Teaching Complexity; moving between parametrics, paradigms and paradoxes

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CONTEXT

Engineering students are strongly influenced by reductionist and deterministic models that dominate their undergraduate learning. Many engineering students, attempting to engage with courses that do not fit this model, such as those dealing with complexity, struggle with the ambiguity and uncertainty associated with such courses. In response to this issue, engineering students at the University of Newcastle study a series of core courses oriented towards professional practice that incrementally work with complexity at several levels. These levels build on existing knowledge frameworks to facilitate students learning more disparate perspectives required to work with complexity.

PURPOSE OR GOAL

In this paper, we investigate and discuss a pedagogical approach to address the challenges of learning to work with complexity. This approach is offered to those involved in engineering education who wish to teach students to work with complex problems. The intent is to develop student's ability to identify aspects of complexity within a problem, thereby differentiating 'complex' from 'complicated'. This is important so that the correct methodology is applied. The project was motivated by the desire to seek complex problems outside of traditional engineering disciplines, to deepen and broaden the relevance for students of applying their engineering skills.

APPROACH OR METHODOLOGY/METHODS

We applied learning frameworks from Cynefin and Meadows to support students to learn to manage complex issues. Qualitative interviews and survey questions, conducted both formally and informally during and after course offerings, were used to evaluate the student experience of learning.

ACTUAL OR ANTICIPATED OUTCOMES

More than 600 students have studied these core and elective courses using the Cynefin and Meadows frameworks to teach complexity over a period of 2 years. Early feedback (6 surveys and 3 sets of interviews) reveals an increasing level of student engagement and comprehension about what makes an issue complex and how to work with complexity. More importantly, students report they can link their own experiences of working with complexity to other problems faced in more traditional, deterministic engineering courses.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

Introducing students to frameworks that teach them to work with complex adaptive systems positively influence their comprehension and confidence when addressing open-ended socio-technical problems. Students, understanding the relevance of their learning, are now requesting exposure to these important concepts earlier in their engineering programs.

KEYWORDS

Complexity, transdiscipline, human-centred design, adaptive systems.

Introduction

Engineering university students are regularly exposed to learning environments which prioritise reductionist and deterministic models. Engineering science knowledge is often backgrounded by concepts that lean towards compartmentalising and isolating system components in order to comprehend and control them. Scientific methods and perspectives are positioned as strongly aligned with practical engineering applications for transferring energy and controlling the relationships between system components. These theoretical, closed systems are challenged by the complexity of the real world, where complex problems are marked by the existence of multiple systems within an open environment. Authentic ‘complexity’ has its grounding in interdependence and cannot be fully comprehended using these reductionist approaches (Morin, 2008).

Many engineering students struggle with the ambiguity and uncertainty associated with courses dealing with system complexity and the nature of open-ended problems. In complex problem scenarios, students tend to apply rules from within their engineering discipline which are more aligned with closed environments and the pursuit of single optimum states. By contrast, working on authentically complex problems demands the students underemphasise the linear relationships between components and prioritise the presences of one or more larger systems (Mason, 2008).

In response to these issues, engineering students at the University of Newcastle (UON) study a core course (ENGG4500 Engineering Complexity) oriented towards professional practices that facilitate them with working with system complexity. In this paper, we discuss pedagogical approaches from this course which were used to address the challenges of students learning to work with complexity.

This approach is offered to those involved in engineering education and wishing to teach students to work with complex problems. The intent is to develop student’s ability to identify aspects of complexity within a problem scenario and to differentiate ‘complex’ from ‘complicated’ phenomena when determining which combination of methodologies to apply. This approach was motivated by the desire to prepare students for the likelihood of working with complex problems outside of traditional engineering disciplines, and to deepen and broaden the student’s application of their engineering skills.

Background

ENGG4500 formed the capstone course in the stream of core courses in the engineering degree programs at UON. These courses were built around ‘professional practice’ and were implemented as new courses in 2017.

Although they may be highly sophisticated, artificial systems devised by engineers tend to be based on the application of finite sets of rules and linear relationships. Even those systems which include randomised values in their variables are positioned as ‘knowable’ and against a backdrop of applying a heavily reduced numbers of options, sequences and formulae. This reductionist approach is effective for students when determining localised interactions between components in what are essentially *complicated* systems. In contrast, within *complex* environments, combinations of components exhibit behaviours and phenomena which cannot be predicted at the macro level (Camillus, 2008).

Complex problems involve open-ended systems which are: highly interdependent, may include a range of scales, are often non-linear and are, therefore, unpredictable. Students may perceive such systems as impossible to manage, however there are established methodologies for working with complexity. To work with complex problems, students needed a framework to increase their awareness of complexity and its distinctions from complicated systems. The Cynefin framework (Kurtz & Snowden, 2003) was offered into the course content and presented five categories of problems to support student decision making: Ordered (simple), Complicated, Complex, Chaotic and Confusion (Figure 01).

Students also need to build their comfort with unpredictable, open and circular problems. The Meadows framework (Meadows, 2008) was then introduced to provide students with a set of methodologies to provide an array of potential 'leverage points' for interacting with systems across a range of complexity levels (Figure 02). These two frameworks were combined/synthesised (Figure 03) to provide students, educators and tutors a reference tool to prompt discussions and scaffold student learning. In particular, to clarify student vocabulary and increasing their competency in using appropriate terms when communicating their own responses in discussions and assessment submissions

In addition to referencing the pragmatics relating to real-world engineering projects and case-studies, the course content purposefully challenged students to: acknowledge and evaluate multiple perspectives of the same situation, assess conflicts of priority and demands for limited resources, consider the potential role of their own judgement and heuristics and to recognise the absence of any single (determinable) optimum state or solution.

Cynefin and Meadows as a combined framework

The Cynefin framework was introduced first and offered a simple 2 x 2 squared matrix as a diagram for distinguishing systems which are Simple / Ordered, Complicated, Complex and/or Chaotic. This model can be seen forming part of the visual information in Figure 01 below. The boundaries between the four dominant fields are shown as curved and irregular to support the concept of flexible, non-rigid boundaries between the domains, while the small solid-shaded area in the centre indicated systems which remain as undefined or in states of Confusion.

Figure 01 below also reveals how the Cynefin model was backgrounded in this course by two meta-level concepts of 1st-Order and 2nd-Order perspectives which were influenced by the science of Cybernetics (Beer, 1974). These two concepts prompted students to consider that those systems on the right-hand side of the diagram (Ordered and Complicated) represented closed systems / problem scenarios where 'known' solutions were viable, and those on the left-hand side represented open system / problem scenarios where there were no 'known' solutions.

As students progressed through the course, this vertical separation was also used to distinguish 'first order' thinking/responding (dealing in the application of metrics and absolutes within a reductionist framework) and 'second order' thinking/responding (dealing in uncertainties and compromises in a context-driven, holistic framework). This relatively simple distinction proved to be one of the most empowering concepts for the students as it clarified the separation of 'complication' (being centred around the concept of objective *interconnection* of components) and 'complexity' (being centred around more subjective *interdependence* of multiple systems of components).

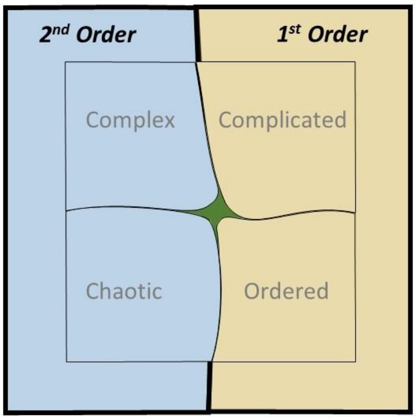

Figure 01 – Cynefin model overlayed with the concepts of '1st' and '2nd' order engineering responses. Note, the region relating to 'Confusion' is the small, unlabelled area in the centre.

The second framework introduced to the ENGG4500 students was the Donella Meadows model (Meadows 2008) for identifying 'leverage points' within complex systems. The Meadows model offered students the opportunity to relate their emerging vocabulary around complexity with different opportunities for system intervention. Rather than position the Meadows model as adding finer resolution to different problem types, it was used to propose an array of potential engineering responses that could be aligned with the nature of the system / problem being addressed.

In Figure 02 below, the various leverage points in a system, were overlayed with the coloured fields representing 1st and 2nd order responses shown in Figure 01. This was to facilitate student discussion and observations when forming connections between; various system / problem types, the nature of their own thinking and the potential qualities in their responses.

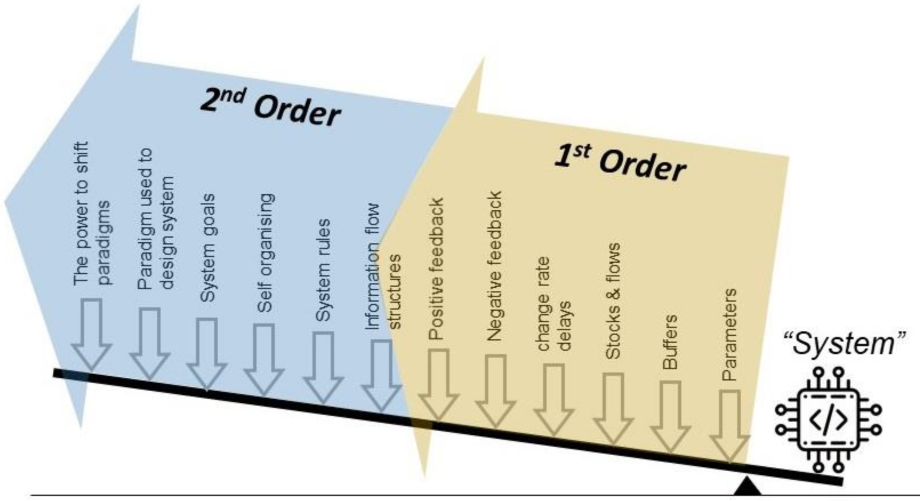

Figure 02 – Simplified Meadows framework overlayed with the concepts of '1st' and '2nd' order thinking / responses.

Figure 02 was positioned as an interim step for students when reflecting on the nature of how they may craft their strategies when interacting with a variety of system / problem types. The final framework offered into the course is shown in Figure 03 below. Here the nature of the two previous diagrams (Figures 01 and 02) are synthesised to provide the students and staff with a device to explore the potential for connectivity between the complexity frameworks and how this may inform students thinking.

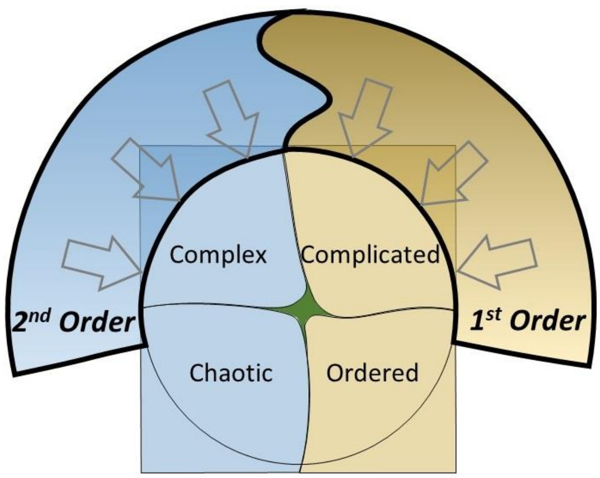

Figure 03 – Cynefin and Meadows frameworks synthesised as a learning device.

The Cynefin model is still centred in the diagram, however the square boundary of the original framework is under-emphasised in favour of a more circular boundary. This was to soften the inference of 'hard, regular boundaries' and to support the idea of both continuity and concentric scaling outwards. The symbolism of the circular boundary was also more supportive of the complexity concepts of non-linearity, feedback loops and scalability. The gradient of colour shading within the 1st and 2nd Order ranges indicates that potential responses from students form part of a nuanced gradient or progression, rather than in pre-determined interim steps or stages.

The zigzag boundary at the top of the diagram, between the 1st and 2nd ordered thinking (coloured) regions was to stimulate student discussion about the nature of any transition between the Complicated and Complex system types and the absence a clinical, predictable threshold – similar in nature to the boundary between Complicated and Complex systems within the Cynefin model. The greyed arrows were transitioned over from the 'leverage points' within the Meadows model and are here positioned to support the concept of students needing to align the nature of their response to the implicit nature of the underlying problems / systems.

Complexity and learning experiences in Engineering

The nature of teaching complexity to large and diverse engineering cohorts is, in itself, a complex problem environment. Learning experiences around complexity have particular challenges for educators with regard to their pedagogical approaches. Both the delivery and the student engagement need to be non-linear in order to be genuinely complex, which can be challenging to reconcile with the need for the course to be directed along a linear timeline of; content sequences, progression of learning and linked assessment structures. Reflecting the behaviour of complex systems within the course structure creates areas of tension when attempting to include aspects of emergent or self-organising behaviour. For instance, the use of pre-existing engineering scenarios and case-studies tend to have their foundations in the past tense and are a review of fixed and prior events implying high levels of predictability and higher degrees of 'known' and/or determinable outcomes.

Tutorials: - Tutorial sessions in ENGG4500 presented an opportunity for students to participate in a more immersive learning environment for evaluating complex phenomena in a range of problem scenarios. Students were provided with prescribed scenarios based on real world case-studies and tasked with identifying aspects of the situation that may be considered as complicated or complex (relating to the various weekly topics). In the apparent absence of any identifiably complex phenomena within the problem scenario, students were tasked with intentionally 'introducing' complex phenomena into the situations and rationalising their proposals.

The bi-directional nature of these exercises were to keep challenging the student's interaction with the course content by tasking them with both: modifying complicated phenomena in order to introduce complexity and to propose strategies to manage existing complex behaviours. The focus of the exercises was on comprehending and exploring phenomena (in a supportive learning environment) rather than offering solutions or 'solving' the problem. Foregrounding their creative explorations meant students became more receptive to the presence of unpredictable, non-anticipated phenomena within problem environments and towards developing their system awareness (and hence a set of diagnostic tools) for them to reference in professional practice. These exercises proved effective as a lead-in to the creative aspects of their assessments.

> *"..[this course] creates an engineer out of an engineer" – ENGG4500 student, Semester 2 2021 commenting on the thought processes involved in the tutorials.*

Assessments: - Assessments were structured around the students designing viable proposals within complex human-centred, problem scenarios provided to them in the form of Design Briefs from (fictitious) clients. 'Clients' were used in all course assessments as platforms to introduce the expectations of professional practice and to shift students' responses to comply with an imposed set of (clients) specifications. The client Briefs presented students with environments where they needed to negotiate between conflicting priorities while ensuring their concepts included empathic design for potential end users and acknowledging multiple viewpoints of the problem stakeholders.

Grounding the assessments in generating functional prototypes for their concepts provided opportunities for students to both conceptualise and execute their designs against a fixed timeline but with an open-ended set of technical specifications. By introducing human dynamics into the design briefs (in the form of the clients demands and the requirements of the target end-users) the ‘problem’ environment immediately became authentically complex. The pedagogical intent of this kind of assessment structure was to promote collaborative review and evaluation of the student proposals (by both academics and peers) from both first and second order perspectives.

Initial course assessments centred on definitions of terms and using the ‘client’ specifications in order to allow students to respond / reflect on varying degrees of *complication*. Latter assessments in the course shifted to *complex* environments involving multiple end-users (eg blind and fully sighted users, low and high literacy/numeracy levels etc) where students needed to include aspects such as; empathy, emotional intelligence and service design (where there were no resulting artefacts and students engineer the ‘experience’ of the end-users instead).

> *“The assessments were some of the most unique and interesting assessments I've had to do so far in my degree.” – ENGG4500 student, Semester 2 2021.*

Measuring student experiences

Gauging levels of student learning in engineering courses with high levels of soft-skills is problematic. ENGG4500 attempted to gain insight into student experience and engagement by using a variety of student feedback forums during the delivery of each course. More than 800 students have completed the course at the time of writing, 600 in the last 2 years.

Formal feedback from students who have completed the course took the form of ‘opt-in’ style surveys and questionnaires heavily promoted by UON. The topics within these surveys seek quantitative ranking of student perceptions of the course value and relevance as well as rating the teaching and delivery of the course content. Figure 04 below is a graphical representation of this quantitative feedback from students of ENGG4500. Note the high levels of (self-reported) student engagement – shown in red, in comparison to the relevant School and Institutional averages for the same reporting periods.

Informal feedback from students took the form of tutorial sessions, discussion forums and focus groups which prompt students to identify areas of improvement while discussing the course content and delivery. In both the formal and informal channels students strongly indicated their increase in confidence when articulating aspects of complicated and complex scenarios as a direct result of doing the course. Students also noted their familiarity with the complexity frameworks from ENGG4500 positively influenced their willingness to engage with open-ended problems in other courses within their program.

> *“I didn't really understand why I wanted to be an engineer or if it was even the right career path for me until this course. Now instead of just doing it because I knew I could, I now not only know I want to be an engineer, but also the type of engineer/ person I want to be in the workforce.” – ENGG4500 student Semester 2 2021.*

Qualitative feedback took the form of open-comment fields within each survey and prompting questions relating to ‘what worked well’ and ‘what could be improved?’. Responses gathered over the preceding 4 years have revealed the students request that the concepts within ENGG4500 to be introduced earlier in their programs in order for them to apply the thinking and frameworks in the first years of their engineering degree.

> *“…after my 6ish years at UON this is by far the most practical and enjoyable course I've done.” – ENGG4500 student, Semester 1 2020.*

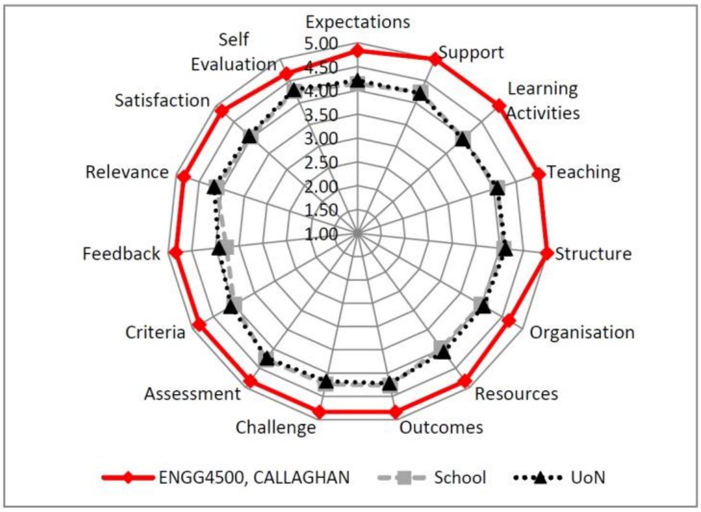

Figure 04 - Student Feedback on Course (SFC) results for ENGG4500 revealing relatively high levels of student self-reporting engagement with the content and the delivery methods.

While the student experiences post-completion were positive, student engagement with the early weeks of the course remained hesitant. The results of the informal focus groups revealed that many students reported being anxious about taking the course based on their expectation that it was about ‘mathematical complexity’ and/or ‘deep technical’ content. When the first few weeks of the course exposed the students to problem scenarios with no pre-determined solution and conflicting priorities, they reported that their concerns moved from those relating to ‘will I be good enough?’ towards those relating to ‘how do I know what to do next?’

Managing potential inferiority-complexes

Student feedback forums were held in the first few weeks of the course revealed students struggling to engage with problem scenarios that have no known determinable solution. Student often needed reassurance relating to them asking ‘am I doing this right?’ as the ambiguities and uncertainties in complex scenarios led many students to perceive they were being tasked with ‘diagnosing’ aspects of a situation, which by its definition, may not be fully diagnosable.

Students of ENGG4500 had reported initial feelings of unease when addressing complexity, due in part to their own perceptions that engineering competency was strongly aligned with the ability to anticipate potential (singular) solutions by using preformed ‘known’ responses. When problem / system complexity increased, their confidence was undermined by their (apparent) inability to predict and wholly apply existing frameworks.

Prior to taking the course students tended to use the phrase ‘complex’ not to offer an explanation of the phenomena present, but to indicate their difficulty in explaining the situation or (potentially) that it defied explanation. Discussion forums with enrolled students revealed that they initially perceived ‘*complicated*’ as something that was multi-faceted, whereas the term ‘*complex*’ was something that was personally difficult or a the same as ‘complicated’. Consequently, the course objectives were oriented towards decrypting the phenomena of complexity to allow students to use the associated terms correctly and to comprehend the implicit phenomena involved in a variety of problem / system types.

> *“..it isn't a course designed to teach a law or a process, but instead it teaches thinking” – ENGG4500 student semester 2 2020, responding to a survey question relating to course content.*

The introduction of the learning framework discussed above was in direct response to student feedback and has proven pivotal for the staff and students within the course, in particular when evaluating student learning, comprehension and communication within assessments.

".. this course has made me excited about the future and has instilled some pride in being an engineer … I could walk away with a feeling of accomplishment that I have a tool I can actually use and exists outside of my lectures." – ENGG4500 student, Semester 1 2020.

During the Covid lockdown, each weekly online session was supported by short duration, plain language videos across multiple broadcast platforms, which regularly exceeded 14,000 views per semester (across approximately 100 videos). While the pre-recorded content was popular in terms of view count, it did not correlate strongly with student comprehension (Winslett 2014). Student feedback foregrounded the lack of 'intensity' that resulted from online delivery modes and that they placed a high value on the dynamic and challenging 'shared learning' experience provided by the face-to-face sessions with the academic staff. This intensity was corroborated by academic staff who noted the face-to-face session had greater flexibility to present/defend alternative perspectives, encourage student immersion into poorly structured / open ended problems and the willingness for students 'translate' new perspectives into their own lived experiences.

Discussion

ENGG4500 avoided trying to 'teach' complexity, rather it focussed on raising student awareness of behaviours and phenomena within both complicated and complex systems and for them to be confident in evaluating and articulating those phenomena. It may not be practical for students to comprehend all elements within a complex system; however, it is achievable for them to predict how such systems behave. Embracing complexity for engineering students may involve shifting the emphasis from 'how the systems work' to 'how the systems behave'.

Engineering students tended initially to relate more strongly to *complicated* systems due the presence of clear internal structures and the likely potential for centralised functions or organisations. Presenting the absence of such structures in *complex* systems may be better served by including aspects of socio-technical systems which often lack such structures and organisations. Their internal structures are not prescribed, rather they are developed by the system itself, as a means of maintaining its adaption to complex and dynamic environments.

Socio-technical contexts may also offer a platform for including aspects such as engineering ethics, multiple worldviews, the absence of any single 'correct' view or outcome, combinations of systems and (ultimately) authentically complex phenomena (Batie, 2008). As such, complexity for engineering students may be more clearly comprehended when framed in terms of where the Artificial meets the Living. Most engineering activities which result in outcomes of artificial entities or energy transference are done with the use of prescribed scientific rules and are more strongly aligned with 'complication'. By comparison, biological systems introduce authentically complex phenomena such as interdependence, multiple scales of co-existing systems as well as emergent behaviour and capabilities (Nadin, 2010). Perhaps the focus of student learning around complexity needs to shift away from the search for purely objective models of reality towards including the exploration of the cognitive and social processes being used to 'construct' those models? (Goldstein, 2013).

The delivery of ENGG4500 had also revealed issues relating to students needing 'time' to formulate their own strategies when dealing with complexity. In particular, evolving strategies that do not attempt to 'solve' the issues, but rather to 'resolve' them towards preferred states and conditions. Even if it were logistically practical for large engineering courses to provide all students with interactive and immersive complex scenarios, students would still be tasked with experiencing the 'inside' of the scenario while attempting to evaluate it from the 'outside' for the purposes of learning outcomes. For students to be confident in reconciling the two perspectives (the 'sense-able' and the 'sensible'), the skills necessary may need to be bolstered by formative experiences in earlier years of their education.

"*I believe they need to have more courses like this as intermediate courses that use these types of notions throughout uni because the content in the course is extremely valuable and if it was applied throughout more of uni it would stick with students better" – ENGG4500 student Semester 2 2021.*

For students to develop the life-skills necessary for them to become comfortable with uncertainty and to form responsive strategies in the absence of engineering precedence, the progression of learning needs to be distributed across the entire engineering program. This way the critical thinking skills of the students are more likely to mature to the point where it can be statistically significant (Behar-Horenstien, 2011).

The ability to project professional activities into the future is crucial to the success of the process of engineering education to identify opportunities to work and develop professionally. Graduating engineers should be able to follow paths that do not currently exist, given that they will likely have a role in the discovering and establishing these paths. It is not a matter of working with certainties concerning known facts but instead, working with uncertainties and building a future for the development of society (Zilbovicius, 2020).

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