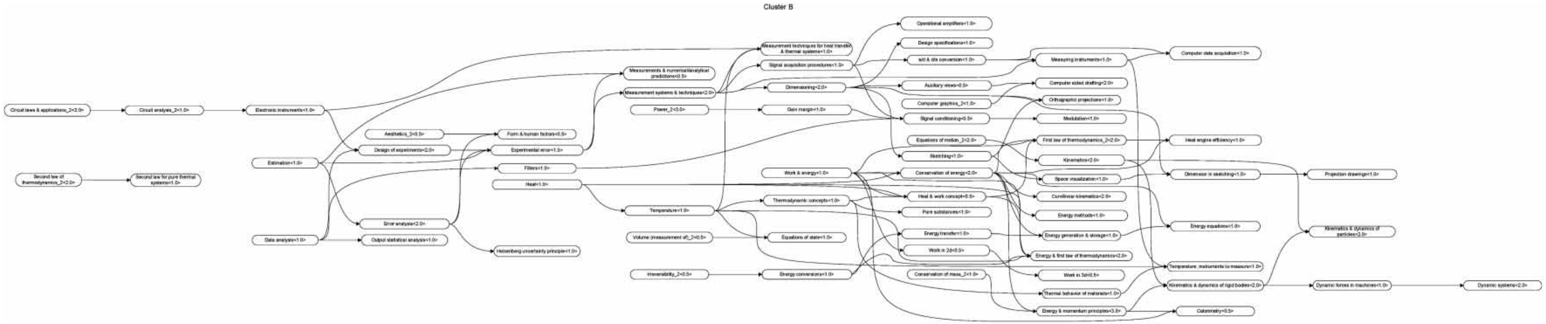

Figure 1. Topics in cluster B. Connections show prerequisites between topics in this cluster.

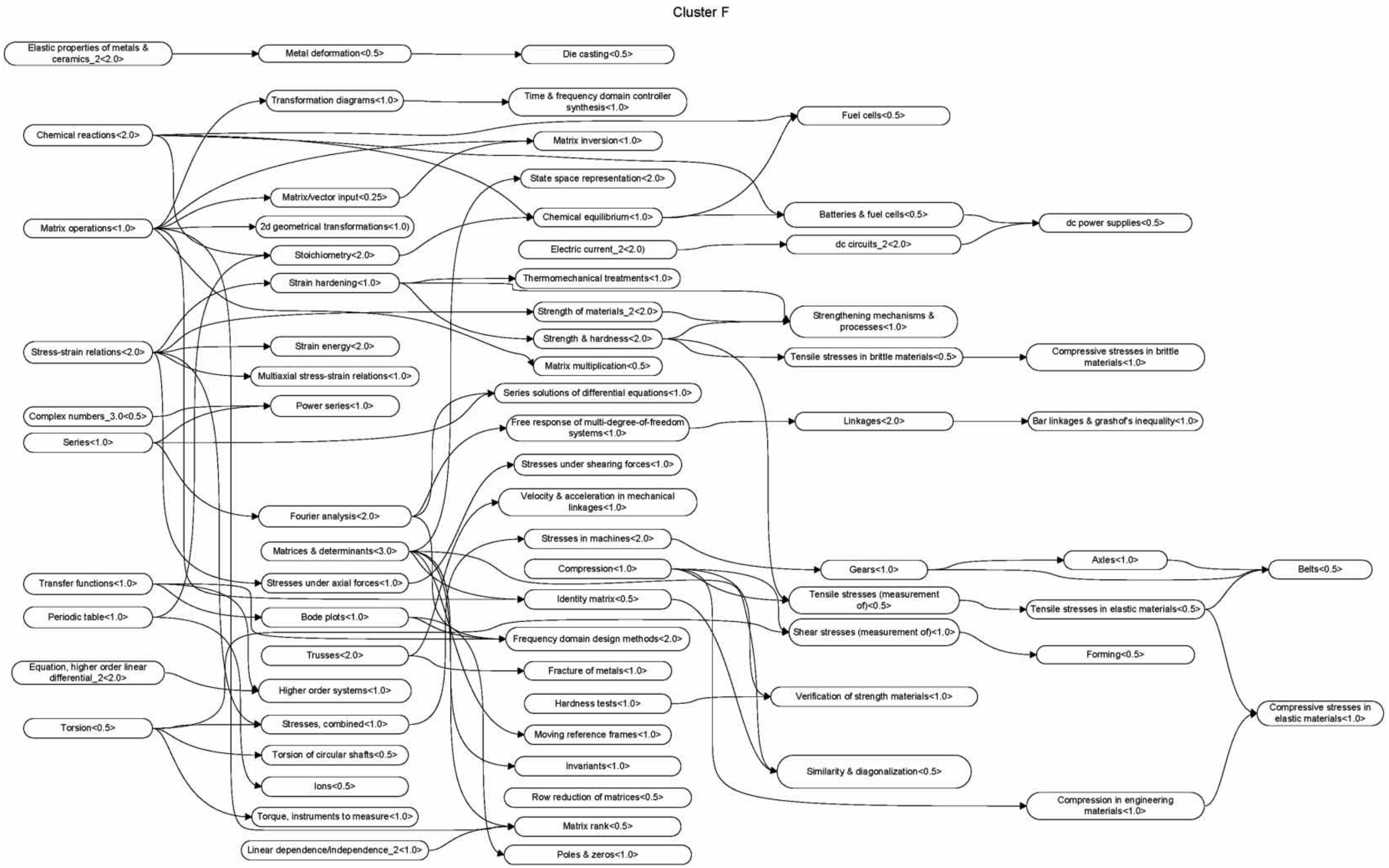

Figure 2. Topics in cluster F and prerequisite relationships for these topics.

4. Discussion

These 12 clusters are an example of an alternative but not necessarily ideal structure for the undergraduate ME degree. There remain some redundancies and there are still a number of dependencies across clusters. It is, however, a viable example of how ME could be restructured. It is important to note that these clusters reflect only the technical component of the ME degree programme. Non-technical components, such as communication skills, have not been addressed and would presumably add to the curriculum presented here.

The methods presented here for ME could be applied more broadly to virtually any curriculum sequence. It would be particularly useful for other disciplines, in technical fields, where there tends to be a long required course sequence that might be made more flexible through this approach.

There are obvious next steps to the work presented here, but none is trivial to pursue. It would be ideal to develop and pilot one or more of the clusters, including applications with broad appeal. This would require development of the course, including the supporting materials, and negotiations as to what course or courses it might replace. Only through piloting can one assess whether the new courses are effective for students and faculty members. In particular, long-term piloting is essential to determining whether the new course structure and embedded applications achieve the goal of enabling a more diverse student body.

Because the new curriculum is a huge change from that currently in use, it would be very interesting to determine which approach produces better student learning and increases the attractiveness of the field. To test this, one would need to pilot at least portions of clusters that are identified as linking items not normally linked in traditional courses.

Note

1. Adapted from Wikipedia, the free encyclopaedia. A more comprehensive introduction to and explanation of genetic algorithms can be found at http://obitko.com/tutorials/genetic-algorithms/

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