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Story arc: The need for narrative to convey disparate concepts, skills, and knowledge

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Abstract

The importance of a degree-spanning narrative structure was identified as important to developing student capability to recognise that their knowledge, concepts, and skills can be applied to achieving tangible outcomes in the 'real world'. The specific example reported herein is the restructure of a 'chemistry for engineers' course into a narrative-based story-arc that only introduces new knowledge, concepts, and skills so far as they are useful for the production of the dye molecule Tyrian Purple. Interviewing students who took the course pre- and post-structural change revealed the power of the story-arc approach for improving student engagement, retention of knowledge, and ability to recognise the relevance of knowledge to their degree. This study highlights the importance of departments and faculties providing students with a connecting narrative for their entire degree, each course, course segment, and individual lectures.

Context

At the University of Canterbury (UC), students take a first general year of engineering courses before specialising into a discipline, such as chemical engineering, for the remaining three professional years of their degree. This first year is highly prescribed and contains a single course in chemistry, with an optional second course. Chemical and process engineering students require a wide range of chemical concepts throughout their degree. Students' primary source of learning is the 200-level course 'ENCH241' containing 36 lectures and 6 labs. Despite the best efforts of teaching staff, high-quality content, and 5+ years of annual iterations of the course which saw 4-8 week course sections added and removed, student feedback on the course consistently indicated students did not understand the relevance of the course to their degree. Teaching staff in 300 and 400-level chemical engineering courses also identified ENCH241 as having unaligned learning outcomes which left gaps in understanding that propagated throughout the degree. In this paper, we discuss how the course was restructured using a story-arc narrative structure to make the course relevant to students and provide them knowledge and skills to succeed in their degree, student interview results that reveal the impact this restructure had on student experience, and ideas for how the story-arc approach can be generalized.

Purpose

The 200-level chemistry for engineers' course (ENCH241) was restructured using a story-arc narrative approach to deliver a wide range of chemistry content, enhance student knowledge retainment, and illustrate the content relevance to chemical and process engineering. Our hypothesis was that a narrative driven course would engage students, illustrate the relevance of the content to the student's degree and future employment opportunities, and allow a wide range of disparate concepts to be covered within the one-semester course.

Keywords

chemical engineering, narrative inquiry, course design, STEM, curriculum design, educational development, undergraduate, utility of knowledge

Approach and methodology

We took a three-stage approach to this project: 1) definition of required content; 2) course restructure; 3) evaluation *via* student interviews.

Phase 1 – Definition of chemistry knowledge needed for the degree

We identified and documented the chemical concepts required for the degree using a departmental review. A list of all 200, 300, and 400-level chemical engineering courses was created and the course coordinators and lecturers were asked to assert and prioritize all the chemical concepts required and utilized in their course(s) (Table 1). For example, a biochemical engineering paper required an understanding of pH, reaction rates, and catalysis. Once collected, the prioritized list of concepts then needed to be mapped onto a course structure that connected the disparate ideas into a teachable framework.

Phase 2 – Course restructure to a story-arc narrative framework

Based on the results of *Phase 1*, the authors brainstormed pedagogical methods and course structures suitable for tying disparate concepts together while co-currently increasing the perceived relevance of the chemistry material to chemical engineering processes and workflow in industry.

The underlying psychological theory used was Subjective Task Value (Eccles, 2005). The four components of subjective task value describe the likelihood of someone engaging with a task:

1. Attainment value, defined as "the personal importance attached to doing well on, or participating in, a given task".
2. Perceived cost, which Eccles refers to in terms of emotions (e.g. fear of failure) or investment of time and energy. Framed the other way, it can be the cost associated of not engaging (e.g. a failing grade).
3. Utility value, defined as usefulness, how engaging with the task fits into future plans. Eccles views utility value similar to extrinsic motivation.
4. Intrinsic value, the inherent worth of the task and the enjoyment of task engagement. Intrinsic value can also be linked to intrinsic motivation (Ryan & Deci, 2000), which itself is mediated by three components, feelings which are innate needs for humans:
    a. Autonomy
    b. Relatedness / belonging
    c. Competence

Producing and refining the narrative course structure was inspired by a collection of literature and course examples. Two components were identified as vital to the course structure: 1) A goal-oriented structure to deliver student satisfaction, attainment, and experiential learning (Chen et al., 2019). 2) Connection of knowledge to societal impact (Demoranville et al., 2020).

We gained inspiration from previous literature describing narrative story-telling (Pabuccu & Erduran, 2016; Peleg et al., 2017) and gamification of education through 'escape room' style labs (Bezard et al., 2020; de la Flor et al., 2020), taking the narrative element from the latter approach. Looking away from chemistry and chemical engineering, we also noted the success of case studies promoted by the Harvard Business Review and Department of Environmental Sciences at the Swiss Federal Institute of Technology, which use analysis of real-life examples to illustrate business and multidisciplinary concepts.

We aligned the idea of a narrative course structure that centred around the synthesis of a molecule with connection to society and culture. After considering several molecular targets and synthetic pathways, we selected a relatively new synthetic route to the dye molecule Tyrian Purple for the reasons discussed in the Actual Outcomes section (Wolk & Frimer, 2010).

Phase 3 – Evaluation of student perception and engagement

Our final step was a critical evaluation of the course-content switch to narrative-structure. The evaluation was completed *via* semi-structured interviews with current fourth-year students, who had taken the old version of the course, and current third-year students, who had taken the restructured version of the course. This phase of the study required ethics approval, which was obtained through the University of Canterbury Human Research Ethics Committee (ref 2022/33). The interviews were conducted by the second author, who is not connected to the department or to the course. As such, the risk of perceived power differential and socially desirable responses from the participants were minimised. Student participants were recruited by the first author through a generic email to third- and fourth-year students. Student replies went directly to the second author, so the first author would be unaware of which students took part.

Ten students agreed to be interviewed, six of them third year and four fourth year. Semi-structured interviews were held in a meeting room on campus or via Zoom and lasted between 7 and 20 minutes. The conversation was semi-structured, with questions pre-determined, but allowing for a free flow of conversation, and not all questions were asked in all cases (see Appendix A for the interview questions). All interviews were recorded using Zoom, which generated both a recording and an automatic transcript. Unfortunately, because of the technical language used in some cases, as well as accented English, the transcripts were not very helpful. Instead, the interviewer re-listened to the interviews, and generated executive summaries around the key interview questions, which were then discussed between the two authors to draw conclusions regarding the student experience. For ethics reasons, the first author had no access to the raw data.

Student interviews were used to compare perceptions and success of students who had experienced the past and restructured course. Our main interest was to see how the conversation about the course differed between the third and fourth-year students. We approached the interview data with two key questions.

- How did the students from different years describe their experiences in the course?
- How did they describe the chemistry / chemical engineering in the course and how did they see this flow on to their degree and professional life?

We opted for this approach, as a fully grounded coding of the data can lead to a significant number of codes that are not necessarily useful. Asking a generic question of the data set and coding only for elements that help answer those questions is a more efficient way of going through interview data, while ensuring rigor by not asking too closed a question and thus minimising confirmation bias. Based on the interviews, the transcripts and the executive summaries, themes were identified for each of these two questions.

Limitations in this method include: Deeper analysis was prevented by the lack of ability to obtain perspectives from many years of past students who had been through past versions of the ENCH241 course. Likewise, the experience of students with the new course structure was likely affected by the issues that confront new courses, i.e. errors in teaching material, inexperience with teaching materials, and first-time assessment design.

Actual outcomes

Phase 1 – Definition of chemistry knowledge needed for the degree

Our 2021 course review identified 33 disparate concepts, techniques, and knowledge that students needed to know and understand for success in the chemical engineering program (Table 1).

For readers without chemistry backgrounds, Table 1 contains a wide variety of concepts that are difficult to connect because they are fundamental to understanding all the other categories (Key Concepts) or independent unrelated topics, e.g. organic reaction mechanisms and redox reactions. Although it is easy to identify many individual examples, such as a specific chemical reaction or molecule, to illustrate each topic, it was impossible (at least for us) to identify a single example that was connected to all these topics. A common solution to this problem is to include many individual examples, however that approach leads to teaching isolated and disparate examples and concepts that can be overwhelming for students.

At this point, the problem became clear: How can we link a series of disparate chemistry concepts and illustrative examples? Shortly after the problem became clear, the answer followed suit: A coherent synthetic scheme. For this, we selected a recent synthesis of the dye molecule Tyrian Purple (Figure 1).

Phase 2 – Course restructure to a narrative framework

The conclusions and inspirations from the analysis in Phase 1 gave rise to the idea of a narrative course structure that centred around the synthesis of a molecule. We then recognized that the choice of molecule provided an opportunity to imbue the chemistry content with connections to chemical engineering careers and wider society, including cultural aspects such as Mātauranga Māori and societal value such as 'wealth' creation (where wealth is broadly defined to consider material wealth, health, security, etc). We perceived that this opportunity linked to the Subjective Task Value, particularly utility value (chemical engineering careers) and intrinsic value (relatedness/belonging), and attainment value (their skills in producing/obtaining societal value and prestige from engineering outputs).

After considering several molecular targets and synthetic pathways, a relatively new synthetic route to the dye molecule Tyrian Purple was selected (Figure 1). Most importantly, this synthetic route contained a diverse selection of organic and inorganic reagents that allowed all identified chemistry concepts to be covered in the course material.

Table 1. Chemistry concepts needed for the chemical and process engineering degree.

Key concepts	Supplementary Concepts	Skills	Key knowledge	Supplementary Knowledge
Equilibrium	Bond structures	Structural drawing	pH, pKa, and pH control	Mass spectrometry
Reaction rates and thermodynamics	Electronic configuration and reactivity	Literature searching (chemical structure and reaction)	Mātauranga Māori (chemistry)	Amine and phosphorous chemistry
Oxidation and combustion reactions	Molecular shape and steric hinderance	Purification of organic reactions	Environmental impact of natural products vs. synthetics	Origin of raw materials (hydrocarbons, metals, halogens)
Reversibility of reactions	Organic reaction mechanisms	Retrosynthetic analysis		Melting point
By-products and incomplete reactions	Purification of metals and organics	Characterization of compounds	Characterization of compounds using online resources	Elemental analysis
Redox reactions and standard potential	Disproportionation	Infrared, NMR, and UV-Vis	Electrochemistry	

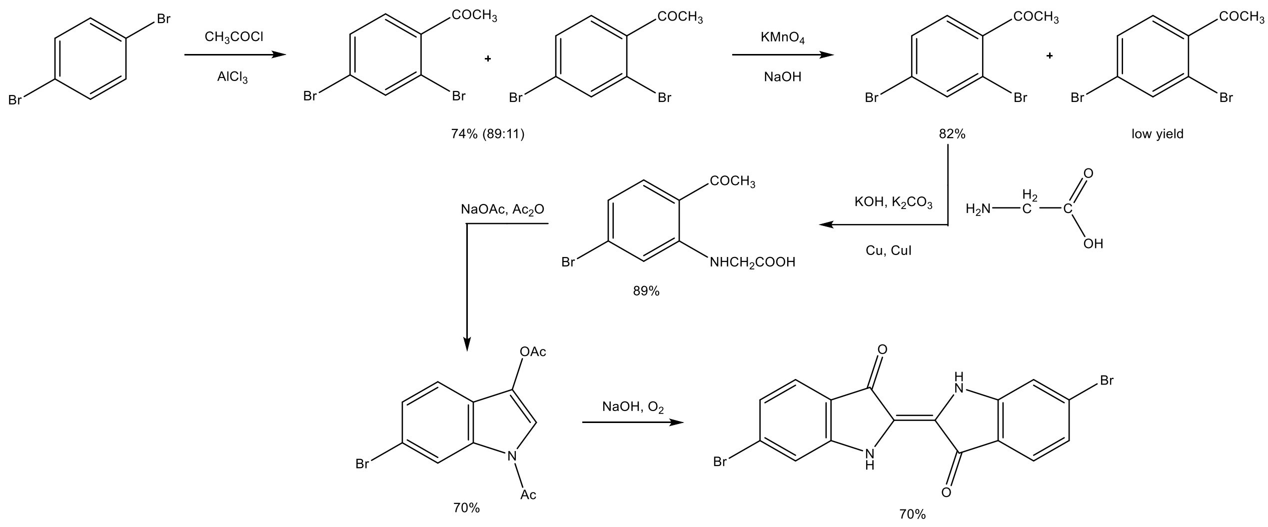

Figure 1. A safe and facile synthetic scheme for Tyrian Purple that utilizes a convenient range of common organic and inorganic chemicals that are in-turn produced from a wide variety of raw materials (Wolk & Frimer, 2010).

We saw Tyrian Purple providing links to various aspects of Subjective Task Value, such as Attainment, Perceived cost, and Utility value. These links included:

1. Cultural significance and hierarchy of historical access to dye products and colours as religious icons, status, and indications of wealth.
2. Example of what happens when historical technical information is lost (the processing of Tyrian Purple dye from sea snails).
3. The environmental impacts of relying on
   a. natural rather than synthetic products (i.e. extinction or endangerment of sea snail species used to make Tyrian Purple).
   b. synthetic products (i.e. fossil fuel resource extraction).
4. The ability, knowledge, and skills to transform raw materials into material wealth that benefits society
5. The ability to reduce environmental impacts associated with production of material wealth.
6. The ability to produce wealth for yourself (i.e. the student) and obtain employment.
7. Examination of Mātauranga Māori used to produce dye materials from natural products and connection to the applied chemistry concepts used in that dye production.
8. The cultural significance of Tyrian Purple to nations throughout the Mediterranean.

The synthetic scheme of Tyrian Purple was elaborated on using a ‘story arc’ approach to deliver the chemical concepts. Story telling is a well-known pedagogical tool that is very effective (Landrum et al., 2019). In this instance, the narrative was generated by considering that we (the class) need to produce the dye molecule Tyrian Purple. Sub-narratives were developed for each step of the synthesis, where the different reagents create a need to understand subsets of the chemistry concepts and skills in Table 1. These skills reintegrate into the overall narrative and give students the power to transform raw materials into the product Tyrian Purple, i.e. a material with social and commercial use.

To provide an explicit example: the first synthetic step of Tyrian Purple requires Aluminium Chloride. Aluminium chloride is a simple common laboratory reagent containing only two elements (aluminium and chlorine). The simplicity of Aluminium Chloride production makes belies an excellent scaffold for covering pH and acid/base chemistry, stoichiometry, equilibrium, precipitation and solubility, redox reactions, and potential energy. This is mapped in Table 2.

Table 2. Mapping of chemistry concepts onto the production of Aluminium Chloride

Concept	Connection to Aluminium Chloride
pH and acid/base chemistry	Production of aluminium chloride requires aluminium oxide, which is produced from Bauxite minerals using sodium hydroxide (base chemistry).
Stoichiometry	Aluminium oxide formation proceeds through several sodium aluminate intermediates and hydroxides, giving opportunities to balance reaction equations.
Equilibrium	Sodium aluminate formation provides an opportunity to recap equilibrium expressions and the magnitude of equilibrium constants corresponding to ‘complete reaction’ vs. ‘no reaction’.
Precipitation and solubility	Widens the equilibrium concept to expand the students’ perception of reactions; in this case looking at purification of aluminium oxide through crystallization.
Redox reactions	The production of aluminium metal and chlorine gas is industrially performed using electrolysis. The provides chances to consider half equations and redox reactions.
Potential energy	The redox and overall reactions are suitable for discussing the components of total potential energy and relating energy changes to reaction spontaneity and equilibrium composition.

Phase 3 – Evaluation of student perception and engagement

Our interview results showed two major differences in student perceptions were achieved by moving to the Tyrian Purple story-arc structure:

1) A greater retention of knowledge and ability to apply and integrate chemistry knowledge

Students who had taken the Tyrian Purple course structure spoke about the course as an example of *chemical engineering as a process*. In stark contrast, students who had taken the pure chemistry content spoke of the course mostly in terms of *individual chemistry concepts*, such as catalysis, reaction schemes, endo- and exothermic reactions. Some of the latter students described their learning as ‘learning in a vacuum’, heavily theory-based without a clear connection to applications, chemical engineering and industry. They implied (but not said explicitly) that they could not always see the reason they were learning specific concepts.

Our hypothesis and conclusion on this aspect is that engineering students have strong motivations to learn when the content provides the ability to utilise their degree for tangible benefit to themselves and others. Therefore, course structures without explicit illustrations of how and when knowledge can be utilized to provide tangible benefit are less likely to lead to student engagement and retainment of information. This conclusion is somewhat supported by additional comments from students who had taken the pure chemistry content, most mentioning that they *had forgotten a lot of it and/or had not used the material since*. Writing as authors familiar with the chemical engineering degree, those student comments are blatantly false, i.e they have definitely needed to utilize the content they learned in the pure chemistry course. However, it is clearly true that the students *have not recognized the connection between the pure chemistry concepts they learned and how those concepts are utilized in their other courses*.

Interested readers teaching engineers can apply this finding by ensuring their course content includes the connection of theoretical content to explicit examples where the knowledge is applied to achieve tangible benefits.

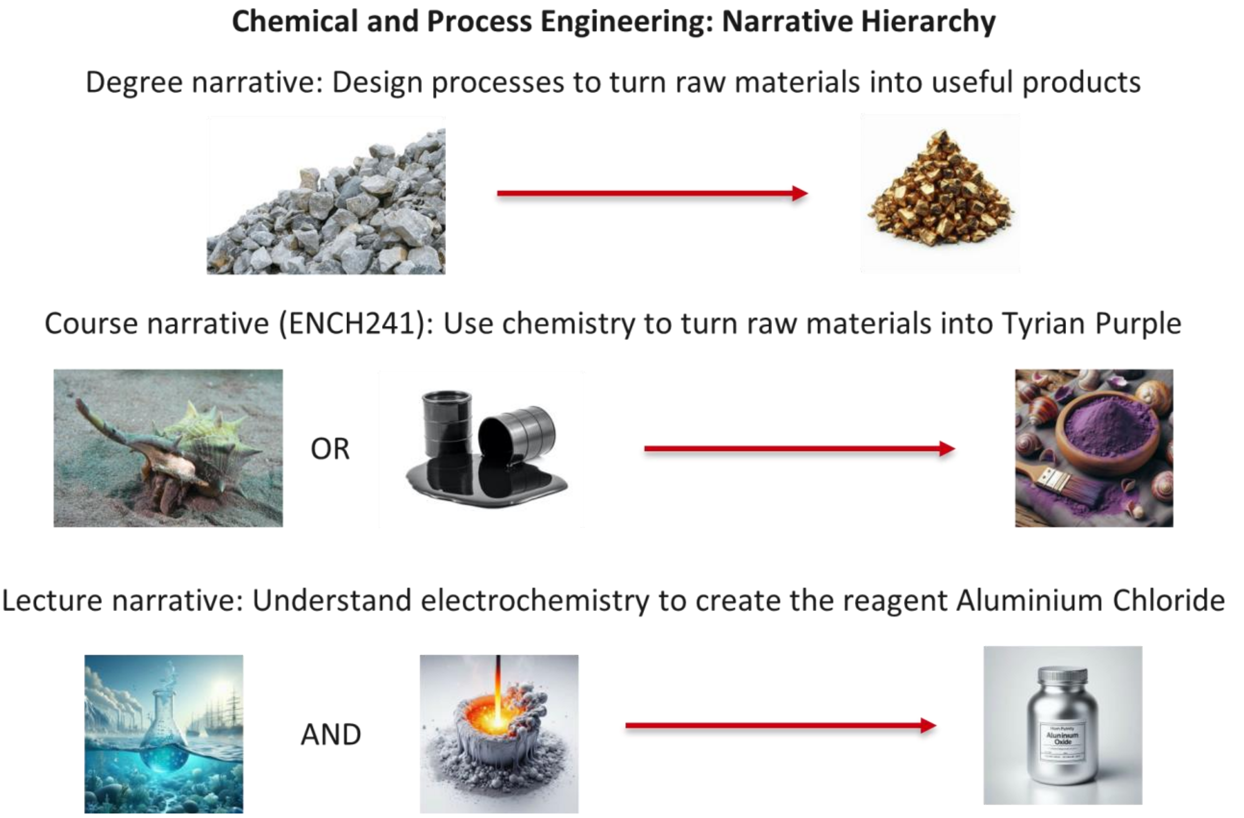

Figure 2. A visual representation of the narrative hierarchy linking the story-arc of the chemical and process engineering degree to the ENCH241 course narrative, then the narrative of individual lectures.

2) A greater understanding of how chemistry fits into the chemical engineering degree

Students taking the Tyrian Purple course structure were very positive about the example, calling it ‘real-life’ rather than theoretical. They noted that it was illustrative to see a chemical production process from start to finish, from sourcing materials to the various reactions that are available along each step of the way to create the final product. They commented that because of the story-arc approach, they could see why they were learning about different types of reactions (which was also reinforced by the lecturer). They also could see the links with chemical engineering in practice, and the different aspects of the engineering process that have to be kept in mind (e.g. sourcing materials, energy use, optimising steps in the process, choices of reaction types in the process steps, by-products and what to do with them).

In contrast, students taking the pure chemistry course commented that they found the material quite overwhelming, with more chemistry knowledge assumed than they possessed, and no contextual clues to connect to the information. Virtually all (third and fourth year) students commented on the extensive and reduced catalysis content, noting that catalysis is only used extensively in one minor in the department (the energy minor), whereas the other minors do not use catalysis to the same degree (if at all). Note that this student perspective is also completely false. Catalysis is used extensively in all three chemical engineering minors (Environmental engineering, and Bioprocess engineering), where the catalyst is often filled by the role of enzymes within microorganisms. Again, this reveals the true conclusion: students were unable to map their conceptual knowledge onto distinct (but fundamentally identical) tangible applications.

For educators attempting to produce students who can leave university education and apply their skills and knowledge to a wide range of career paths, our conclusion from these student perspectives is that the content of an individual lecture needs to tie into both the narrative arc of the course AND the overall narrative of the degree (Figure 2). Obviously, this presupposes and requires that the degree structure is given a cohesive narrative structure, e.g. "*Chemical engineers design processes to transform raw materials into valuable products*". The presence of this overall narrative and layering of the narratives at the course level, lecture series level, and individual lecture level requires concrete leadership, buy-in, and cooperation of all teaching staff delivering the degree. An easily overlooked requirement is that all teaching staff understand the story-arc of the degree, purpose of university education, and how their courses fit into the degree narrative.

3) Minor observations

A criticism of the Tyrian Purple example is that the narrative structure, combined with the availability of recorded lectures, means that some students 'binge watch' the videos at the end of the semester to get the whole story in one go.

Students reported a similarly high positive engagement with the lab work component of the course, where the chemistry was more applied, and students learned about fundamental chemistry concepts in the context of doing practical experiments with tangible outcomes.

Conclusions and recommendations

The course restructure achieved our aim of successfully eliminating student complaints about the course and has provided a stable course format for 4 consecutive years. Student interview results from an independent peer review identified that the story-arc narrative structure helped student to retain information, integrate individual concepts into a body of knowledge, and recognise the utility of their knowledge.

A surprising outcome was that the students lacked the ability to recognize how their pure knowledge is relevant to other courses—glaringly obvious in their assertion that catalysis only applies to the energy minor and not bioprocessing or environmental engineering. The story-arc narrative alleviated this weakness, allowing students to connect their knowledge of chemistry principles to utility in chemical engineering.

In the specific case, the Tyrian Purple story engaged students and contextualized chemical knowledge, enhancing students' ability to recognize and apply chemical concepts. The weakness of encouraging binge watching to facilitate narrative coherence, potentially reducing deep knowledge retention, will be addressed with experimentation in creating 'episode recaps'. In addition, we will employ examples and assessment with near-transfer tasks that emphasize the generalizability and utility of the students' chemistry knowledge to investigate if they can successfully apply what they learned about the process in a novel, but related situation.

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