Engineering Thresholds: An Approach to Curriculum Renewal

Integrated Engineering Foundation
Threshold Concept Inventory 2012

The University of Western Australia

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List of acronyms used

UWA: The University of Western Australia

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* 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 is not to 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 theoretical framework of threshold concept theory (S.A. Male & Baillie, 2011a; Meyer & Land, 2003). However, during the research, items that were capabilities rather than concepts were identified. Rather than dismissing these, the researchers broadened the scope to include threshold capabilities (S.A. Male & Baillie, 2011b). Consequently, Baillie, Bowden and Meyer (2012) developed threshold capability theory.

The inventory has a nested structure. Threshold concepts are inter-related. 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 academics.

Items appear in the inventory because participant responses, and in some cases cited literature, indicated that students can experience these items as thresholds (S.A. 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, and 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 motivation and capability to developing understanding and capability identified in the items in the second section. Items in the third section are required to mobilise the items in the first and second sections 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*.

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LEARNING TO BECOME AN ENGINEER

1. Roles of engineers

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 final year thesis.

a. Engineering as more than technical

Engineering involves communication, teamwork, coordination, managing politics, etc, 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:

- 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 organizations

i. Knowledge as an engineering product

Transformative because:

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

Troublesome features:

- alien concepts due to assumption that engineering is about engineering and science: “I thought it was an engineering course.”, “How are we expected to do a project that does not include much actual engineering?” (student)
- uncomfortable concepts for students and engineers because many students choose engineering because they are good at engineering and science and like to identify with this
- limited public awareness: “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, that 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:

- problem-based learning
- Ask students to connect and test a power plug and then reveal weakness

by referring to standards.

- case studies in which failure occurs for non-technical reasons
- case studies of 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 / vacation employment.
- Facilitate industry mentors for students.
- Hold sessions with panels of engineers from industry.
- Employ some teachers with industry experience.

3. Self-driven learning

Taking responsibility for one's own learning. This includes motivation and taking responsibility for finding or creating required resources and learning opportunities. This concept was identified as a potential threshold concept by David Parkinson.

a. Value of learning

This concept was identified as a potential threshold concept by David Parkinson.

Troublesome features:

- fear of uncertainty: "What is this course trying to achieve once we've completed it?" (student)
- acquiring interest and deep motivation in learning: "To overcome that attitude of 'I don't really need this, why am I here?'" (academic)

Suggestions:

- problem-based learning to demonstrate applicability
- Give students opportunities to develop awareness of roles of engineers. [*see concept "Roles of engineering"*]

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

not only from lectures but also from peers, textbooks, and online resources such as free online lecture materials

Troublesome features:

- moving from a reliance on memory as the focus of learning
- judging quality of evidence and sources of information
- discerning underlying properties of information and applicability for problems

Suggestions:

- problem-based learning to force students to identify relevant information themselves
- peer mentoring
- study groups
- teaching 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: "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 distributing tasks, but thinking and working together: "Then once you get to 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 feature:

- requires a different perspective because it is alien to many preconceived epistemologies i.e. 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 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:

- working with people students 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)

- working with students from different backgrounds: "learning to communicate and make products together with different culture/country students" (student)
- appreciating the value of different ways of looking at the world: People with different background 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 i.e. 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 feature:

- working in a different way from the style personally preferred
- taking into consideration factors that the student might not usually consider relevant
- uncertainty
- accepting a group decision even if it is not one's personal decision

Suggestions:

- Teach how to work in a team, rather than just expecting student 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, e.g. their preferences, in order to understand others.
- Give students activities and projects that require diverse backgrounds and strengths e.g. interdisciplinary projects.

5. Communication

Communication for engineering practice including

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

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

Troublesome features:

- Students can forget the power of visual tools.
- This 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.

Selecting the required level and scope of details. This 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 and audience 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:

- experience with artificial problems without the complexities of real life

Solutions:

- 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

"How to socialise away with each other." (student)

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:

- complex

6. Synchronous engagement in learning

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
- "being there when it counts" e.g. meetings, concrete pours" (academic)

Troublesome features:

- lack of incentive for students due to online lectures and email communication

Suggestions:

- interactive learning in class
- regular formative assessment

7. Importance of the grammar of programming languages in computing

The significance of grammar of programming languages over the need to memorise commands.

This is a high level threshold concept related to students' approach to learning 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:

- initial fear
- understanding that it is not necessary to know every command
- what a computer is and how it works (memory, data, instructions, control mechanism)
- different types and outcomes of programs (procedural, non-procedural, event-driven, object-oriented, graphical user interface)
- knowing the scope of variables (when a variable is available)
- formulating algorithms

Suggestions:

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

8. Engineering as gendered

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; Sally Amanda Male, Bush, & Murray, 2009; Tonso, 2007). [*This is the only item 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:

- alien way of thinking inconsistent with the expectation that engineering is objective
- hidden nature of familiar culture
- confronting and potentially hazardous to one's acceptance to question assumptions behind decisions "common sense" and established hierarchies

Suggestions:

- Role play university-based 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.

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, and by 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 think conceptualise an abstraction of a physical system, analyse and synthesise in the abstract domain, and conceptualise the physical implications of abstract solutions. *[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 even the most basic circuit analysis, and especially more complex concepts such as reactive power
- recognise features, of a system, that have familiar patterns and using 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 e.g. Thevenin's Theorem
- Along with dimensional reasoning, this can be used to estimate relationships based on empirical evidence.
- where appropriate, to decompose a system to modules, and consequently understanding the whole

Troublesome features:

- the significance and limitations of models: models, and theories are only simplifications and explanations that unify many individual instances and help to predict something not seen before. e.g. 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 to realise that models and constructs are not identical to the real world.
- Elements of a model are usually not physical but a representation that captures only the attribute 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 (e.g. to understand transform, 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 applying to the same system and useful under different circumstances, e.g. 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 e.g. 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

Taking a real life problem and putting it into a form ready for modelling/analysis
Using e.g. 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 applying the concept of energy, mass, and momentum balance are derived from trouble with system identification and definition

Troublesome features:

- realising that many systems change in time and space i.e. a free body diagram may be valid for a particular position or instant only
- This 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.
- identification of important variables, as some processes are negligible at larger or smaller scales. (e.g. gravity between two objects, Coriolis force, surface tension)

Examples

i. Free body diagrams

Troublesome features:

- isolating the body
- defining the system and replacing everything else with forces or moments
- understanding the limitations of generalisations used at school e.g. forces acting on simply supported items
- action and reaction forces (easier when normal but friction is difficult) (difficulty is remembering which body is being isolated and therefore students choose the wrong direction for friction)
- terminology: e.g. "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 acts are significant.

ii. Shear force diagrams

Troublesome features:

- why the shear force is drawn above or below and given a positive or negative sign (this is just a convention) *[This related to trusting* *mathematical models.]*

- difficulty with visualisation

iii. Bending moment diagrams

Troublesome features:

- why the bending moment is drawn above or below
- simultaneous compression and tension in a beam causing an internal moment
- Practice is required to the point where the diagrams can be drawn immediately.

iv. Control volumes

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.

v. 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:

- abstraction
- having faith that a complicated circuit can be modelled e.g. Thevenin equivalent for a battery (Jonathan Scott)
- the short circuit and open circuit definitions for components of the models are not always helpful as ways to calculate elements of the model
- recognising series and parallel components in a circuit diagram

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 e.g. 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:

- In situations where it is not obvious which model applies (e.g. transistors), teach as a game: these are the rules, work out what applies

(academic)

- In situations where it is not obvious which model applies (e.g. transistors): use a flow chart: 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)

i. Proofs

the concept of a proof, awareness of kinds of proof, common terminology

Transformative because required to:

- understand how to judge whether a model is satisfactory: This concept is transformative for engineers, not simply because it allows recognition of a proof, but because it opens up ways of determine 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, p41) 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: e.g. necessary and sufficient conditions, *QED*

d. Creating visual or symbolic representations

constructing meaningful visual representations of systems including representations of dimensions that are outside everyday observations

Transformative because required to:

- communicate ideas, concepts, 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
- This is a tacit engineering skill, meaning that teachers can overlook the need to help students develop this.
- 3^{rd} angle projection

Suggestions:

- practice
- Ask students to sketch and explain first in groups and then as group representatives explaining to the class.

Example:

i. Sketching phase diagrams and process paths

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

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

Transformative because required to:

- use models in engineering

For example:

- read and connect a circuit using a circuit diagram (Scott & Harlow, 2011)
- identify pins on a chip
- read a spring-mass diagram
- visualise 3-dimensional space
- understand implications of models in the frequency domain (Carstensen & Bernhard, 2009)
- read engineering drawings and sketches
- interpret bending moment diagrams
- read phase diagrams (e.g. *T-S*, *P-V*, etc.) and process paths and understand physical meaning
- understand physical implications of graphical representations such as oscilloscope outputs (Carstensen & Bernhard, 2009)

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.
- visualising the physical system e.g., 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 example without logically positioning earth. Therefore they have difficulty troubleshooting

Suggestions:

- problem-based learning and variation theory (Carstensen & Bernhard, 2009)
- practice
- peer teaching: 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

[*This item manifests differently in different contexts. Understanding of any one of these 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 3 dimensions
- understand transforms and implications of models in the frequency domain
- visualise the significance of numbers e.g. Reynolds Number in hydraulics (although these are likely to be beyond 2nd year)
- visualise the physical meaning of equations governing a feature such as fluid flow (e.g. visualising gradients and integrals)
- understand the physical meaning and the limitations of applicability of phasors e.g. to understand physical meaning of reactive power

Troublesome features:

- conceptually difficult and complex
- Perhaps the mathematics is not understood.
- unfamiliar notation - Mathematics is a different language.

Suggestions:

- peer teaching
- Remember to teach the physical implications of the mathematical concepts, rather than the mathematical relationships alone.
- animations and models
- dialogue between engineering and mathematics academics to enhance teaching
- Provide practice with examples in engineering contexts, e.g. by using mathematics tutors with engineering backgrounds positioning mathematics within engineering problems, or bringing engineering academics into mathematics lectures when new topics are introduced.

Examples:

i. Concept of derivatives

Transformative because required for:

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

ii. Relationships between systems and differential equations

(Similarly 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 t before differentiating

- dimensionality: recognising how many solutions any differential equation has: none, one, or many
- Linked to the above concept is realising that a differential equation has 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, use mathematics to represent a concept or relationship
- describe systems with more than 3 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:

- peer teaching – explaining the link between the physical and abstract is a way to demonstrate and develop understanding

Examples:

i. Vectors and dimensionality

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:

- difference between scalars and vectors (e.g. velocity and speed)
- physical interpretation of dot and cross products
- variety of representations for vectors (arrow in space, mathematical symbol with underscore or over-score or some other symbol, component form)
- confusion between use of the term “vector” to mean a 3-dimensional quantity (as in mechanics), and a multidimensional quantity (as in mathematics)
- difficulty visualising or drawing vectors of four or more dimensions
- coordinates e.g. polar coordinates in which circular motion can be represented as sine and cosines

Suggestions:

- a diagnostic test on entry and later
- facilitate individual exploration and build on this

- be sure to link the different notations

1. 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?
- the meaning of the k axis
- trusting 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.

2. Vector calculus

Transformative because required to understand:

- velocity
- acceleration
- electromagnetics [*higher than foundation level*]

Troublesome features:

- A vector at constant magnitude can have non-zero derivative.
- time cannot be substituted before differentiation
- difference between velocity and acceleration
- 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
- difference between acceleration and rate of change of speed in curvilinear motion

ii. Temporal and spatial frames of reference

Different coordinate systems and frames of reference, such as used to define relative motion, also differential and integral forms of equations
[*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 frame of reference e.g. to cylindrical coordinates, their advantages
- switching between a continuous and particle approach - e.g. 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 - Many reference systems change in time and space.

- relative definitions: e.g. displacement vs position, relative velocity, relative acceleration; potential difference, datum points and earth in electrical circuits

iii. Relationships between systems and differential equations

(as above)

iv. 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 inter-related features of systems

Troublesome features:

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

1. Linearity

Transformative because required for:

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

Troublesome features:

- superposition and homogeneity

2. Linear independence and the link to dimensionality

Transformative because required for:

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

v. Complex numbers

Transformative because required for:

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

vi. 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

The principle that nothing is lost. Which quantities are conserved and how? e.g. mass, energy (including Kirchhoff’s Voltage Law (KVL)), momentum, 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:

- “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.
- counter-intuitive: Newton’s 2^{nd} Law (Inertia) (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 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, p1) 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 e.g. 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

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:

- measurement of energy
- dozens of different forms of energy and different language
- voltage and potential difference
- the terms “potential/voltage drop” and “potential/voltage difference”
- stored energy
- In circuit analysis, assumptions about energy and charge entering and leaving the circuit are frequently unstated, although understood by the academics.
- KVL in the outer loop on a circuit diagram is not obvious to students because they do not recognise the outer loop as a closed loop.
- arbitrary nature of signs for current
- “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)
- Students often prefer to solve problems using forces rather than energy because forces are less abstract.

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 is a vector and is conserved.

Troublesome feature:

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

c. A fluid is a continuum, rather than discrete objects. Therefore 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

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, p461) called “holistic current flow… appreciation that current flows “incompressibly” through conductors”. Carstensen and Berhard (2008, p145) 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 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, not only connect a circuit, but also trouble-shoot

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 in real life processes into an abstract world and 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. [*This is an example of an application of modelling and abstraction. This item is one of several that are 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 (i.e. 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 (above)
- understand the iron/carbon system: steels and how we process steels, including working out proportions of phases present and microstructure (morphology), e.g. as an alloy solidifies

Troublesome features:

- abstraction required
- understanding that the two or three elements do not necessarily change phase independently
- 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]*
- complex to use - 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, what arrangement the phases will be in.

12. For a pure substance, only two independent thermodynamic properties (e.g. entropy and pressure) are required to define the state

Transformative because:

- simplifies analysis considerably

Troublesome feature:

- 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 etc.
- Ask students to describe what is happening, rather than referring only to numbers and calculations
- peer-teaching

13. Ideal gas equations

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 such as 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
- counter intuitive e.g. 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)
- lack of familiarity with thermodynamics when the concept is introduced in fluid mechanics e.g. 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, physical experiments.
- Help students develop a mental framework to understand what is happening at the molecular level. Relate these to high level averages, pressure, volume, etc. Relate to real life e.g. 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 to understand:

- 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 but the power does exist, although it does not perform work.
- the multiple terms and units for power: average, reactive, real, apparent, rms measured in Watts, VARs, and VAs
- terms such as ‘load’ resistance and ‘line’ resistance that might be used by teachers but not explained

a. Phasors

a convenient way to represent the magnitude and phase of a sinusoidal signal using the complex exponential such that a circuit with indictors 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 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

i. Complex numbers

Troublesome features:

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

15. The second law of thermodynamics

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.
- To maintain a state of disequilibrium requires energy or work.
- No process converting heat into work can ever be completely efficient.
- "How the disorderliness of something comes into play and affects a reaction, or amount of heat you can get out, or the efficiency of come cycle… it's not intuitive" (student). It is not easy to relate disorder to the physical world.

Troublesome feature:

a. Entropy

Troublesome feature:

- hard to describe conceptually

Suggestions

- study group to talk about the concepts
- other resources such as YouTube
- 'statistical approach' "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) [*At UWA this approach is not taught at the foundation level*.]

16. All systems, and their parts, tend to equilibrium. Engineers can manipulate this tendency in design.

Transformative because required to:

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

Troublesome feature:

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

Suggestion:

- 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 3-D aspects, integrating ideas of forces and geometry, the significance of the orientation of the plane for which stress is calculated
- stress transformation and principle stresses
- 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 3-D nature of stress is not clear to students until they learn about tensors, often not until 3rd year. Consequently, many students start with an incorrect understanding and many engineers never realise it is incorrect.
- cause and effect
- different types of stress and strain e.g. shear and torsional
- moment equilibrium in statically determinate systems, torque
- unique solution to statically determinate structure
- unique solution to a statically indeterminate structure - To solve a statically indeterminate structure, three sets of conditions are solved simultaneously: constitutive conditions relating stresses and strains, compatibility conditions relating strains and displacements, and equilibrium conditions relating forces and stresses.
- material failure models/theories: how to analyse the structural integrity of a component under multidirectional loading [*This is beyond 2nd year*.]

Suggestion:

- 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 depends on the material behaviour and the structural design.

Transformative because required for:

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

Troublesome features:

- remembering to include boundary conditions and compatibility conditions (in perhaps 3rd 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. 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. There is a 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 (e.g. 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 can change the properties.

Transformative because:

- influences 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.
- 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.

- complexity of theories e.g. quantum theory, band theory [*above the foundation level*]
- counterintuitive e.g. surfactants [*although surfactants would not be taught at the foundation level*]
- concept of how current flows through a conductor and [*perhaps in 2nd 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.
- reverse engineering - "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 micro-structure. What influences the micro-structure? 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 occurs through the motion of dislocations and therefore anything that stops dislocations from moving will increase the strength

Transformative because required for:

- understanding that all of the metal strengthening mechanisms work fundamentally the same way.
- "A fundamental concept is really micro-structure 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 3-D models or animations to help student visualise the phenomenon

b. Polymerisation

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:

- hard to visualise

20. Dimensional reasoning

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

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 (e.g. 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

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

SHAPING THE WORLD AS AN ENGINEER

21. Approaching open ended problems

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 final year thesis.

Transformative because:

- "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.137-138)
- problem definition
- framing the boundary of the problem
- diverging: allowing 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
- focusing on the significant decisions rather than being unnecessarily bogged down in detail
- identifying which variables and constraints are significant
- identifying assumptions that can be made

22. Integration of concepts

Considering the overall perspective / big picture / inter-relation between various models and theories. This concept was identified as a potential threshold concept by David Parkinson in his final year thesis.

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, p149)
- 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

This concept, "lateral thinking in problem solving" was identified as a potential threshold concept by David Parkinson.

Transformative because required for:

- problem solving

- approaching unseen styles of problems

Troublesome features:

- Students are used to ritual learning: being given a question and 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
- lack of practical experience, leading to lack of familiarity with common materials, mechanisms, etc
- 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

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

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

Transformative because required for:

- building sustainability into designs and solutions

Troublesome features:

- vague
- “Sustainability” can have multiple meanings.
- complicated
- influenced by and requires understanding of culture
- Students understand the idea but have difficulty using it.
- This requires students to think about topics that engineering students might rather avoid e.g. spirituality, love, social context.
- revisiting the concept of sustainability when students think they already know about it from school
- thinking more critically and broadly than students have learnt to think of sustainability at school

- integrating the concept of sustainability with engineering
- relevance of sustainability to engineering
- considering social, environmental and other aspects of the context
- waste

Suggestions:

- Ask student to consider planetary boundaries in solutions to problems.
- Using the systems, accounting, and modeling approach, every system interacts with its surroundings, and thus this approach emphasizes how a system and its environment are related.

25. Globalisation

This concept was identified as a potential threshold concept by David Parkinson.

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.”, “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.” (students)

Troublesome features:

- complexity - “I found the concept of globalisation confusing as it has pros & 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, 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)
- conceptually difficult - “The link between poor people and rich people. How does our economic system increase the gap between rich and poor?” (student)
- requires foreign knowledge - knowledge about different perspectives
- ritual knowledge - assumptions must be explored

Suggestions:

- ask students to debate a real scenario close to home e.g. decisions on boards in Europe leading to a factory closing in Australia, and production and/or maintenance moving offshore

26. Trusteeship

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, p322) 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” (p321).

Transformative and troublesome because:

- critiques commonly accepted assumptions

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