Office for
Learning & Teaching
supporting · rewarding · innovating

Engineering Thresholds: an Approach to Curriculum Renewal

Integrated Engineering Foundation
Threshold Concept Inventory 2012

The University of Western Australia

Project Team: Caroline Baillie (Project Lead), Cara MacNish, Angus Tavner, James Trevelyan, Gordon Royle, Dianne Hesterman, Jeremy Leggoe, Andrew Guzzomi, Carolyn Oldham, Matt Hardin, Jasmine Henry, Nathan Scott, James Doherty

Author, Project Manager, Researcher: Sally Male

<ecm.uwa.edu.au/engineeringthresholds>

The University of Western Australia
Achieve International Excellence

Support for the production of this publication has been provided by the Australian Government Office for Learning and Teaching. The views expressed in this publication do not necessarily reflect the views of the Australian Government Office for Learning and Teaching. Further acknowledgements are made below.

2012

ISBN 978-1-922218-35-3 PRINT
ISBN 978-1-922218-36-0 PDF

Acknowledgements

This inventory was written as part of the research project 'Engineering thresholds: an approach to curriculum renewal'. The project evaluator, John Bowden, provided valuable formative evaluation during the project. The reference group members are gratefully acknowledged for their advice: Erik (Jan) Meyer (Consultant), Denise Chalmers, Roger Hadgraft, Robin King, Euan Lindsay, Sally Sandover, Charlotte Tay.

Participants include many who participated anonymously and the following (in alphabetical order): Paul Abbott, Kazem Abhary, Reem Al-Mahmood, Tim Aubrey, Mahfuz Aziz, John Bamberg, George Banky, Iouri Belski, Susan Bertei, Aaron Blicblau, Robert Bucat, Gavin Buskes, David Callaghan, Antonio Cantoni, Hui Tong Chua, Gregory Crebbin, Brenton Dansie, James Deeks, Alice Devillers, Llana Dzananovic, Kate Edgeloe, Cameron Esslemont, Ciara Farris, Chris Fraser, Clive Ferguson, Tyrone Fernando, Andrew Fitch, Darryl Fitzgerald, Kate Fitzgerald, Chris Ford, Andy Fourie, Gillian Gan, M. Garrett, Rosalie Goldsmith, Jane Goodyer, Greg Griffin, Andrew Guzzomi, Ali Habibi, Roger Hadgraft, William P. Hall, D.J. Hargreaves, Dianne Hesterman, Des Hill, Julienne Holt, Ian Hooper, Yuxia Hu, David Huang, Rob Jarman, Dhammika Jayalath, Randika Anjalie Jayasinghe, David Jenner, Chris Jones, Matthew Joordens, Jurij Karlovsek, Alan Kerr, Blake Klyen, Yarra Korczynskyj, Erin Langworthy, Jeremy Leggoe, Nicholas Ling, Brett Linke, Wei Liu, Bill McBride, Chris McDonald, Pat McMillan, Cara MacNish, Llewellyn Mann, Alex Mazzolini, Mauro Mello Jr, Wendy Miller, Euan Nichol, Carolyn Oldham, Jad Osseiran, Gia Parish, Lyndal Parker, Christopher Parkin, Roshun Paurobally, Robert Prast, Aaron Pytte, Kathleen Quinlan, Felicity Reynolds, Robert Ross, Christopher Rowles, Geoffrey G. Roy, Tom Rufford, Stephen Russell, Sally Sandover, Shivvaan Sathasilvam, Johannes Scholz, Tim Sercombe, Brice Shen, Paul Slatter, Liz Smith, Laurence Spencer, Ibrahim Sultan, Geoff Sutherland, Peter Sutton, Siong Tang, Angus Tavner, Roger Thompson, Mark Tingay, Roberto Togneri, Anh Tran, James Trevelyan, Ray Volker, Anya Waite, Phillip White, Stephen Whitely, Keith Willey, Adam Wittek, Lin Ye, Marjan Zadnik. Three troublesome features and a suggestion for identified threshold concepts were noted during several valuable conversations with Donald Richards.

Members of The University of Western Australia (UWA) Engineering Science Working Party, Foundation Team, are gratefully acknowledged for their contributions to identifying and negotiating threshold concepts in meetings, workshops, and discussions.

David Parkinson and Julian O'Shea interviewed first-year students. David Parkinson is acknowledged for his valuable analysis of interview and extensive survey data.

Support for this research has been provided by the Australian Government Office for Learning and Teaching (OLT). The regional workshops were further supported by the Australian Council of Engineering Deans (ACED).

The following people are gratefully acknowledged for providing venues and support for regional workshops held at their universities: Elizabeth Smith and Martin Shanahan at University of South Australia; Roger Hadgraft at the University of Melbourne; Tim Aubrey and Rosa Tay at University of Technology Sydney; Graham Schaffer, Lisa Deacon, Peter Sutton, Lou Wheeler, and Kamilla Wells of the University of Queensland; and Friso De Boer and Asma Khan of Charles Darwin University.

Gerard Rowe and Elizabeth Godfrey are thanked for initiating and organising the New Zealand workshop at the University of Auckland.

Jens Kabo and Tom Adawi, of Chalmers University in Sweden, are thanked for discussing methodology with the project team and co-facilitating a workshop at UWA. Jonathan Scott from the University of Waikato in New Zealand is gratefully acknowledged for generously spending a day at UWA sharing his experiences.

The project received a UWA Research Collaboration Award for invaluable collaboration with researchers in England: Kathleen Quinlan, Chris Trevitt and Johnny Fill of the University of Oxford, and Artemis Stamboulis and Zahira Jaffer of the University of Birmingham.

The author is deeply grateful to Rebecca Benson for editing the inventory. It was a pleasure working with Rebecca.

The author sincerely thanks the following members of the project team for maintaining enthusiasm and engagement throughout this research, and stepping up at critical times by helping to plan and co-facilitate workshops, check transcripts and analysis when requested, and frequently linking the research with teaching experiences: Andrew Guzzomi, Dianne Hesterman, Jeremy Leggoe, Cara MacNish, Gordon Royle, Angus Tavner, and James Trevelyan. The author acknowledges Dianne Hesterman, Jeremy Leggoe, and Andrew Guzzomi for generously responding to her request to contribute their skills, expertise, and time by joining the project team after the grant was awarded.

Preamble

This inventory is an outcome of the project 'Engineering thresholds: an approach to curriculum development'. The inventory was developed iteratively during research described in the *Guide for Engineering Educators on Curriculum Renewal using Threshold Concepts,* also prepared as part of the project. Project information is available at <ecm.uwa.edu.au/engineeringthresholds>.

The threshold concepts have been identified at The University of Western Australia (UWA) and negotiated nationally and internationally. Listed are threshold concepts in an integrated engineering foundation program. 'Integrated' refers to integration of all engineering disciplines. 'Foundation' refers to the first year of a Bachelor of Engineering, or first and second year of an Engineering Science major.

This threshold concept inventory should not be confused with key concept inventories. Not all key concepts are threshold concepts, as they are not all transformative for students. Conversely, using a threshold concept framework, researchers can identify threshold concepts that are not in previous concept inventories because, for example, they are tacit to experts.

Many of the identified items are 'capabilities', rather than concepts. The research was originally positioned in the framework of threshold concept theory (Male & Baillie, 2011a; Meyer & Land, 2003). However, during the research, items that were capabilities rather than concepts were also identified. Instead of dismissing these, the researchers broadened the scope to include threshold capabilities (Male & Baillie, 2011b). At a similar time, Baillie, Bowden and Meyer (2012) developed 'threshold capability theory'.

The inventory has a nested structure and threshold concepts are interrelated. The nested structure indicates how understanding one threshold concept can depend on understanding another threshold concept, and also how one threshold concept can be manifested in various examples. For example, the items 'value of learning' and 'there are many different ways to learn and sources of information' are listed under 'self-driven learning', because both items are required for self-driven learning.

Each item is identified for readers with engineering backgrounds. Items also include any details about how the concept is 'transformative', how it is 'troublesome', and 'suggestions' for how engineering educators might help students understand the threshold concept. Where quotations from participants are included, they are identified as comments made by either 'student' or 'academic'.

Items appear in the inventory because participant responses—and in some cases cited literature—indicated that students can experience these items as thresholds (Male, Guzzomi, & Baillie, 2012). Troublesome features of a concept can arise from the nature of the concept, the curriculum including pedagogy and other aspects such as faculty culture, as well as students' backgrounds, including their previous education and other life experiences.

The inventory is in three sections: 'Learning to become an engineer', 'Thinking and understanding like an engineer', and 'Shaping the world as an engineer'. The first section includes items that form a backdrop to the motivation and capability needed for developing the understanding and capability identified in the second section. Items in the third section are required to mobilise the items in the first and second sections, in order to make a positive difference to the world as an engineer through engineering practice, including design and problem-solving.

This threshold concept inventory could be used by engineering educators to help them to focus teaching, learning, and assessment on concepts that are most critical to students' progress and most troublesome for students. They could use this inventory to help refine a foundation program, or a single unit or topic within a foundation program. Alternatively, they could use this inventory as an initial framework for research to identify threshold concepts and develop curriculum enhancements at higher levels of engineering programs. Approaches are described in the *Guide for Engineering Educators on Curriculum Renewal using Threshold Concepts*.

Table of Contents

HOW TO USE THE INVENTORY

This threshold concept inventory is designed as a tool for educators, to complement the *Guide for Engineering Educators on Curriculum Renewal using Threshold Concepts*. This inventory could be used by engineering educators to help focus teaching, learning, and assessment on concepts that are most critical to students' progress and most troublesome for students.

Educators could also use this inventory to help refine a foundation program, or a single unit or topic within a foundation program. Alternatively, they could use this inventory as an initial framework for research to identify threshold concepts and develop curriculum enhancements at higher levels of engineering programs. Such approaches are described in the *Guide for Engineering Educators on Curriculum Renewal using Threshold Concepts*.

SECTION HEADINGS

The inventory is presented in three sections: Section 1: 'Learning to become an engineer', Section 2: 'Thinking and understanding like an engineer', and Section 3: 'Shaping the world as an engineer'. The different sections are colour-coded and presented in Figure 1 below.

Section 1 includes items that form a backdrop to the motivation and capability needed for developing the understanding and capability that is identified in Section 2. Items in Section 3 are required in order to mobilise the items in both Sections 1 and 2, to make a positive difference to the world as an engineer through engineering practice, including design and problem-solving.

1. Threshold Concept Headings

a. Threshold Concept Headings (nested)

Each threshold concept is presented within its relevant section and is part of a nested structure, which indicates how understanding one threshold concept can depend on understanding another threshold concept, and also how one threshold concept can be manifested in various examples. For example, in Figure 1 below, the items 'value of learning' and 'there are many different ways to learn and sources of information', are listed under the threshold concept of 'self-driven learning', because both items are required for self-driven learning.

Transformative because:

- Under this heading, explanation is provided about what makes a particular threshold concept 'transformative'—in other words, how the concept opens new ways of thinking and understanding, as required for future learning in engineering and/or working as an engineer.

Troublesome features:

- Under this heading, explanation is provided about what makes a particular threshold concept 'troublesome' for students.

Suggestions:

- Under this heading, a list of suggestions for educators is provided on how they might help students understand the threshold concept. The above italicised headings also include quotes from students and academics and citations where relevant.

Figure 1 presents the most integrative engineering foundation threshold concepts among those in the inventory.

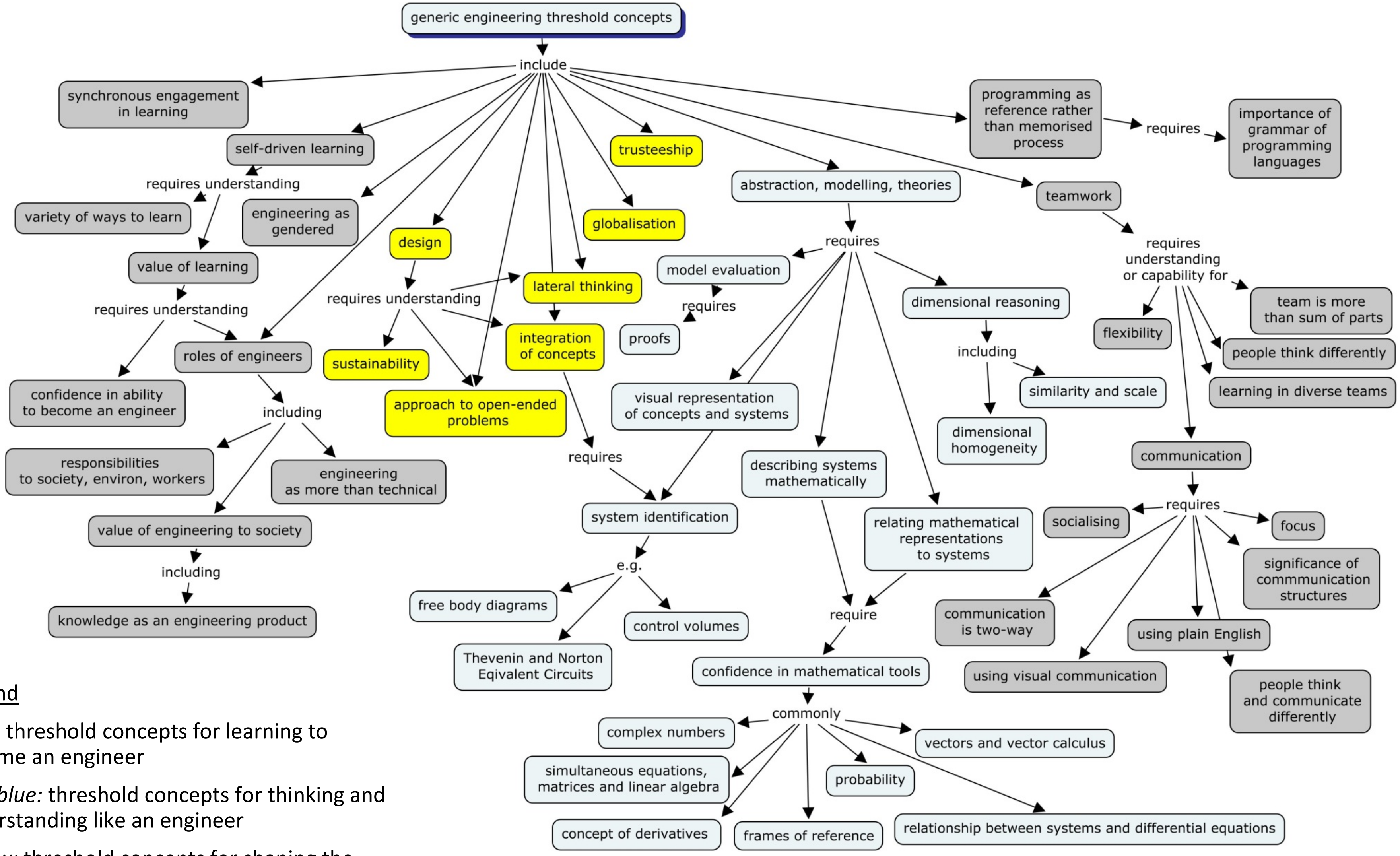

Figure 1: Concept map of most integrative engineering foundation threshold concepts

Legend

Grey: threshold concepts for learning to become an engineer

Pale blue: threshold concepts for thinking and understanding like an engineer

Yellow: threshold concepts for shaping the world as an engineer

SECTION 1: LEARNING TO BECOME AN ENGINEER

1. Roles of engineers

This item includes the value and responsibilities of engineers, and the nature of engineering practice. This concept was identified as a potential threshold concept by David Parkinson in his analysis of first-year students' responses.

a. Engineering as more than technical

Engineering involves elements of communication, teamwork, coordination and managing politics, rather than technical work alone. Communication and relational practice are vital to the success of projects. Managing relationships and reputation are part of engineering work.

b. Responsibility of engineers to society, the environment, and workers

Transformative and troublesome because:

- It requires critical thinking, including questioning assumptions that a student might not have recognised previously, because the assumptions are part of dominant culture.

c. Value of an engineer to society and to organisations

Includes: Knowledge as an engineering product

Transformative because:

- It expands the competencies and learning a student expects to need in order to become an engineer.

Troublesome features:

- This can be an alien concept due to the common assumption that engineering is about engineering science.

  I thought it was an engineering course. How are we expected to do a project that does not include much actual engineering? (student)

- These can be uncomfortable concepts for students and engineers, as many students choose engineering because they are good at mathematics and science and like to identify with this.
- There is limited public awareness about engineering.

  Before when people mentioned engineering, I just link to cars or buildings. However, in this course, I realise that the connection between engineering and the environment is close as well. (student)

  When you talk to some engineers, and particularly project engineers, it's about dealing with people, it's about communicating with clients, it's about managing schedule, and that's engineering work. If you're say working on a road construction, and the students then say where do I actually design the road? And it's like one person did that a while ago, and now we've got five engineers here working on this. (academic)

Suggestions:

- Incorporate problem-based learning techniques as a learning approach.
- Ask students to connect and test a power plug and then reveal weakness by

referring to standards.

- Use case studies in which failure occurs for non-technical reasons.
- Use case studies which demonstrate the social and environmental consequences of engineering solutions—especially where judgement of the benefits or disadvantages is complex.

2. Confidence in ability to become an engineer and do engineering

Transformative because required for:

- gaining employment
- indicating competence and thereby leading and gaining cooperation
- motivation to study.

Troublesome features:

- lack of practical experience
- lack of role models (especially for women)
- identity conflict for people who do not fit the dominant culture
- real and perceived difficulty of the course.

Suggestions:

- Provide opportunities for practical, hands-on experience at university and outside university.
- Facilitate well-structured internships and vacation employment opportunities.
- Facilitate industry mentors for students.
- Hold sessions with panels of engineers from industry.
- Employ some teachers with industry experience.

3. Self-driven learning

This item relates to taking responsibility for one's own learning, which includes motivation and taking responsibility for finding or creating the required resources and learning opportunities. This concept was identified as a potential threshold concept by David Parkinson in his analysis of first-year students' responses.

a. Value of learning

This concept was identified as a potential threshold concept by David Parkinson in his analysis of first-year students' responses.

Troublesome features:

- Students can be afraid of uncertainty, for example:

  What is this course trying to achieve once we've completed it? (student)

- Students often lack interest and deep motivation in learning.

  To overcome that attitude of 'I don't really need this, why am I here?' (academic)

Suggestions:

- Incorporate problem-based learning to demonstrate applicability of the curriculum.

- Give students opportunities to develop awareness of roles of engineers. (See 1. Roles of engineers)

b. There are many different ways to learn and sources of information

Learning and information sources include not only lectures, but also learning from peers, textbooks, and online resources, such as free online lecture materials.

Troublesome features:

- Moving away from a reliance on memory as the focus of learning.
- Judging the quality of evidence and sources of information available.
- Discerning the underlying properties of information and applicability for problems.

Suggestions:

- Use problem-based learning to force students to identify relevant information themselves.
- Incorporate peer mentoring in learning activities.
- Establish and encourage study groups.
- Use a pedagogy that carefully treads the line between developing autonomous learners and 'hand-holding'. Students need to be given responsibility to learn independently.

4. Teamwork

Transformative because required for:

- all engineering practice.

Troublesome features:

- Communication is behind much of the trouble students experience with teamwork.

> *For discussing problems, more people always have more ideas, but not easy to get the best one, people need to communicate with each other thoroughly*. (student)

a. A team can achieve more than individuals

Teamwork is not just about distributing tasks, but thinking and working together.

> *Then once you get to a design project you finally understand how everything you've learnt is still not sufficient to do appropriate design unless you have others working as well*. (student)

b. People think differently

Troublesome features:

- This concept requires a perspective that is alien to many preconceived epistemologies, that is, it conflicts with ideas about where knowledge resides, what is knowledge, and what is the nature of engineering knowledge. There is not just one correct version of knowledge, residing with the lecturer. There might be variations that can be found among peers and through observations. There might be multiple responses to a situation or problem.
- Students' perceptions change as the team operates.

c. Learning in diverse teams

Troublesome features:

- Students must learn to work with people they have never met before.

  When you're with the group you're stuck with them for the whole time and we're all strangers. (student)

- Students must learn to work with people from different backgrounds.

  Learning to communicate and make products together with different culture/country students. (student)

- This capability requires appreciation of the value of different ways of looking at the world. People with different backgrounds and standpoints can make different contributions and inspire and learn from each other. This requires a perspective that is alien to many engineering students' preconceived epistemologies, that is, it conflicts with ideas about where knowledge resides, what is knowledge, and what is the nature of engineering knowledge. There is not just one correct version of knowledge, residing with the lecturer. There might be variations that can be found among peers and from observations. There might be multiple responses to a situation or problem.
- Students' perceptions change as the team operates.

d. Flexibility in group process

Troublesome features:

- May require working in a different way from the style personally preferred.
- May require taking into consideration factors that the student might not usually consider relevant.
- May require accepting a process, despite uncertainty about whether it is ideal.
- May require accepting a group decision, even if it is not one's personal decision.

Suggestions:

- Teach students *how* to work in a team, rather than just expecting them to work in teams.
- Engage students in exercises that help them experience transformations to overcome the alien and uncomfortable concepts required for teamwork.
- Help students to understand themselves (for example, their own preferences) in order to understand others.
- Give students activities and projects that require diverse backgrounds and strengths (for example, interdisciplinary projects).

5. Communication

Communication for engineering practice requires a number of capabilities, including the following items.

a. Communication is at least two-way, rather than always one-way

Engineering communication is not limited to transmitting information to other people in one direction. It includes, for example, negotiation and coordination.

Troublesome features:

- If the only assessments based on communication are presentations and reports, this can mislead students about the nature of engineering communication.

b. Using visual representations

This includes having appreciation for and competencies to enhance communication with visual representations (such as graphs and diagrams), rather than words alone.

Troublesome features:

- Students can forget the power of visual tools.
- This type of communication mechanism requires visualisation skills.
- Sometimes communication is taught to engineers by non-engineers, who have little awareness of engineering drawing and graphs.

c. Focusing written and oral communication

This includes selecting the required level and scope of details. It is not about focusing on specifics, but selecting the right level of focus. For example, students in a first-year design project spoke extensively about how different batteries work, when a simple table indicating the choice of battery would have been better.

Troublesome features:

- This reflects trouble focusing efforts and attention in general. Students can be bogged down in details and must learn to identify and focus on critical aspects of problems, and the most relevant and useful information.

d. Structures used to communicate

Transformative because required to:

- write essays and theses
- write reports for a professional workplace
- communicate in diverse contexts.

Suggestions:

- Stipulate the purpose, audience and other participants of any set communication task.

e. Understanding that different people think and communicate differently

Transformative because required to:

- work in diverse teams
- understand others
- manage one’s image, which is essential to forming teams
- influence one’s communication style to understand others and be understood by others.

f. Explaining engineering in plain English

Transformative because required to:

- work with non-engineers.

Troublesome features:

- Students have experience with artificial problems, without the complexities of real life situations.

Suggestions:

- Ask students to present to non-engineers, collect opinions from family and friends, and work in teams with students from other disciplines and perhaps community members.

g. Socialising

Transformative because required to:

- form and maintain teams
- work in teams
- seek and find information from others
- coordinate the work of others over whom one has no responsibility.

Troublesome features:

- The complexity of social relationships can be challenging for students.

6. Synchronous engagement in learning

This item involves coordinating learning activities with teaching and project schedules.

Transformative because required for:

- allowing time to overcome threshold concepts
- attending meetings
- working as a professional in teams
- ensuring the success of critical events, or '*being there when it counts*' (for example, meetings, 'concrete pours'). (academic)

Troublesome features:

- There is a lack of incentive for students to coordinate their activities, due to the convenience of online lectures and email communication.

Suggestions:

- Conduct interactive learning activities in class.
- Undertake regular formative assessment of student progress.

7. Importance of the grammar of programming languages in computing

This concept relates to the significance of the grammar of programming languages over the need to memorise commands. This is a high level threshold concept related to students' approaches to learning how to program. Threshold concepts in computer science have been investigated extensively (Shinner-Kennedy, 2008; Zander et al., 2008). More specific potential threshold concepts in computing that were suggested by participants included interrupts and event-based programming, and pointers and use of memory. Pointers have been previously identified as potentially threshold (Thomas et al., 2010).

Transformative because required for:

- Approaching learning to program such that it is achievable, rather than overwhelming.
- Recognising learning to program as a reference, rather than memorising activity.

Troublesome features:

- Overcoming the initial fear of programming held by students with limited prior experience.
- Understanding that it is not necessary to know every command.
- Understanding what a computer is and how it works (for example, memory, data, instructions, control mechanism).
- Knowing the different types and outcomes of programs (for example, procedural, non-procedural, event-driven, object-oriented, graphical user interface).
- Knowing the scope of variables (meaning, when a variable is available).
- Formulating the algorithms for a program to manifest.

Suggestions:

- Offer basic programming to all students to accommodate those with less experience than others.

8. Engineering as gendered

This item is based around the idea that engineering organisations, faculties and curricula have been shaped by a masculine culture (Gill, Mills, Sharp, & Franzway, 2005; Godfrey & Parker, 2010; Ihsen, 2005; Male, Bush, & Murray, 2009; Tonso, 2007). Note that this is the only item in the inventory based on literature, rather than evidence collected from participants.

Transformative because required for:

- Seeing relevance in non-traditional parts of engineering curricula.
- Recognising unconscious bias among women and men, for example when students work in teams and when they peer assess.
- Reconciling potential identity conflict.

Troublesome features:

- It represents an alien way of thinking, inconsistent with the expectation that engineering is objective.
- The hidden nature of familiar cultures means that existing viewpoints and attitudes behind many frequent actions and language are not recognised. Instead, the assumptions behind everyday experiences are taken for granted.

- It can be confronting and potentially hazardous to one’s acceptance in the faculty or profession to question the assumptions behind decisions, ‘common sense’, and established hierarchies.

Suggestions:

- Conduct university-based role play scenarios that are relevant to engineering students and professional engineers.
- Ask students to reflect on decisions in their lives and how they were influenced.
- Ask students to read, discuss, and debate examples of feminist literature in the fields of engineering and engineering education.

SECTION 2: THINKING AND UNDERSTANDING LIKE AN ENGINEER

9. Abstraction, modelling and theories

A system can be modelled for analysis by reducing the system to the components that are salient for the problem, recognising the infinite extensions of system processes (abstraction), and using mathematics and visual representations to better understand the processes in the system. Engineers must be able to conceptualise an abstraction of a physical system, analyse and synthesise in the abstract domain, and conceptualise the physical implications of abstract solutions.

Note that this is an overarching threshold concept, which depends on many threshold concepts, and has manifestations in many contexts. Students need specific examples of models and abstraction, such as the use of complex numbers and phasors to analyse reactive power, and the use of free body diagrams, to appreciate this threshold concept.

Carstensen and Bernhard (2008) identify the relationship between theories and models, and objects and events as potentially threshold, with the examples of Laplace Transforms, Bode Plots, graphs of transient responses, and circuits.

Transformative because required to:

- Undertake analysis of complex systems and complex concepts—in electrical engineering this includes even the most basic circuit analysis, and especially more complex concepts such as reactive power.
- Recognise system features that have familiar patterns and use these patterns to make predictions.
- Reduce complex systems to simpler equivalent components in a way that unifies many instances, to help predict something not seen before (for example, Thevenin's Theorem).
- Estimate relationships based on empirical evidence, along with dimensional reasoning.
- Decompose a system to modules and consequently understanding the whole, where appropriate.

Troublesome features:

- Students must understand the significance and limitations of models and theories. These are only simplifications and explanations that unify many individual instances and help to predict something not seen before (for example, small and large signal analysis in electronics, models for transistors under limited operating regions, impedance defined only in the frequency domain, circuit theory limitations and adaptations when assumptions are violated). Students must realise that models and constructs are not identical to the real world.
- Elements of a model are usually not physical, but are representations that capture only the attributes essential for the purposes of the theory (Cantoni & Budrikis, 2008). This requires a change in thinking about an issue from the physical system to abstract features (for example, to understand transforms, the frequency 'domain' and consequently transfer functions). Students find it easier to solve problems with given values for variables because then they do not have to conceptualise the abstraction.

- The variety of models that apply to the same system and that are useful under different circumstances (for example, pole-zero diagrams, step response, transfer functions, all applying to the same system under different circumstances).

Suggestions:

- Keep reminding students of where the model fits in the big picture (for example, the conditions under which it applies, and other models that apply under different conditions).
- Give students problems without values for the variables.

a. Confidence in the mathematical models

Transformative because required for:

- using complex numbers to represent sinusoidal signals and impedance in the frequency domain
- trusting the use of sign conventions
- later trusting tensors.

b. System identification and definition

This item involves taking a real life problem and putting it into a form ready for modelling/analysis using, for example, free body diagrams in statics and dynamics, control volumes in thermodynamics and fluid dynamics, equivalent circuits in circuit analysis.

Transformative because:

- Many of the difficulties in applying the concept of energy, mass, and momentum balance are derived from trouble with system identification and definition.

Troublesome features:

- Many systems change in time and space (for example, a free body diagram may be valid for a particular position or instant only).
- This capability requires abstraction.
- Definition of the system is the 'smart choice' selected to solve the problem, rather than the only choice.
- The system of interest may be a subset of a larger system.
- The identification of important variables, as some processes are negligible at larger or smaller scales (for example, gravity between two objects, Coriolis force, and surface tension).

Example: Free body diagrams

Troublesome features:

- Isolating the identified system from surrounding bodies.
- Defining the system and replacing everything else with forces or moments.
- Understanding the limitations of generalisations used at school (for example, forces acting on simply supported items).
- Understanding action and reaction forces. This is easier when forces are normal to a body but friction is difficult. A particular difficulty is remembering which body is being isolated, and therefore students choose the wrong direction for friction.
- Using unfamiliar terminology (for example, 'load', 'stable', 'reaction').

- Students learn to draw free body diagrams in physics with a body represented by a point, or by drawing forces acting on the centre of mass. In contrast, in many engineering problems the dimensions of a body and point at which forces act are significant.

Example: Shear force diagrams

Troublesome features:

- Understanding why the shear force is drawn above or below and is given a positive or negative sign (which is just a convention). Note that this is related to 'trusting mathematical models'.
- Visualisation of the shear forces.

Example: Bending moment diagrams

Troublesome features:

- Understanding the concept of bending moments.
- Simultaneous compression and tension in a beam causing an internal moment.
- Understanding why the bending moment is drawn above or below.
- Practice is required to the point where students can draw the diagrams immediately.

Example: Control volumes

This involves defining the boundary and nature (open or closed) of a volume for analysis and/or measurement of change in thermodynamic properties along a process path.

Troublesome features:

- As for all system identification, the control volume is not unique, but is instead selected for convenience for the problem.

Example: Thevenin's and Norton's Equivalent Circuits

Thevenin's Equivalent Circuit was also identified as a potential threshold concept by researchers in New Zealand (Harlow, Scott, Peter, & Cowie, 2011).

Troublesome features:

- Thinking about the circuit abstractly, such that sections can be recognised regardless of the original shape of the circuit diagram. This includes, for example, recognising series and parallel components in a circuit diagram.
- Having faith that a complicated circuit can be modelled, for example, Thevenin's Equivalent for a battery (Jonathan Scott, personal communication).
- The short circuit and open circuit definitions for components of the models are not always helpful as ways to calculate elements of the model.

Suggestions:

- Ask students to sketch a system and explain the definition and selection in groups and then to the class.

c. Judging whether a model is satisfactory

Transformative because required to:

- select a model to use (for example, Thevenin's Equivalent Circuit)
- judge whether ideal gas equations apply.

Troublesome features:

- proofs, axiomatisation/abstraction (see below)
- familiarity with identifying hypotheses and inconsistent solutions.

Suggestions:

- Teach the concept as a game in situations where it is not obvious which model applies (for example, transistors). '*These are the rules, work out what applies*.' (academic)
- Use a flow chart in situations where it is not obvious which model applies (for example, transistors).

  Is it a linear system? If not, assume a region of operation and set up a hypothesis to test it. If results are consistent, good. If a contradiction is created, then try another region. (academic)

Requires: Proofs

This item includes the concept of a proof, awareness of kinds of proof, and common terminology.

Transformative because required to:

- Understand how to judge whether a model is satisfactory.
- Open up ways of determining whether a statement is true. Through this, the concept of a proof is one of many examples of threshold concepts in engineering that have 'double trouble', using Perkin's (2006, p.41) expression. These concepts are transformative not simply due to their categorical value, but also in the 'activity systems' these concepts open.
- Develop an analytical test for a hypothesised operating state for a circuit element, or for a hypothesised thermodynamic process path, such as isothermal reversible expansion.

Troublesome features:

- understanding what is sufficient to be a proof
- terminology (for example, necessary and sufficient conditions, *QED).*

d. Creating visual or symbolic representations

This item involves constructing meaningful visual representations of systems, including representations of dimensions that are outside everyday observations.

Transformative because required to:

- Communicate ideas, concepts, and designs by sketching engineering drawings and other representations.
- Sketch visual representations of models for analysis, problem-solving, and design.

Troublesome features:

- conceptually difficult and complex
- third angle projection
- a tacit engineering skill, meaning that teachers can overlook the need to help students develop this.

Suggestions:

- Practice sketching and reading drawings.
- Ask students to sketch and explain, first in small groups and then as group representatives explaining to the wider class.

Example: Sketching phase diagrams and process paths

This example involves sketching phase diagrams (for example, *T-S*, *P-V*) and process paths to support hypothetical process pathways, in order to conveniently track the change of thermodynamic state properties in real life processes.

e. Relating visual or symbolic representations of systems to physical systems

Examples of this capability include the following:

- Reading and connecting a circuit using a circuit diagram (Scott & Harlow, 2011).
- Identifying pins on a chip.
- Reading a spring-mass diagram.
- Visualising three-dimensional space.
- Understanding the implications of models in the frequency domain (Carstensen & Bernhard, 2009).
- Reading engineering drawings and sketches.
- Interpreting bending moment diagrams.
- Reading phase diagrams (for example, *T-S*, *P-V*) and process paths and understand physical meanings.
- Understanding physical implications of graphical representations such as oscilloscope outputs (Carstensen & Bernhard, 2009).

Transformative because required to:

- use models in engineering.

Troublesome features:

- This is a tacit engineering skill for many academics and not necessarily explicitly taught.
- The information represented can be conceptually difficult and complex.
- It can be difficult to visualise the physical system. For example, some students can go through the steps of connecting a circuit from a circuit diagram, but they have not visualised the circuit and therefore have not arranged the circuit in an organised way on the board, for instance without logically positioning earth. Therefore they have difficulty troubleshooting.

Suggestions:

- Use problem-based learning and variation theory (Carstensen & Bernhard, 2009).
- Practice using visual representations.

- Use peer teaching. For example, explaining the link between the physical system and the representation is a way to demonstrate and develop understanding.
- Remember to teach the physical implication of the representation, rather than the representation alone.

f. Relating mathematical representations of systems to physical systems

Note that this item manifests differently in different contexts. Understanding of any one of these mathematical representations does not imply understanding of others. However, appreciation of the value of relating mathematical representations to physical systems, and proficiency and confidence to use this power, is likely to develop through experience with multiple examples.

Transformative because required to:

- Understand the language in which engineering is often situated.
- Conceptualise systems with more than three dimensions.
- Understand transforms and implications of models in the frequency domain.
- Visualise the significance of numbers (for example, Reynolds Number in hydraulics, although this is likely to be beyond second year).
- Visualise the physical meaning of equations governing a feature such as fluid flow (for example, visualising gradients and integrals).
- Understand the physical meaning and the limitations of applicability of phasors (for example, to understand the physical meaning of reactive power).

Troublesome features:

- conceptually difficult and complex
- mathematics may not be understood
- unfamiliar notation—mathematics is a different language.

Suggestions:

- Use peer teaching as a learning approach.
- Remember to teach the physical implications of the mathematical concepts, rather than the mathematical relationships alone.
- Use animations and models to assist with visualisation.
- Encourage greater dialogue between engineering and mathematics academics to enhance teaching practice.
- Provide opportunities to practice with examples in engineering contexts. For example, by using mathematics tutors with engineering backgrounds to position mathematics within engineering problems, or by bringing engineering academics into mathematics lectures when new topics are introduced.

Example: Concept of derivatives

Transformative because required for:

- understanding the consequence of elements such as inductors and capacitors
- optimisation.

Example: Relationships between systems and differential equations

The following also applies to difference equations for discrete systems.

Transformative because required for:

- analysing a system
- optimisation
- identifying limitations within physical systems
- understanding the performance of elements such as inductors and capacitors
- understanding oscillation, resonance, and damping.

Troublesome features:

- The nature of solutions to differential equations as functions rather than numbers.
- Differentiating at an instant cannot be undertaken by substituting values for time before differentiating.
- Dimensionality, that is, recognising how many solutions any differential equation has—none, one, or many.
- Linked to the above concept is realising that a differential equation can have a solution, even when the solution is not a familiar one such as a sine, cosine function, or a polynomial.

g. Describing systems mathematically

Transformative because required to:

- Generate models and use mathematics to represent a concept or relationship.
- Describe systems with more than three dimensions.

Troublesome features:

- conceptually difficult and complex
- perhaps the mathematics is not understood
- this is a tacit engineering skill
- abstract nature of the mathematical representation.

Suggestions:

- Use peer teaching as a way to help students become familiar with describing systems mathematically.
- Explaining the link between the physical and abstract is a way to demonstrate and develop understanding.

Example: Vectors and dimensionality

This item includes vectors as multidimensional mathematical constructs that combine magnitude and direction, represented as arrows or using vector notation.

Transformative because required to understand:

- representation of multidimensional quantities
- force, displacement, linear momentum, velocity and acceleration
- grouping properties within an object, as in programming.

Troublesome features:

- The difference between scalars and vectors can be difficult to grasp (for example, velocity and speed).
- The physical interpretation of dot and cross products can be challenging.
- There is a variety of representations for vectors (for example, arrow in space, mathematical symbol with underscore or overscore or some other symbol, component form).
- There is confusion between use of the term 'vector' to mean a three-dimensional quantity (as in mechanics), and a multidimensional quantity (as in mathematics).
- Students have difficulty visualising or drawing vectors of four or more dimensions.
- Students can have difficulty with coordinates, for example, polar coordinates in which circular motion can be represented as sine and cosines.

Suggestions:

- Conduct a diagnostic test on entry and later in the course.
- Facilitate individual exploration of the topic and build on this.
- Where a variety of notations is possible, be sure to alert students to the relationships between these.

Example: Representing angular motion as a vector using the axis of rotation

Transformative because required for:

- convenient analysis.

Troublesome features:

- Why does the right hand rule work?
- What is the meaning of the *k* axis?
- Having confidence to trust that the sign of the vector will take care of the direction of rotation.
- Angular displacement is not a vector, because the order in which displacements occur affects the resulting displacement.

Example: Vector calculus

Transformative because required to understand:

- velocity
- acceleration
- electromagnetics (this is higher than foundation level).

Troublesome features:

- A vector at constant magnitude can have non-zero derivative.
- Time cannot be substituted before differentiation.
- The difference between velocity and acceleration can be problematic.
- Acceleration and force can be in directions different from velocity.
- Velocity is always tangential to the path and denotes direction of motion, but acceleration is a result of an unbalanced force and affects the velocity vector.

- The difference between acceleration and rate of change of speed in curvilinear motion can be problematic.

Example: Temporal and spatial frames of reference

This item relates to different coordinate systems and frames of reference, such as those used to define relative motion, and also differential and integral forms of equations. Note that this is also a concept central to transforms that allow mapping between time and frequency domains. However this application is higher than the foundation level.

Transformative because required for:

- Understanding ways of viewing and analysing motion.
- Moving away from fixed perpendicular frames of reference (for example, to cylindrical coordinates), and understanding the potential benefits of doing this.
- Switching between a continuous and particle approach, for example, the idea that a fluid can be observed from a stationary perspective watching it go by, or the frame of reference can move with a particle.
- Using phasors in electrical engineering, in rectangular and polar form, to represent sinusoidal wave forms and impedance in the frequency domain.

Troublesome features:

- continuously changing frames (for example, many reference systems change in time and space)
- relative definitions (for example, displacement vs. position, relative velocity, relative acceleration, potential difference, datum points and earth in electrical circuits).

Example: Relationships between systems and differential equations

Transformative because required for:

- Understanding ways of viewing and analysing motion and other systems in which variables change as functions of the rate of change of other variables.
- Using phasors in electrical engineering, in rectangular and polar form, to represent sinusoidal wave forms and impedance in the frequency domain.

Troublesome features:

- continuously changing frames (for example, many reference systems change in time and space)
- relative definitions (for example, displacement vs. position, relative velocity, relative acceleration, potential difference, datum points and earth in electrical circuits).

Example: The value of matrices and linear algebra for solving simultaneous equations in multiple dimensions

Transformative because required for:

- Confidence solving for variables in many engineering problems.
- Understanding the significance of the interrelated features of systems.

Troublesome features:

- application to engineering problems
- conceptual understanding of eigenvalues/eigenvectors
- conceptual understanding with more than three dimensions.

Example: Linearity

Transformative because required for:

- knowing when a system can be analysed as a linear system.

Troublesome features:

- superposition
- homogeneity.

Example: Linear independence and the link to dimensionality

Transformative because required for:

- identifying the number of solutions for a system
- indeterminate systems and inconsistencies.

Example: Complex numbers

Transformative because required for:

- using phasors and transforms for analysis in power, communications, and control.

Example: Probability

Transformative because required for:

- communications
- physical electronics
- data analysis
- understanding uncertainty and error analysis.

Troublesome features:

- abstract nature of stochastic processes
- interpretation of *p* values
- different approaches to probability for stochastic processes and quantitative methods
- different use of the term ‘independent variables’ in statistics and in experimental method.

10. Application of the conservation principle

This item is based on the principle that nothing is lost. It includes questions such as ‘which quantities are conserved and how?’ It can be applied to mass, energy (including Kirchhoff’s Voltage Law (KVL)), momentum, and charge (Kirchhoff’s Current Law (KCL)). Richards (2002) has established a ‘systems, accounting, and modelling’ approach as the basis of an integrated engineering foundation at Rose-Hulman Institute of Technology.

Transformative because:

- It has many applications across engineering.

  This principle has many applications across engineering and can be very useful in modelling real world complex systems. (academic)

- Conservation of mass, momentum balance, and energy balance, are key to understanding fluid dynamics: heat transfer, energy transfer and mass transfer.

  If you can understand that then it makes understanding Kirchhoff's Voltage Law so much easier, because all of a sudden there's a reason why you do these particular steps rather than just rote learning this and then if someone changes something subtly, you're lost. (academic)

Troublesome features:

- KCL is often confused in circuits with capacitors, inductors, diodes, or transistors, and in circuits that are complex, or drawn such that nodes and branches are not obvious.
- The principle can be counter-intuitive. Newton's Second Law (Inertia), that is, a body keeps moving at constant velocity unless a force is applied, is inconsistent with students' experiences.
- There is always energy loss in real systems, but academics design simplified problems 'ignoring friction' or 'assuming no energy loss', or assuming that other necessary conditions for the model apply, without noting the assumptions.
- Especially in electrical engineering, models are frequently used without noting the assumptions, or deriving the models from first principles because this is complex. For example, Black (2012, p.1) notes that KCL is not simple conservation of charge as it applies only under 'lumped circuit' assumptions.
- Students often find it difficult to apply the laws because they are unsure how to account for the conserved quantity (for example, energy can have many forms).

Suggestions:

- Build models conserving only one quantity at a time.
- Refer to 'balance' rather than 'conservation', as there is always energy loss in a system.

a. First law of thermodynamics

This item relates to the idea that energy can be stored or transformed, but not created or destroyed. Energy is always conserved in a system.

Transformative because required for:

- thermodynamics
- understanding KVL in circuits
- understanding that reactive power and real power are each balanced in a closed circuit.

Troublesome features:

- The measurement of energy can be problematic.
- There are dozens of different forms of energy and different language.
- The additional complexity introduced in systems by stored energy items.
- Students have a preference for solving problems using forces rather than energy,

because forces are less abstract.

- The related concepts of voltage and potential difference.
- Confusion between the terms 'potential/voltage drop' and 'potential/voltage difference'.
- Assumptions about energy and charge entering and leaving the circuit are frequently unstated in circuit analysis, although understood by the academics.
- There is difficulty in recognising KVL in the outer loop on a circuit diagram, because students do not recognise the outer loop as a closed loop.
- The arbitrary nature of signs for current can be difficult.

> *There's a lot of students who can't just understand why in parallel it becomes a current division and why in series it becomes a voltage division—just that mere fundamental concept, it's key to circuit analysis, nodal analysis, Kirchhoff laws, Thevenin's laws. I've taught both at X Uni and at Y Uni first-year electrical engineering and that's one of the key breakers.* (academic)

Suggestions:

- Refer to energy or power 'balance' rather than 'conservation'.
- Ask students for explanations, rather than always using numerical examples.

b. Momentum is conserved as a vector, unlike energy and mass

Momentum, energy, and mass are all conserved. However, momentum is a vector unlike mass and energy.

Troublesome features:

- Conservation of momentum is less intuitive than conservation of mass or energy because momentum is a vector.

c. A fluid is a continuum

This relates to the idea of considering fluid a continuum, rather than discrete objects. Then conservation of mass mandates a whole system-wide response.

Transformative because required to understand that:

- In a fluid, pressure can be applied in one place and sensed elsewhere.
- Friction does not cause fluid to slow down. It causes it to lose pressure. If pressure is fixed at both ends, then fluid flows at a rate to make it lose the necessary pressure.

d. Holistic analysis of circuits

Involves analysing how a circuit works as a whole, rather than trying to analyse one component at a time. This concept is important due to the concept that Scott and Harlow (2011, p.461) called 'holistic current flow … [the] appreciation that current flows "incompressibly" through conductors'.

Carstensen and Bernhard (2008, p.145) note research by Margarita Holmberg on local and sequential reasoning in circuits, also found by Smaill, Rowe, Godfrey and Paton (2011).

Transformative because required for:

- Understanding how a circuit behaves.

- Recognising the implications of short circuits and open circuits and other patterns in circuits, such as equal current in and out of a complicated passive circuit.
- Having a feel for the consequences of a change in a circuit before performing any numerical analysis.
- Recognising the most convenient ways to analyse circuits.
- Visualising the overall structure of a circuit so that students can both connect a circuit, and also troubleshoot any problems that arise.

Troublesome features:

- tendency for sequential reasoning rather than holistic reasoning
- tacit and therefore not explicitly taught
- often developed through years of experience
- understanding earth as a reference point.

Suggestions:

- Ask students to analyse the same circuit using multiple techniques.
- Ask students conceptual questions about what they expect to happen when one feature of a circuit is changed.

11. Conceptualisation of the change in thermodynamic state properties and identification of a process pathway

This item involves the conceptualisation of the change in thermodynamic state properties in real life processes into an abstract world and also the identification of a process pathway that is physically possible.

The abstract conceptualisation is used to identify a process pathway to conveniently track the change of thermodynamic state properties in real life processes. Note that this is an example of an application of modelling and abstraction. This item is one of several that are considered threshold 'capabilities' rather than threshold concepts.

Transformative because required to:

- Exploit the path independent characteristic of thermodynamic state properties to contrive convenient pathways in which properties can be tracked, so as to solve engineering thermodynamic problems.

Troublesome features:

- abstraction required
- students' lack of faith in the axiom of process path independence (possibly due to experience learning over-simplified models that are replaced at later stages in their studies).

a. Relationship between phase diagrams and composition, configuration, and properties

At the foundation level, a binary phase diagram, that is, with two elements, should be understood. Tertiary phase diagrams are used at higher levels.

Transformative because required to:

- Sketch phase diagrams and process paths to support hypothetical process pathways, to conveniently track the change of thermodynamic state properties in real life processes (as above).
- Understand the iron/carbon system, steels and how we process steels, working out proportions of phases present and microstructure (morphology), for example, as an alloy solidifies.

Troublesome features:

- Abstract thinking is necessary to make the conceptual link between the real world and phase diagrams.
- Understanding that the two or three elements do not necessarily change phase independently.
- Requires Lever Law to work out the proportions of each phase and morphology for points within regions where more than one of these is present (although not at the foundation level).
- It is complex to use. For example, after finding the point on the phase diagram, a student must track to the sides to see what the composition of the phases will be and then also use the Lever Law to calculate the proportions of each phase and then, depending on the process used to reach that point, identify what arrangement the phases will be in.

12. Two independent thermodynamic properties are required to define the state for a pure substance

This item relates to the idea that for a pure substance, only two independent thermodynamic properties—for example, entropy and pressure—are required to define the state.

Transformative because:

- simplifies analysis considerably.

Troublesome features:

- Students' lack of faith in the axiom, possibly due to experience learning over-simplified models that are replaced at later stages in their studies.

Suggestions:

- Give students opportunities to change pressure and observe temperature change.
- Ask students to *describe* what is happening, rather than referring only to numbers and calculations.
- Use peer teaching as a way to convince each other of this phenomenon.

13. Ideal gas equations

This item is concerned with applying ideal gas equations to physical systems and knowing when they can be applied and when they start to fail.

Transformative because required for:

- practical applications (for example, emergency gas release in the LNG industry and coal seam gas industry)
- process control.

Troublesome features:

- Ideal gas laws are not laws of ideal gases, which the name suggests. Rather, they are an idealised model for the behaviour of real gases.
- They are counter-intuitive, for example, in the case of 'blowdown'.

  When you crack a cylinder off and vent half its contents, all of a sudden you've got ice all over the bottom. (academic)

- There is a lack of familiarity with thermodynamics when the concept is introduced in fluid mechanics. For example, students might not be familiar with 'adiabatic processes'.

Suggestions:

- Mix two 'ideal' gases together, explain what happens and talk about it. Students can use simulations or better still, conduct physical experiments.
- Help students develop a mental framework to understand what is happening at the molecular level. Relate to things such as high level averages, pressure and volume. Relate these also to real life applications, for example, car engines.
- Be careful about the use of language. Refer to 'approximate' rather than 'ideal' equations.

14. Reactive power

Flanagan, Taylor and Meyer (2010) previously identified reactive power as a threshold concept.

Transformative because required for:

- understanding, analysing, and managing power efficiency.

Troublesome features:

- Students think the power is imaginary because of its representation as the imaginary part of a complex number. However, the power does exist, although it does not perform work.
- The multiple terms and units for power can be problematic. For example, average, reactive, real, apparent, rms measured in Watts, VAR, and VA.
- Terms such as 'load' resistance and 'line' resistance that might be used by teachers but not explained.

a. Phasors

Phasors are used as a convenient way to represent the magnitude and phase of a sinusoidal signal using the complex exponential, such that a circuit with inductors and capacitors can be analysed in the frequency domain, in a manner similar to that by which a passive circuit can be analysed in the time domain.

Transformative because required for:

- analysing AC circuits

- representing active and passive power
- estimating frequency domain characteristics of systems for applications (for example, in power, electronics, communications, signal processing, and control systems).

Troublesome features:

- the complex plane is a representation only
- relating phasors back to the phenomenon they represent (especially regarding reactive and real power in the time domain).

b. Complex numbers

Troublesome features:

- counter-intuitive
- the inverse of j is negative j.

15. The second law of thermodynamics

This item relates to the tendency of entropy to increase, resulting in processes being irreversible.

Transformative because required to understand:

- Over time differences in chemical potential, temperature and pressure tend to even out.
- Maintaining a state of disequilibrium requires energy or work.
- No process converting heat into work can ever be completely efficient.

Troublesome features:

- It is not easy to relate disorder to the physical world.

  > *How the disorderliness of something comes into play and affects a reaction, or amount of heat you can get out, or the efficiency of some cycle … it's not intuitive*. (student)

a. Entropy

Troublesome features:

- hard to describe conceptually.

Suggestions:

- Establish and encourage study groups to talk about the concepts.
- Utilise other learning resources such as those found online.
- Consider adopting a 'statistical approach'. (Note that at UWA this approach is not taught at the foundation level.)

  > *I'm just thinking back to my own university days and I remember when we did thermo. Thermo to me one year was just memorising all these equations … And it wasn't until we did it a little bit later with somebody else and he took the statistical approach and to me all of a sudden this made a whole lot more sense because there was this one thing, how many states do you have and what are those states in? And everything else followed on from that and I found … understanding that fundamental principle, then*

helped me understand everything else that flowed from it so that it wasn't a whole lot of disjointed things, but rather part of this.' (academic)

16. All systems, and their parts, tend to equilibrium

This item relates to the idea that all systems, and their parts, tend to equilibrium. An important implication is that engineers can manipulate this tendency in design.

Transformative because required to:

- '*understand how the world works*' (academic)
- '*predict where systems are going*' (academic)

Troublesome features:

- Although students are taught much about equilibrium, they also need to understand that steel processing is often designed to avoid equilibrium.

Suggestions:

- Emphasise the integrative nature of the threshold concepts.

17. Stress and strain and their relationships

Transformative because required for:

- predicting structural behaviour.

Troublesome features:

- Overall, stress and strain are handled badly by students.
- Comprehending three-dimensional aspects can be problematic. For example, integrating ideas of forces and geometry, and the significance of the orientation of the plane for which stress is calculated.
- Understanding stress transformation and principle stresses can be problematic.
- Understanding stress as a tensor. Tensors are tools that can be used to combine stresses and make coordinate transformations. They also help students understand stress. However, stress is taught as uniaxial to avoid using tensors, and the three-dimensional nature of stress is not clear to students until they learn about tensors, often not until third year. Consequently, many students start with an incorrect understanding and many engineers never realise it is incorrect.
- Identifying the cause and effect relationships between forces, stress, and strain.
- Different types of stress and strain can be challenging, for example, shear and torsional.
- Moment equilibrium in statically determinate systems and torque can be difficult to comprehend.
- Deriving a unique solution to a statically determinate structure.
- Deriving a unique solution to a statically indeterminate structure. To solve a statically indeterminate structure, three sets of conditions are solved simultaneously, that is, constitutive conditions relating stresses and strains, compatibility conditions relating strains and displacements, and equilibrium conditions relating forces and stresses.
- Material failure models/theories, including how to analyse the structural integrity of a component under multidirectional loading. Note that this is beyond second year.

Suggestions:

- Provide opportunities for more practical hands-on experience.
- Do an Instron® test, where a load is applied and converted to a stress, and students see the strain and perhaps even fracture.
- Teach the concept, rather than just the equations.

18. Macroscale behaviour

This item relates to the idea that macroscale behaviour depends on the material behaviour and the structural design.

Transformative because required for:

- statics (for example, material behaviour and dimensions, geometry, leading to forcing and boundary conditions)
- electrical systems (for example, material behaviour and physical and circuit design, leading to circuit behaviour).

Troublesome features:

- Remembering to include boundary conditions and compatibility conditions (perhaps in third year). The displacements/deformation of all parts of a structure must be compatible with each other and boundary conditions. These conditions are required to solve the partial differential equations and the solution is unique to the situation.
- Awareness that electromagnetic theory, circuit theory, and physical electronics combine with different theories applied to different aspects of electrical networks.

19. Relationship between atomic structure, microstructure, material properties, and processes

There is a relationship between atomic structure, microstructure, and material properties and processes. Engineers can manipulate this relationship in design. Microstructure dictates material properties. Processing can change microstructure and therefore change the properties. Properties can also dictate available processing techniques. For example, a material with a very high melting point is not suitable for casting and a very brittle material is not suitable to be shaped using plastic deformation. The processing technique can change the properties of the material.

Transformative because:

- These relationships influence how things are made and the properties of things after they are made.

Troublesome features:

- Students often see some but not all of these relationships. For example, they realise that structure dictates properties, but not that properties influence available processing techniques, or that the processing can change the properties. These relationships are not readily observed.
- Atomic structure and bonding are key to understanding, yet atomic structure is described in many different ways. It is often taught by building through the theories, moving through theories that are not accurate but are easy to understand and eventually reaching the current status.

- Understanding the iron–carbon system, steels and how we process steels is complicated by the focus, in teaching, on equilibrium and then processes that are designed to avoid equilibrium. Most phase diagrams imply things happen slowly. They represent the equilibrium state. Most processes are too fast for equilibrium to be achieved. It can be confusing for students, because teachers spend time with them working on phase diagrams, which represent an equilibrium state that may not be achieved in practice. When processing steels, the processes are designed to deliberately avoid the equilibrium state and rely on the transformation back to the equilibrium state being so slow that the properties of the metals are effectively locked in place. So, on the one hand students are taught about equilibrium and then other ideas are how to dodge equilibrium.
- The complexity of the theories involved. For example, quantum theory and band theory, although these are above the foundation level.
- The counter-intuitive nature of the concept. For example, surfactants—although surfactants would not be taught at the foundation level.
- The concept of how current flows through a conductor and (perhaps in second year) a semiconductor.
- Polymers, metals, and ceramics can all exist in crystalline form, as well as amorphous form.

Suggestions:

- Make the multiple contexts explicit and teach them in parallel.
- Use 'reverse engineering' as a teaching technique.

  They say 'What do we need to know to be able to put an I-beam in our building?' They find out what they need to know. It's to do with strength and stiffness. What leads to strength and stiffness? The microstructure. What influences the microstructure? The grain structure. What influences the grain structure is the bonding between atoms. We reverse engineer … We take an object … We say what do we need in terms of properties, manufacturing, marketing characteristics, put the subject together, how to get the final structure … A car is fantastic … A car encompasses all types of materials. (academic)

a. Plastic deformation in metals

Plastic deformation in metals occurs through the motion of dislocations and therefore anything that stops dislocations from moving will increase the strength.

Transformative because required for understanding:

- All of the metal strengthening mechanisms work fundamentally the same way.

  A fundamental concept is really microstructure of materials. Understand the concept really of dislocation motion and that fits into the classic deformation materials, which then leads you to the ability to make components and structures. So this dislocation is the main concept. That's a very difficult concept to understand. (academic)

Troublesome features:

- Students can think that different strengthening mechanisms involving doing different things to a material must be working differently inside the material.
- Students can think that plastic deformation occurs due to the same mechanism in polymers as it does in metals, although the mechanism is actually very different.

Suggestions:

- Use the analogy of dragging a piece of carpet over carpet. It is easier to drag a piece of carpet with a kink in it than to drag a flat piece of carpet.
- Use three-dimensional models or animations to help student visualise the phenomenon.

b. Polymerisation

This item relates to how chains grow and the fact that polymers have a chain structure.

Troublesome features:

- The structure is much more complicated than that of metals.

c. Viscoelasticity

Troublesome features:

- Polymerisation can be hard to visualise.

20. Dimensional reasoning

This item relates to the significance of dimensions and scale in engineering design and analysis.

Transformative because required for:

- simplifying and assessing the validity of an analysis or design.

a. Dimensional homogeneity

This item relates to the idea that the dimensionally homogenous quality of equations can be used to derive relationships in complex systems. The concept is powerful, as it can provide insight into engineering systems when the underlying equations are too complex to solve.

Transformative because required to:

- Check that equations are dimensionally consistent (for example, e cannot equal mc^3).
- Generate a mathematical model for a physical system, which is frequently useful when relationships are identified empirically, such as for hydraulics in civil engineering.
- Design experiments, for example, understanding which variables could be part of a relationship and therefore which to constrain and vary.

Troublesome features:

- dimensionless variables.

Suggestions:

- Set a physical task and ask students to identify the equation that applies.
- Set an equation and ask students for a physical task that the equation might represent.
- Ask students for a physical explanation for an equation.

b. Similarity and scale

Transformative because required for:

- estimating validity of solutions
- identifying suitable models, assumptions, and significant variables.

Troublesome features:

- lack of practical experience.

SECTION 3: SHAPING THE WORLD AS AN ENGINEER

21. Approaching open-ended problems

This concept involves approaching problems with multiple possible solutions and—at a more specific level—open-ended questions. This concept was identified as a potential threshold concept by David Parkinson in his analysis of first-year students' responses.

Transformative because:

- The complex nature of many 'real world' problems can require new ways of thinking.

  > *Very few problems in the world are clear cut and the answers to those questions are even harder to define as good or bad solutions.* (student)

Troublesome features:

- recursive solutions
- when to stop iterating
- fear of uncertainty (Baillie & Johnson, 2008, pp.137–8)
- problem definition
- framing the boundary of the problem
- focusing on the significant decisions (rather than being unnecessarily bogged down in detail)
- identifying significant variables and constraints
- identifying assumptions that can be made
- diverging (see below).

'Diverging' means allowing for sufficient ideas to be explored before selecting one, rather than 'thrashing around' briefly trying an approach and abandoning it for something else because it did not work on the first attempt. Osmond and Turner (2010, pp.358–9) identified 'confidence to challenge' as a threshold concept required in the design process, and 'toleration of uncertainty' as transformative in developing this.

22. Integration of concepts

This item involves considering the overall perspective—or rather, the 'big picture' or interrelation—between various models and theories. This concept was identified as a potential threshold concept by David Parkinson in his analysis of first-year students' responses.

Transformative because required for:

- knowing when and how to use concepts learnt in different units, or as separate concepts
- transferring concepts to projects
- connecting theories and models and objects and events (Carstensen & Bernhard, 2008, p.149)
- using a systems approach.

Troublesome features:

- Students often fail to apply a concept outside the unit in which it is taught.

- Students can fail to understand the connections between concepts (Carstensen & Bernhard, 2008).

23. Lateral thinking

The concept of 'lateral thinking in problem-solving' was identified as a potential threshold concept by David Parkinson in his analysis of first-year students' responses.

Transformative because required for:

- problem-solving
- approaching unseen styles of problems.

Troublesome features:

- Students are used to ritual learning, that is, being given a question and shown how you solve it using a set of steps. They need to break away from following a given procedure. This is tacit—it is not usually taught.
- Thinking about the context and the problem, rather than simply looking for a formula and values to plug into it.
- A lack of practical experience, leading to lack of familiarity with common materials and mechanisms.
- Trying to solve problems using theory, rather than taking into account observations such as colour and feel, and even instructions from demonstrators.

24. Design process

This item relates to how to proceed with a design.

Troublesome features:

- combining multiple topics
- variability in the real world
- information gathering
- integration of information from multiple sources
- justifying your answer
- approaching open-ended problems.

Suggestions:

- Teach a design process, rather than asking students to design without guidance.

a. Sustainability

This relates to the viability for an activity to be continued for ever, or the long-term viability of an activity such that the needs of future generations are not compromised.

Transformative because required for:

- Building sustainability into designs and solutions.

Troublesome features:

- The concept of sustainability is vague, complicated, and has multiple meanings.
- An understanding of the concept is influenced by and requires understanding of culture.

- Students understand the idea of sustainability, but have difficulty using it.
- It requires students to think about topics that engineering students might rather avoid, for example, spirituality, love, and social context.
- Revisiting the concept of sustainability—when students think they already know about it from school—can be challenging.
- Requires thinking more critically and broadly than students have learnt to think of sustainability at school.
- Requires integrating the concept of sustainability with engineering and demonstrating the relevance of sustainability to engineering.
- There is a need to consider social, environmental and other aspects of the context.
- The idea of a sustainable way of dealing with waste is challenging.

Suggestions:

- Ask students to consider planetary boundaries in solutions to problems.
- Use the systems, accounting, and modeling approach, which demonstrates how every system interacts with its surroundings. The approach therefore emphasises how a system and its environment are related.

25. Globalisation

This concept was identified as a potential threshold concept by David Parkinson in his analysis of first-year students' responses.

Transformative because required for:

- Understanding social and economic issues related to engineering problems.

  I have learnt to think more holistically about the processes involved in the products we purchase. (student)

  I have learnt how to look at the complete impact that a product we consume can have on the world, such as where it came from, how it was produced, people affected by the production of this product. (student)

Troublesome features:

- The complexity of globalisation and its related issues can be challenging.

  I found the concept of globalisation confusing as it has pros and cons about it. It influences quality of services and is economically beneficial, but confronts us with morality and issues. (student)

- There is no one clear definition. Globalisation has aspects related to:
  - economics, free trade, the relationship between poverty and development internationally
  - multinational corporations
  - culture and diversity within the workforce, workplace, home, and society
  - communication and technology connecting parts of the globe.

  How poverty, water shortage, literacy, birth rates, etc are all linked together. (student)

- The conceptual difficulty of understanding globalisation.

  The link between poor people and rich people. How does our economic system increase the gap between rich and poor? (student)

- Understanding globalisation requires foreign knowledge, that is, knowledge about different perspectives.
- Understanding globalisation requires challenging ritual knowledge—existing assumptions must be explored.

Suggestions:

- Ask students to debate a real scenario close to home (for example, decisions on boards in Europe leading to a factory closing in Australia, and production and/or maintenance moving offshore).

26. Trusteeship

This item is a theory critiquing the idea of development (Bain, 2003). The idea that one nation thinks it is superior to another, and has the right to go to another nation and develop it, puts the other nation in a position of inferiority.

Kabo and Baillie (2009, p.322) previously identified ‘trustee care’ as part of some students’ understanding of seeing engineering through a social justice lens. In their adapted phenomenographic study they identified five positions with respect to the concept. Trustee care was an example of the middle of these positions. Students adopting the highest position saw the concept as a ‘lens for deconstruction and critical analysis’ (p.321).

Transformative and troublesome because:

- It critiques commonly accepted assumptions about humanitarian projects.

References

Baillie, C., Bowden, J. A., & Meyer, J. H. F. (2012). Threshold Capabilities: threshold concepts and knowledge capability linked through variation theory. *Higher Education, online first*.

Baillie, C., & Johnson, A. (2008). A threshold model for attitudes in first-year engineering students. In R. Land, J. H. F. Meyer & J. Smith (Eds.), *Threshold Concepts within the Disciplines* (pp. 129–41). Rotterdam & Taipei: Sense Publishers.

Bain, W. (2003). The Political Theory of Trusteeship and the Twilight of International Equality. *International Relations, 17*(1), 59–77.

Black, B. (2012). *From Conservation to Kirchhoff: Getting Started in Circuits with Conservation and Accounting*. Paper presented at the Frontiers in Education. Retrieved 31 July 2012, from http://fie2012.org/sites/fie2012.org/history/fie96/papers/317.pdf

Cantoni, A., & Budrikis, Z. L. (2008). *Introduction to the modelling and analysis of electrical systems*. Perth WA: Western Australian Telecommunication Research Institute.

Carstensen, A.-K., & Bernhard, J. (2008). Threshold concepts and keys to the portal of understanding: Some Examples from Electrical Engineering. In R. Land, J. H. F. Meyer & J. Smith (Eds.), *Threshold Concepts within the Disciplines* (pp. 143–54). Rotterdam: Sense Publishers.

Carstensen, A.-K., & Bernhard, J. (2009). Student learning in an electric circuit theory course: critical aspects and task design. *European Journal of Engineering Education, 34*(4), 393–408.

Flanagan, M. T., Taylor, P., & Meyer, J. H. F. (2010). Compounded Thresholds in Electrical Engineering. In J. H. F. Meyer, R. Land & C. Baillie (Eds.), *Threshold Concepts and Transformational Learning* (pp. 227–39). Rotterdam: Sense Publishers.

Gill, J., Mills, J., Sharp, R., & Franzway, S. (2005). *Education Beyond Technical Competence: Gender Issues in the Working Lives of Engineers*. Paper presented at the 4th ASEE / AaeE Global Colloquium on Engineering Education.

Godfrey, E., & Parker, L. (2010). Mapping the Cultural Landscape in Engineering Education. *Journal of Engineering Education, 99*(1), 5–22.

Harlow, A., Scott, J., Peter, M., & Cowie, B. (2011). 'Getting stuck' in analogue electronics: threshold concepts as an explanatory model. *European Journal for Engineering Education, 36*(5), 435–47.

Ihsen, S. (2005). Special Gender Studies for Engineering? *European Journal of Engineering Education, 30*(4), 487–94.

Kabo, J., & Baillie, C. (2009). Seeing through the lens of social justice: a threshold for engineering. *European Journal of Engineering Education, 34*(4), 317–25.

Male, S. A., & Baillie, C. A. (2011a). *Engineering Threshold Concepts*. Paper presented at the SEFI Annual Conference. Retrieved 10 February 2012, from http://www.sefi.be/?page_id=24

Male, S. A., & Baillie, C. A. (2011b). *Threshold Concept Methodology*. Paper presented at the Research in Engineering Education Symposium.

Male, S. A., Bush, M. B., & Murray, K. (2009). Think engineer, think male? *European Journal of Engineering Education, 34*(5), 455–64.

Male, S. A., Guzzomi, A. L., & Baillie, C. A. (2012). *Interdisciplinary threshold concepts in engineering*. Paper presented at the Research and Development in Higher Education: Connections in Higher Education. Retrieved 9 July 2012, from http://www.herdsa.org.au/wp-content/uploads/conference/2012/HERDSA_2012_Male.pdf

Meyer, J. H. F., & Land, R. (2003). Enhancing Teaching–Learning Environments in Undergraduate Courses Occasional Report 4. Retrieved 31 May 2010, from http://www.etl.tla.ed.ac.uk/docs/ETLreport4.pdf

Osmond, J., & Turner, A. (2010). The Threshold Concept Journey in Design: from identification to application. In J. H. F. Meyer, R. Land & C. A. Baillie (Eds.), *Threshold concepts and Transformational Learning* (pp. 347–64). Rotterdam: Sense Publishers.

Perkins, D. (2006). Constructivism and troublesome knowledge. In J. H. F. Meyer & R. Land (Eds.), *Overcoming Barriers to Student Understanding: Threshold concepts and troublesome knowledge* (pp. 33–47). London and New York: Routledge.
Richards, D. E. (2002). *Basic Engineering Science—A Systems, Accounting, and Modeling Approach*. Terre Haute, Indiana: Rose-Hulman Institute of Technology.
Scott, J., & Harlow, A. (2011). *Identification of threshold concepts involved in early electronics: Some methods and results*. Paper presented at the Australasian Association for Engineering Education Conference.
Shinner-Kennedy, D. (2008). The Everydayness of Threshold Concepts. In R. Land, J. H. F. Meyer & J. Smith (Eds.), *Threshold Concepts within the Disciplines* (pp. 119–28). Rotterdam: Sense Publishers.
Smaill, C. R., Rowe, G. B., Godfrey, E., & Paton, R. O. (2011). An Investigation into the Understanding and Skills of First-Year Electrical Engineering Students. *IEEE Transactions on Education*.
Thomas, l., Boustedt, J., Eckerdal, A., McCartney, R., Mostrom, J. E., Sanders, K., et al. (2010). Threshold Concepts in Computer Science: an Ongoing Empirical Investigation. In J. H. F. Meyer, R. Land & C. Baillie (Eds.), *Threshold Concepts and Transformational Learning* (pp. 241–57). Rotterdam: Sense Publishers.
Tonso, K. L. (2007). *On the Outskirts of Engineering*. Rotterdam: Sense Publishers.
Zander, C., Boustedt, J., Eckerdal, A., McCartney, R., Mostrom, J. E., Ratcliffe, M., et al. (2008). Threshold concepts in computer science: a multinational empirical investigation. In R. Land, J. H. F. Meyer & J. Smith (Eds.), *Threshold Concepts within the Disciplines* (pp. 105–18). Rotterdam & Tapei: Sense Publishers.