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Teaching Animal Science

Design thinking for engaged learning in animal science: lessons from five semesters of a senior capstone course

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Abstract

This study presents a design-based research approach involving five iterations (semester) of implementing design thinking for engaged learning (DTEL) in an animal science capstone course. DTEL scaffolds design thinking into 10 stages for collaborative project-based learning to foster skills like problem solving and teamwork. Across five semesters (spring 2021 to spring 2023), student reflections ($n = 276$) were analyzed to identify aspects that worked well or were challenging. Network analysis visualized relationships ($P < 0.05$; $Q > 0.4$) between codes representing strengths, struggles, and alignment with principles from learning theories. Utilizing the relationships between strengths and theory-based principles to address struggles, resulted in changes to the design of the capstone course each iteration (time that the course was taught). The complexity of maps increased over iterations. Initially, struggles were prominent but decreased as responsive design refinements were made. Alignment of student experiences with principles from learning theories grew substantially from the first iteration to the last (theory-related nodes representing 11.4% vs. 24.4% in each network map, respectively), with learning theories also occupying more central positions in the last map (iteration five) compared to earlier ones (iterations one through four). These changes suggest student experiences increasingly aligned with principles of cognitive constructivism, social constructivism, constructionism, situated learning, and transformative learning. Design principles derived from the five-iteration study include: (1) allocating most time to hands-on lab work vs. lecture, (2) designating a coordinator faculty, (3) scaffolding for instructors unfamiliar with DTEL, (4) emphasizing consistency in processes over grades, and (5) intentionally developing teamwork skills. The study demonstrates the value of design-based research for iteratively refining and studying learning experiences to foster critical skills for undergraduate students in animal science.

Lay Summary

Preparing students for complex real-world problems requires learning experiences that foster critical thinking, problem-solving, and teamwork skills. This study implemented and evaluated an instructional approach called design thinking for engaged learning (DTEL) in an animal science capstone course over five semesters. DTEL breaks creative problem solving into stages for real-world team projects. Students reflected on beneficial and challenging aspects after each semester. Their anonymous feedback was analyzed to see what worked well or needed improvement. Network maps were created to visualize relationships between strengths, struggles, and alignment with learning theories. The maps grew more complex over time, and student experiences improved after data-driven design changes were made. Alignment of student experiences with principles from learning theories increased, suggesting the approach effectively engaged students. Key lessons learned include dedicating most class time to hands-on work, designating a coordinator instructor, providing scaffolding for new instructors, emphasizing learning processes over grades, and intentionally building teamwork skills. The study shows the value of continuously gathering student input to refine animal science courses to develop critical skills.

Key words: collaboration, learning theories, project-based learning, teaching, undergraduate education

Introduction

Political and economic pressures of elements such as climate change (Grossi et al., 2019), feed prices (Wright, 2011), fuel utilization (Balat and Balat, 2009), and consumer demands (Stampa et al., 2020) contribute to the complexity that is an inherent component of in animal agriculture (Turner et al., 2016). Livestock producers must continually evaluate their production practices and, if necessary, implement changes to maintain competitiveness and profitability of their operations (Fraser, 2001). The process of evaluation, analysis, and creation of potential solutions for complex problems that may face producers requires critical thinking, creativity, and innovation. Furthermore, there is an increased need for skills in the effective conveyance of information between agriculturalists and consumers (Bullock et al., 2019). This is of particular importance within the field of animal science, as it frequently falls under public scrutiny due to challenges with communication (Capper and Yancey, 2015; Bullock et al., 2019). Consequently, students graduating with a Bachelor of Science degree in Animal Science with the intention of joining the animal science industry must possess more than discipline-specific content knowledge and skills. Teamwork, problem solving, decision-making, and ideation

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are examples of skills that have been identified as desirable by employers and have been shown to increase the employment success of students exiting higher education (Carnevale and Smith, 2013). A recent survey of 496 executives and hiring managers representing companies across more than 19 industries conducted by the Association of American Colleges and Universities reinforced the need for universal skill development. Notably, the ability to work effectively in teams and critical thinking were identified as the most needed skills, rated as very important by 62% and 60% of respondents, respectively, (Finley, 2021)

Despite their importance, these skills are not often intentionally included in the syllabi and course design of most animal science classes (Al-Mazroa Smith et al., 2020). Intentionally designing animal science courses to foster the development of these skills is a strategy that has yielded positive results relating to the application of content knowledge and should translate to increased preparedness of graduating students for the job market (Hazel et al., 2013; Mracek and Karr-Lilienthal, 2015).

Design thinking for engaged learning (DTEL) is a framework developed to serve as a scaffold to structure learning experiences based on collaborative project-based instruction (Donaldson and Smith, 2017). The framework breaks down the design thinking process into 10 stages through which students develop ways of thinking that can be categorized as designerly ways of knowing, which is defined by Donaldson and Smith (2017) as:

"Designerly ways of knowing are the cognitive approaches and mindset characteristic of expert designers such as framing, reflection-in-action, and abductive reasoning. Design thinking strategies are the processes involved in design, including frame creation, ideation, prototyping, iteration, and deploying in real-world contexts".

Design thinking is a powerful approach to learning because it engages students in creative problem-solving to address complex real-world problems while remaining human-centered (Jamal et al., 2021). Additionally, DTEL is versatile, allowing for discipline-specific approaches, which makes it a good fit for a wide range of disciplines, including animal science.

Based on this, the current study presents the results of five consecutive semesters of a capstone animal science course, from the implementation of DTEL in the spring of 2021, followed by consecutive design moves and reiterations until the spring of 2023.

Materials and Methods

Course Basic Structure

Animal Science Capstone (ANSC 498) aims to serve as a preparatory summative experience for graduating seniors, which combines project-based learning, teamwork, and utilization of concepts from the core undergraduate curriculum in animal science. ANSC 498 is offered annually every fall and spring semester, as a 4-credit-hour course, consisting of lectures, and lab sessions. Initially lab and lecture corresponded to 2 credit hours each, currently, lab and lecture correspond to 3 and 1 credit hours, respectively.

During the lectures, the entire student cohort meets with the same instructor, who provides general direction, tools, and information for the execution of activities in the students' subsequent laboratory sections. Lectures also typically feature guest speakers to present relevant industry context and expertise from disciplines beyond animal science. Whereas, the labs (identified as individual course sections) consist of smaller groups, randomly divided into teams (four to five members per team) led more closely by a section-specific instructor, that is different from the lecture instructor. This design allows all students to receive uniform instruction in the lecture including exposure to topic experts and enables them to also experience a smaller student to faculty ratio in their laboratory sections where they will receive greater instructor and peer feedback. The overall scale of the course requires the engagement of multiple instructors for the laboratory sections. Thus, the combination of an individual lecture cohort and smaller laboratory sections aids in providing continuity of material and dedicated work time and space. A more detailed description of the course structure, student deliverables, lecture, and laboratory topics, as well as their alignment with the steps of DTEL are presented in Table 1. Student enrollment, the number of course sections and instructors are presented in Table 2.

Implementation of DTEL

The DTEL process is a framework that can be applied to a variety of situations and approaches, but in most—if not all—of them, its main desired outcome is to promote problem-solving and, consequently, critical thinking. ANSC 498, a senior level course aiming to engage students with the DTEL process for an entire semester, required that students worked with complex and engaging problems.

Thus, as an effort to provide students with some guidance and direction in their work, while safeguarding the freedom of their creativity, sustainability in animal agriculture is the common overarching theme of choice for contextualization of students' projects. Due to its inherent complexity, current relevance, and overall relatability, "Sustainable Animal Agriculture" supports the application of the DTEL framework, as well as provides students with a large range of diverse, engaging, and applicable potential subtopics to elect from Capper (2020); Jamal et al. (2021).

This rationale was presented to students during the first introductory lecture of each semester and in a more specific and in-depth lecture on "Sustainability in Animal Agriculture" that was also part of the schedule later in the semester, as shown in Table 1. Meanwhile, during lab, also in the first session of the semester, teams were randomly assigned, and then instructed to work collaboratively to identify a topic related to the overarching theme of "Sustainable Animal Agriculture".

While researching and identifying their topics, teams were also specifically instructed to consider the potential end-user or target audience related to their topics, by reflecting on who the people involved in the context of that topic were and how they were affected by its different elements. Students were also strongly encouraged to reach out to representants of these people and gain perspective on what their actual viewpoint about the topic was. For example, to provide an artifact of this scenario, a given group of students was interested in working with sustainable goat production, so they reached out to a goat producer in the state of Texas and gained new insight into what the pressing issues of the industry were. This corresponds to the first step of the design thinking process, *Empathize*, as shown in Figure 1, a simplified version of the DTEL process, adapted from Donaldson and Smith (2017).

Table 1. Conserved structure of Animal Science Capstone (ANSC 498) over the five-iteration period (from spring 2021 to spring 2023)

Week	Lecture topic	Lab topic	DTEL stage	Student deliverables
1	Course introduction	Topic selection	Empathize	Syllabus quiz[1] Weekly reflection[2]
2	Design thinking process	Problem identification	Empathize	Weekly reflection
3	Strategies for teamwork	Problem research	Empathize + define	Weekly reflection
4	Overview of the library	Problem research	Empathize + define	Background research report[3] and weekly reflection
5	Sustainability in animal agriculture	Problem statement framing	Define + ideate	Weekly reflection
6	Wicked problem statements	Divergent and convergent thinking	Ideate	Weekly reflection
7	Problem-solving in real-life	Low-fidelity solution	Ideate + prototype	Weekly reflection
8	Human behavior and problem-solving	Peer revision	Prototype	Technical solution report (first draft)[4]
9	Macroeconomics in animal agriculture	Evaluate feedback	Prototype + deploy	Weekly reflection
10	Microeconomics in animal agriculture	Analyze and revise	Prototype + deploy	Weekly reflection
11	Scientific and lay communication	High fidelity solution	Deploy	Weekly reflection
12	Planning for career success	Evaluate feedback	Ideate + prototype	Weekly reflection
13	Q&A session	Analyze and revise	Prototype + deploy	Weekly reflection
14	No lecture	Working day	Deploy	Video[5] and weekly reflection
15	No lecture	Videos and final presentation	Deploy	Technical solution report (final version)[6] and final reflection[7]

[1]Individual submission. Online asynchronous quiz launched through the learning management system (LMS; Canvas, Instructure, Salt Lake City, UT). Approximately 1% to 2% of the total grade.
[2]Individual submission. Written reflection about the week's progress. Students were required to provide meaningful thoughts on what they had achieved with their teams, if they believed changes were needed and how they planned to implement such changes. All weekly reflections combined represented, approximately 15% to 25% of the total grade.
[3]Individual submission. Literature review about the chosen topic. Formatted as a traditional scientific review manuscript and required students to provide a minimum of 15 peer-reviewed sources validating their topic choice. Approximately 8% to 10% of the total grade.
[4]Group submission. First version of a proposed solution. Among the required components were environmental, economic, and social impacts of each proposed solution, as well as a proposed budget, limitations, and an evaluation plan for solution efficacy. Approximately 10% to 12% of the total grade.
[5]Group submission. A 3-minute video displaying, pitching, explaining, or marketing the solution to an identifiable audience. Among the requirements were the minimal use of text and the inclusion of closed captioning for ADA compliance. Approximately 8% to 12% of the total grade.
[6]Group submission. Reviewed version of the first draft after peer-evaluation. Approximately 15% to 25% of the total grade.
[7]Individual submission. Written reflection about the semester's progress and what students achieved working with their teams and how the course impacted them. Approximately 4% to 10% of the total grade.
DTEL, Design thinking for engaged learning.
Student deliverables represent assignments that were due each week of the semester. The stages of the design thinking process are adapted from Donaldson and Smith (2017)

Table 2. Student enrollment, number of laboratory sections, and student-to-faculty ratio per semester in Animal Science 498: Animal Science Capstone (ANSC 498), in the Animal Science Department, Texas A&M University (College Station, TX) from spring 2021 to spring 2023.

Item	Spring 2021	Fall 2021	Spring 2022	Fall 2022	Spring 2023
Total student enrollment	25	53	168	84	201
Reflections analyzed	14	21	28	26	187
Number of course sections	3	3	7	6	11
Student: faculty ratio	8.3	17.7	24	14	18.3

Each laboratory section was taught individually by a different instructor. Reflections analyzed per semester refer to the number of text documents collected in the form of reflection assignments each semester. Enrollment and section numbers increased due to department adaptation of revised undergraduate curriculum catalog that requires all senior students to complete ANSC 498 prior to graduation. Students in spring 2021 were first to complete new catalog requirements.

When performing this step the teams of designers (students) should first connect to the human element behind each topic to only then fully understand and attempt to solve the problem.

The DTEL process continues with teams clearly defining their topics and target audiences, by framing them in the format of problem statements, and questions with conserved structure (*How can we help certain target audience solve this problem in this region?*). Once teams define their problems, engaging in the second step of the DTEL process (*Define*), they can then initiate the third step (*Ideate*), which relies intensively on creativity and brainstorming to produce an innovative and implementable solution. The criteria to determine innovation within each solution was based on a student-led evaluation of existing solutions easily accessible online, as well as instructors' and lab peers' judgment. More specifically, the lack of evidence on the internet of already existing practices or products identical to any of groups' proposed solutions, along with agreement among instructors and other students that they were not familiar with any of the proposed solutions in their lab sections. Regarding implementation, the evaluation criteria followed basic biological, physical, and logical laws, as in, solutions should not be fictional. Other

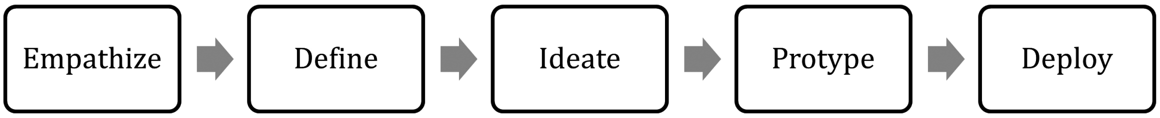

Figure 1. The steps of the design thinking process, are adapted from Donaldson and Smith (2017). "Empathize" represents the connection between the designer (student) and the end-user. "Define" refers to the clear definition of the problem to be solved. "Ideate" is the core of the creative process, during which designers will explore ideas, it mainly consists of brainstorming. "Prototype" is the stage at which decisions will be made regarding solving the problem and the first drafts of the solution should take form. "Deploy" represents the final stage of an iteration, in which the proposed solution is tested and evaluated. Although stages are graphically represented in a sequential form, the design thinking process itself is not, nor it is linear. Design thinking is also inherently iterative and infinite, with designers always having the opportunity to improve their design repeatedly. Ultimately what dictates the "end" of a design thinking process is the designer decision and the end-user's satisfaction with the product achieved.

criteria included economic aspects, convenience, and logistics of general management of livestock operations, basic concepts of marketing, and human behavior. Common examples of solutions being considered not implementable are solution is too expensive, it requires excessive animal handling or facilities, it is marketed to the wrong audience, or it is inconvenient to the end-user. As mentioned, and presented in Table 1, lecture topics were selected to support student understanding of these concepts.

After engaging in divergent and convergent thinking (Table 1; Donaldson and Smith, 2017), teams should then produce a low-fidelity solution to be presented in their first draft of a technical solution report (Table 1), which is then peer-reviewed by students in other groups. This entire dynamic—production of a low-fidelity solution, gathering, evaluating, and revising feedback—represents the fourth stage of the DTEL process (*Prototype*). The peer-reviews generate feedback necessary for the teams to analyze and revise their low-fidelity solutions, and subsequently launch the perfected and finalized version of their solution, which will then be presented in the form of a written technical report, a 3-minute video and an oral presentation during the last lab session of the semester, concluding the coursework and also the DTEL process with its last and final stage (*Deploy*).

Data Collection

All data were collected, anonymized, and processed in compliance with the study protocol approved by an Institutional Review Board of Texas A&M University (IRB2020-0629D; IRB2023-0053M).

The data utilized in this study consisted of students' Final Reflections collected at the end of the semester from students who had provided informed consent. The reflections were created as assignments that were part of the required activities for ANSC 498. To ensure student accountability and commitment to the quality of these assignments, and consequently of the data, a point value equivalent to approximately 4% to 10% of the final grade was assigned to these reflections each semester (Table 1). Reflections were submitted individually by students through a Learning Management System (Canvas by Instructure, Salt Lake City, UT). Students' reflections utilized the following prompts:

(1) What aspects of your work this semester on the project did you find particularly enjoyable, and WHY?
(2) What aspects of your work on the project were challenging, problematic, or uncomfortable—and WHY?
(3) If learning is not "acquisition of knowledge" (the dominant myth in society about learning), what insights does engaging in the design thinking process reveal to you about the nature of learning and how to go about doing the work of learning?
(4) What aspects of the project work this semester would you revise if you were teaching this course?
(5) Reflect on how your work on the project this semester relates to your identities (multiple) and your possible future career paths?

A total of 276 reflections were evaluated in this study. There were 14 collected in the spring of 2021; 21 in the fall of 2021; 28 in the spring of 2022; 26 in the fall of 2022, and 187 in the spring of 2023, as described in Table 2. The increasing number of submissions over subsequent semesters was due to the increased course enrollment that was the result of departmental adoption of a revised curriculum. As students transitioned to the new catalog which added ANSC 498 as a new course and a graduation requirement, enrollment increased. As the typical degree plan places the course in the graduating semester, enrollment is typically greater in the spring rather than fall semesters.

Data Processing and Coding

Data, in the form of text documents corresponding to students' final reflections (Table 1; $n = 276$), was coded by trained individuals using computer-assisted data analysis of text and multimedia-based data software (MAXQDA Analytics Pro 2022, VERBI Software, Berlin, Germany). Both inductive and deductive coding methods were utilized as described in the literature (Fereday and Muir-Cochrane, 2006).

More specifically, an initial codebook with seven identified themes or parental codes of interest was established according to deductive coding methods (Crabtree and Miller, 1992). These parental codes, with their names capitalized in the parentheses, were labeled in the text by the trained coders, every time they captured *struggles* students had (*STRUGGLE*); aspects of the experience that *worked* very well for students (*WORKED*); and alignment of student experiences with principles from *cognitive constructivist theory* (*THRY-COGCONSTR*), *social constructivist theory* (*THRY-SOCCONSTR*), *constructionist theory* (*THRY-CONSTRUCTIONIST*), *situated learning theory* (*THRY-SIT*), and *transformative learning theory* (*THRY-TRNSF*). The choice of parental codes was based on the nature of the research methodology utilized in this study (design-based research), which will be explained in further detail in the following section.

Once a text segment was identified as one of the parental codes, it was also assigned to a subcode, within that parental code. Subcodes were determined using inductive coding methods, which, briefly, consists of themes or codes emerging from the data (Boyatzis, 1998). To illustrate, this process, the following exert from the data, for example: "Hoping to eventually own my own clinic, the design thinking process will help my team and I overcome the everyday challenges that arise in veterinary practices and create solutions that address the needs of my clients, staff, and industry", was assigned to the parental code *WORKED,* under the subcode *Relevance—future career, project,* having its final coded identity be *WORKED—Relevance—future career, project.* Another example: "This class has taught me how to approach, dissect, and research these issues in a manner that promotes the development of real-world solutions to industry problems" was coded under two different parental codes, *WORKED* and *THRY-CONSTRUCTIONIST*, because the fragment depicts the relatability of the course experiences to real-life which was both effective to this student, as well as it is aligned with constructionist leaning theory, by Kafai (2006). Its final coded identity was: *WORKED—Relevance—real world—impact—come to life* and *THRY-CONSTRUCTIONIST—authentic audience, purpose—real-world.*

The entire codebook for this dataset yielded 2,748 coded segments and 97 individual codes assigned to at least one segment. Due to the large number of codes, a summarized version of the codebook is presented in Table 3 and a complete description of codes, with examples of coded segments for all codes, can be found in Supplementary Material.

Statistical Analysis

At the end of each iteration (i.e., semester) correlations between codes were analyzed using Pearson Product-Moment Correlation in MAXQDA (Kuckartz and Rädiker, 2021). More specifically, frequency of co-occurrence of codes in each document (i.e., student reflections) were utilized as variables to generate the correlation coefficients (r) calculated by MAXQDA (Kuckartz and Rädiker, 2021). The resultant table was then used to generate matrices containing only the correlation coefficients from the statistically significant ($P \leq 0.05$) correlations.

Correlation matrices were then utilized for the creation of network maps using UCINET with Netdraw (Borgatti et al., 2009). Creation of network maps was based on the generation of clusters using the Girvan-Newman algorithm (Girvan and Newman, 2002). Number of clusters within the map was determined using the highest Q value as the deciding criterion (Rousseau and Zhang, 2008). Betweenness was elected as the centrality measure for each individual variable, as it measures the importance of a node in a network in terms of connecting other nodes together (Rousseau and Zhang, 2008). This value is reflected by the size of each node—the larger the node, the greater its betweenness value and more important its role in connecting other nodes together. For more details about the statistical analysis and an artifact of a matrix table the reader can refer to Brandão et al. (2023).

Design-Based Research Methodology

Design-based research is initiated by selecting learning theories to guide the design of a learning experience. The design of ANSC 498, viewed as a learning experience was grounded in cognitive constructivist theory (Piaget, 1977), social constructivist theory (Vygotsky, 1978), constructionist theory (Harel and Papert, 1991; Kafai, 2006), situated learning theory (Lave, 1991), and transformative learning theory (Mezirow, 2018).

Briefly, in ANSC 498 students were tasked to solve a real-world problem by creating an implementable and innovative solution through interaction with teammates, faculty, and industry stakeholders, while engaging in frequent reflection and self-examination. These experiences align with the importance of interactions with the environment in building mental schemas coined by the constructivist learning theory (Piaget, 1977). They also foster social and cultural interactions through collaboration and communication, as postulated by social constructivist learning theory (Vygotsky, 1978). The previous and latter, both align with situated learning theory, as well (Lave, 1991), which also includes the idea of a community of practice. Hands-on creation of tangible artifacts, is proposed by constructionist theory (Harel and Papert, 1991; Kafai 2006). Finally, reflection on one's own experiences and change of perspectives are key characteristics of transformative learning theory (Mezirow, 2018).

Once these core ideas in each learning theory were identified, they then served as a template for the establishment of the parental codebook used to analyze the data, together with a simple classification of experiences which, according to students, worked, or caused struggle, as previously described. These parental codes, when applied to the data produced results from which researchers were able to extract a set of principles then used to guide and justify decisions about changes to course design.

After each semester, data was analyzed using learning experience network analysis (Donaldson et al., 2024) to identify aspects of the course that needed to be changed. Briefly, decisions about changes to course design were based mainly on the attempt to leverage the strengths, as perceived by the

Table 3. Coded segments within parental codes and number of their respective subcodes

Parental codes	Number of subcodes	Coded segments
Theory—cognitive constructivist (*THRY-COGCONSTR*)	2	28
Theory—social constructivist (*THRY-SOCCONSTR*)	3	39
Theory—situated learning (*THRY-SIT*)	4	77
Theory—constructionist (*THRY-CONSTRUCTIONIST*)	7	154
Theory—transformative learning (*THRY-TRNSF*)	4	204
Student struggles, issues, difficulties (*STRUGGLE*)	38	884
What worked well (*WORKED*)	39	1,092

Parental codes were preestablished using deductive coding and subcodes, inductive coding. Coded data corresponded to reflection assignments (n = 276) produced by students enrolled in Animal Science 498: Animal Science Capstone (ANSC 498), in the Animal Science Department, Texas A&M University (College Station, TX) from spring 2021 to spring 2023.

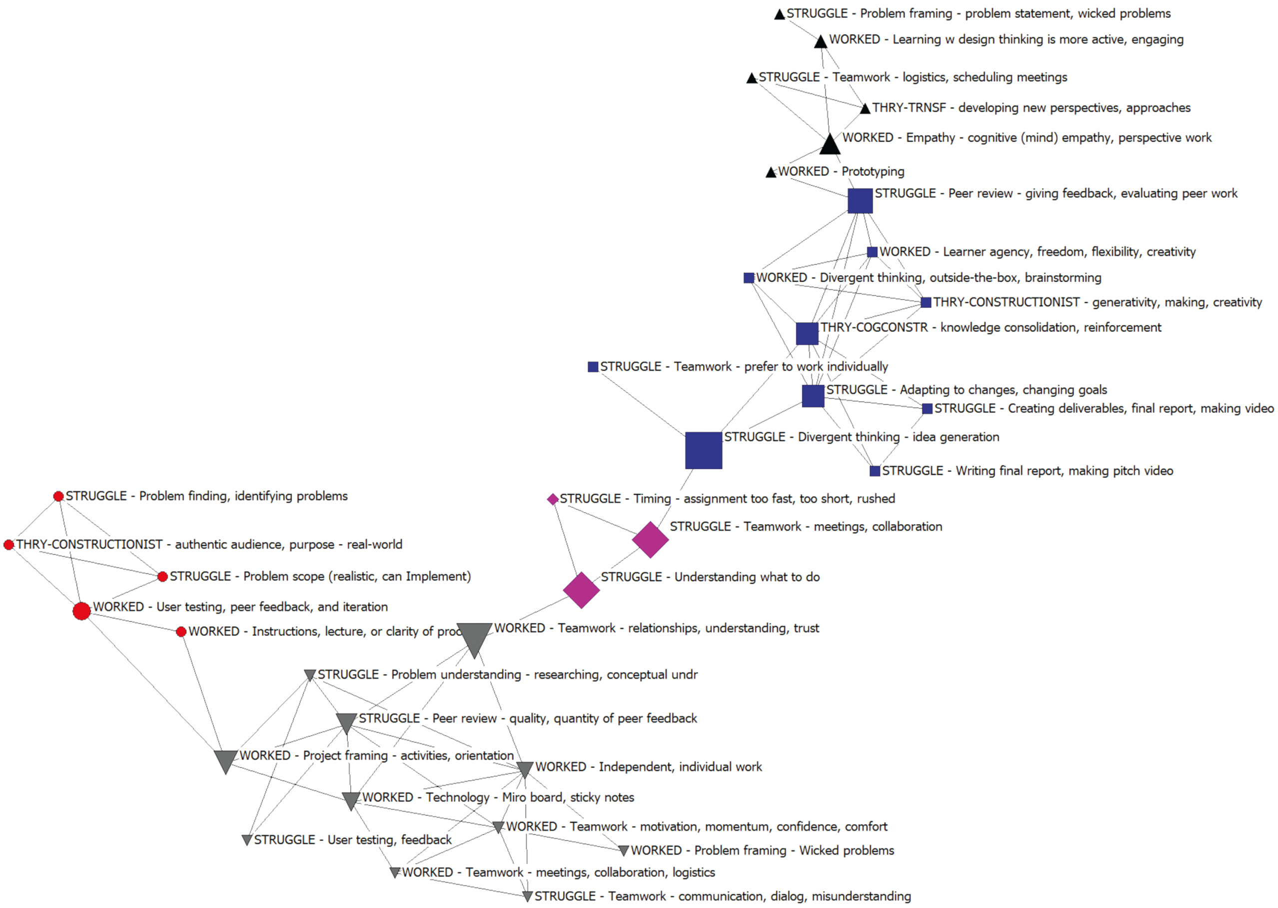

Figure 2. Network analysis map generated from the symmetrical correlation of the codes from student-generated reflections submitted by the end of the first iteration (spring 2021) of the designed-based research study ($P \leq 0.01$; $Q = 0.630$). Color and shape of nodes represent different clusters ($n = 5$), according to Girvan-Newman algorithm (Girvan and Newman, 2002). The number of clusters within the map was determined using the highest Q value as the deciding criterion. Betweenness was elected as the centrality measure for each individual variable, which is reflected by node size, reflected by the reported resulting Q-value. A version of this network map containing the betweenness values for each individual node is presented in Supplementary Material.

students (*WORKED*), and the experiences associated with principles from learning theories. The data-driven changes were then implemented prior to the subsequent semester of instruction (iteration).

After a sufficient number of iterations ($n \geq 3$; Barab (2014)) findings that were analyzed to identify generalizable course design principles and implications for theory the (Puntambekar, 2018). For the present study, after five iterations the overall course design changes made were minimal, and therefore it was determined that this was enough iterations relative to the design-based research model.

Results

Results are described in chronological order, starting with the earliest iteration (spring 2021), progressively until the most recent iteration (spring 2023), with each iteration corresponding to an individual network analysis map. Network maps consist of strength-related (*WORKED*), struggle-related (*STRUGGLE*), and theory-related (*THRY*) nodes. In each map, nodes represent codes obtained from previously described text analysis. Each unique code generated a unique node. Isolated nodes not linked to any clusters were removed from the maps, with 33, 35, 7, 34, and 17 isolated nodes excluded from maps depicted in Figures 2 to 6, respectively.

Node color and shape represent different clusters and node size represents centrality values, with bigger nodes having greater values for this parameter. The betweenness centrality also applies to each individual network map, in which its value (Q) suggests a denser connection within the clusters, indicating stronger interactions and relationships among the nodes.

Iteration 1 (Spring 2021)

The network map resulting from this iteration of the study is presented in Figure 2. It yielded 35 nodes grouped in five clusters at the $P < 0.01$ level of significance with a confidence value of $Q = 0.630$.

In the blue cluster, with square-shaped nodes, it is possible to see a generalized presence of nodes categorized as *STRUGGLE*, ranging from the early stages of the process, such as idea generation to the final stages, such as production of final reports and video assignments.

Divergent thinking appeared as both a strength (*WORKED—Divergent thinking, outside-the-box, brainstorming*) and a struggle in this cluster (*STRUGGLE—Divergent* *thinking—idea generation*) with the node representing the struggle being directly linked to the node representing the struggle with teamwork, both in this cluster (*STRUGGLE—Teamwork—prefer to work individually*) and in an adjacent cluster (pink cluster with diamond-shaped nodes; *STRUGGLE—Teamwork, meetings, and collaboration*).

The red cluster, with circular-shaped nodes, shows struggles with problem identification and framing residing together with the strength of peer feedback associated with user testing and iteration (*WORKED—User testing, peer feedback, and iteration*). These aspects are related to constructionist learning theory, more specifically, with a sense of purpose and real impact of work produced (Kafai, 2006).

In the black cluster, with triangular-shaped nodes, difficulties reported involved the logistical aspects of teamwork and the problem-framing stage of the DTEL process. The most prominent node in this cluster was empathy-related (*WORKED—Empathy—cognitive (mind) empathy, perspective work*), and it was closely linked to the node that indicates active and engaging learning with design thinking (*WORKED—Learning w design thinking is more active, engaging*).

Similarly, in the pink cluster, with diamond-shaped nodes, difficulties with logistical aspects of teamwork (*STRUGGLE—Teamwork—meetings, collaboration*) and the overall course timeline (*STRUGGLE—Timing—assignments too fast, too short, and rushed*) were described. Additionally, the node denoting *STRUGGLE—Understand what to do* could also be interpreted as a reflection of *STRUGGLE—Problem framing—problem statement, wicked problems*, found in the previous cluster, as both relate to overall student understanding and clarity of instruction throughout the course.

The gray cluster with down-triangle-shaped nodes is predominantly composed of experiences that were perceived as positive by the students. Briefly, it was shown that different aspects of teamwork (*WORKED—Teamwork—relationships, understanding, trust; WORKED—Teamwork—motivation, momentum, confidence, and comfort; WORKED—Teamwork—meetings, collaboration*), of the DTEL framework (*WORKED—Problem framing—wicked problems; WORKED—Project framing—activities, orientation*), and even the materials utilized for instruction (*WORKED—Technology—Miro Board, sticky notes*) had a beneficial impact on student learning. Conversely, there were also difficulties perceived in the teamwork sphere (*STRUGGLE—Teamwork—communication, dialog, and misunderstanding*) and the overall understanding of some elements related to DTEL (*STRUGGLE—Problem understanding—researching, conceptual understanding*), corroborating with findings of previous clusters. Additionally, there were difficulties described in this cluster pointing to the same direction of an overall lack of quality feedback (*STRUGGLE—User testing, feedback; STRUGGLE—Peer-review—quality, quantity of peer feedback*).

From these results, several course design moves were implemented. To remedy the issue with logistics of teamwork, the credit hours were redistributed within the course. Previously, the 4 credit hours were divided equally between laboratory and lecture, with 2 credit hours for each instruction modality. After realizing the need for more time dedicated to teamwork, the schedule was rearranged into 1 credit hour dedicated to lecture and three to laboratory, to better accommodate students' needs. Instructors also provided specific guidance and more actively monitored progress made by each group during lab hours, to ensure students were using their allotted time productively. Additionally, in iteration 1 the course incorporated the university mandated hybrid course requirement initially necessitated by the coronavirus disease-2019 pandemic. This requirement was lifted after iteration 1 and the option to retain the hybrid design was abandoned as balancing team participation across different formats (virtual and in-person) was found to be a barrier to student immersion in team building and collaborative work. An additional change made was that approaching the end of the semester, two lecture periods were reserved for students to work on their projects, and the use of time for that purpose was also actively communicated and reinforced by instructors.

Other design moves for this iteration included moving one of the lectures on wicked problems, problem framing, and design thinking to earlier in the semester, from the fourth to the second week, so students could have more time to understand the process and ask questions. More interaction and feedback among students and instructors were also intentionally added to the problem-framing process.

Iteration 2 (Fall 2021)

The network map from the second iteration of the study (fall semester 2021) is presented in Figure 2. Four clusters were identified at the $P < 0.05$ level of significance and at the confidence of $Q = 0.627$, comprising a total of 24 linked nodes.

In the blue cluster, with square-shaped nodes, challenges with procrastination and time management both at a personal level and team level were described (*STRUGGLE—Time management—team; STRUGGLE—Procrastinating in work and collaboration; STRUGGLE—Teamwork—meetings, collaboration; STRUGGLE—Time management—personal*). Despite these struggles, independent, and individual work within this cluster demonstrated positive outcomes (*WORKED—Independent, individual work*).

In the black cluster with triangular-shaped nodes, challenges were related to problem identification and framing (*STRUGGLE—Problem finding, identifying problems; STRUGGLE—Problem framing—problem statement, wicked problems*). However, despite these struggles, students demonstrated effective teamwork, especially regarding brainstorming sessions (*WORKED—Teamwork—meetings, collaboration, logistics; WORKED—Divergent thinking, outside-the-box, brainstorming*).

In the gray cluster, with diamond-shaped nodes, difficulties encountered belonged to different categories and were related to teamwork, more specifically role assignment and accountability (*STRUGGLE—Teamwork—roles, role negotiation, and accountability*), but also related to stakeholder participation (*STRUGGLE—User testing, feedback*) and course pace (*STRUGGLE—Timing—assignment too fast, too short, and rushed*).

The red cluster with circular-shaped nodes was the only one aligned with learning theory principles, more specifically, principles of the constructionist learning theory (*THRY-CONSTRUCTIONIST—authentic audience, purpose—real-world; THRY-CONSTRUCTIONIST—generativity, making, and creativity).* This cluster was also predominantly represented by aspects of the learning experiences that were perceived positively by the students (*WORKED—Project*

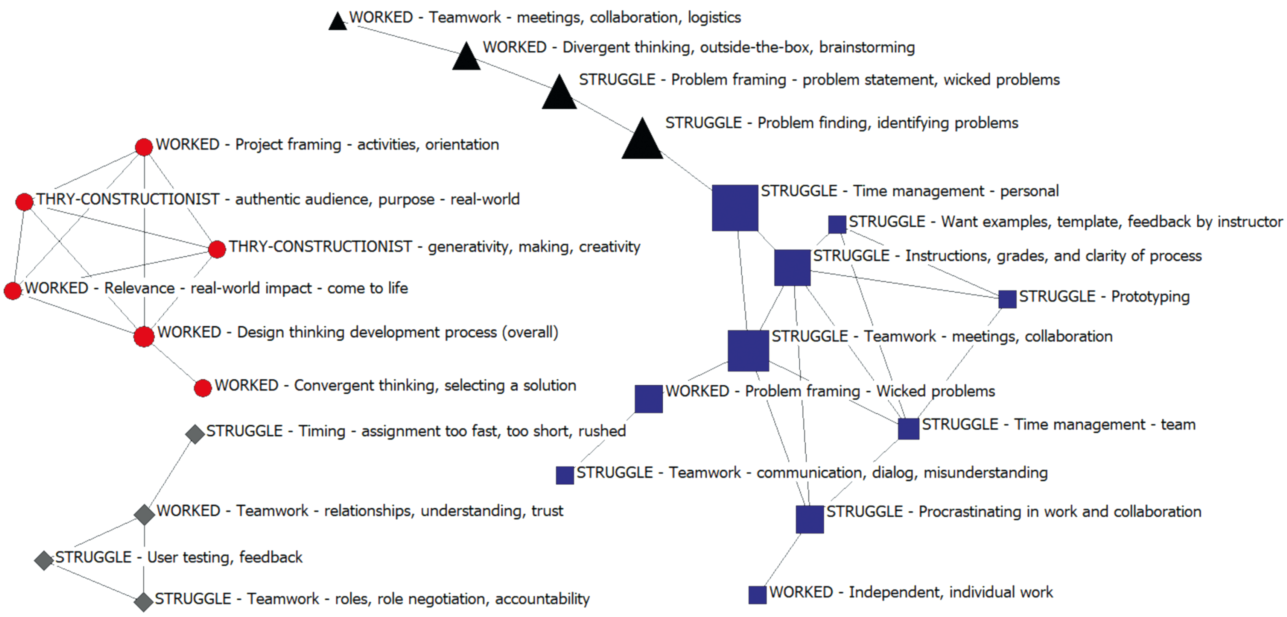

Figure 3. Network analysis map generated from the symmetrical correlation of the codes from student-generated reflections submitted by the end of the second iteration (fall 2021) of the designed-based research study ($P \leq 0.05$; $Q = 0.627$). Color and shape of nodes represent different clusters ($n = 4$), according to Girvan-Newman algorithm (Girvan and Newman, 2002). The number of clusters within the map was determined using the highest Q value as the deciding criterion. Betweenness was elected as the centrality measure for each individual variable, which is reflected by node size, reflected by the reported resulting Q-value. A version of this network map containing the betweenness values for each individual node is presented in Supplementary Material.

framing—activities, orientation; WORKED—Relevance—real-world impact—come to life; WORKED—Design thinking development process (overall); WORKED—Convergent thinking, selecting a solution). This supports the use of design principles from learning theories to develop positive learning experiences for students.

Thus, the design moves following the second-course iteration, including guidelines on effective team meetings and collaboration, and more intentional guidance from instructors on meeting deadlines. Additionally, the instructions for team meetings were revised to include specific strategies for organizing ideas, fostering productive discussions, and building trust during the problem-finding stage, emphasizing the use of a growth mindset and early positive feedback to students. Teams were also encouraged to hold their members accountable for completing pre-meeting work.

Iteration 3 (Spring 2022)

The third iteration of the network map from spring semester of 2022 is presented in Figure 3. The analysis identified five clusters at the $P < 0.001$ level of significance, at the confidence of $Q = 0.519$, comprising a total of 84 linked nodes.

The largest leap in map complexity can be observed from the second iteration (Figure 2, fall 2021) to the third (Figure 3, spring 2022). The network map resulting from the analysis of the second iteration yielded a total of 24 linked nodes, while the one for the third iteration contained a total of 84 linked nodes, 3.5 times more than the previous one. This significant increase in complexity was associated with an increase in the number of nodes representing struggles identified by the students (13 vs. 42, for iterations 1 and 2, respectively). Despite this, the increase in number of nodes representing struggles did not reflect an increase in their representation of the entire map as a percentage of the total nodes (54.2% vs. 50%, for iterations 1 and 2, respectively). Additionally, it is important to note that their location and their role on the map changed substantially. In iteration 2, although some struggle nodes play an important role in connecting clusters and sustaining the structure of the map, this role is significantly intensified in iteration 3, where the struggle nodes populate the center of the map, corresponding mainly to the pink cluster with diamond-shaped nodes. This cluster is vital to the integrity of the map and its connecting role, through the numerous nodes representing different struggles students identified, is clearly observed in the network.

In Iteration 3, the red cluster, with circular-shaped nodes, data suggests predominantly learning experiences perceived as positive by students. The only difficulty identified was related to students' desire for examples, templates, or feedback from the instructors (*STRUGGLE—Want examples, template, feedback from instructor*). Notably, this cluster displays a positive trend in developing new perspectives, benefiting from the diversity and differences among team members, as well as actively engaging with community stakeholders.

In the blue cluster, with triangular-shaped nodes, major difficulties related to a perceived irrelevance of assignments and tasks within the design thinking process (*STRUGGLE—Relevance—design process, lack interest, motivation; STRUGGLE—Relevance—no authentic real-world implementation*) which were deemed too slow or lengthy by students (*STRUGGLE—Timing—assignment too slow, too long).* This was also related to students being reluctant to trust the process and embrace change (*STRUGGLE—Instructions, grades, clarity of process; STRUGGLE—Not wanting to follow instructions, process; STRUGGLE—Adapting to changes, changing goals*). Interestingly, there is an emergence of identity exploration, as observed through the lens of situated learning theory (*THRY-SIT—identity exploration,* *development;* Lave, 1991) and greater emphasis placed on the creative process rather than solely focusing on the end results or product itself (*THRY-CONSTRUCTIONIST—focus on process not product or result*) which aligns with constructionist learning theory (Kafai, 2006).

In the pink cluster with diamond-shaped nodes, the overall learning experience with the design thinking development process was identified as positive (*WORKED—Design thinking development process [overall]*). Other positive aspects mentioned in this cluster include teamwork (*WORKED—Teamwork—relationships, understanding, and trust*), empathy (*WORKED—Empathy—affective (emotion) empathy work*), and relevance to future career (*WORKED—Relevance—future career, project).*

Much of the central cluster (more than 80%); however, is composed of nodes representing students' struggles in many different categories. These categories include grading (*STRUGGLE—Point allocation, grade, and penalty*), feedback (*STRUGGLE—Peer-review—quality, quantity of peer feedback*), use of technology (*STRUGGLE—Technology—Miro Boards, sticky notes*), and even some aspects of the design thinking process (*STRUGGLE—Divergent thinking—idea generation*).

Similarly to what was seen in the previous cluster, in the gray cluster, with square-shaped nodes, nodes representing challenges were the majority and they also had a diverse and broad range of categories but were particularly centered around problem framing including realistic implementation, problem statement, organizing ideas, and selecting solutions (*STRUGGLE—Problem scope (realistic, can implement); STRUGGLE—Problem framing—problem statement, wicked problems; STRUGGLE—Organize ideas, solutions, and projects*).

The black cluster, with down-triangle-shaped nodes, is composed exclusively of nodes representing experiences perceived positively by students and it contains aspects from different learning theories. No nodes related to challenges or difficulties were identified. The learning experiences perceived positively in this cluster align with principles of constructionism (*THRY-CONSTRUCTIONIST—learner agency, authority, autonomy*) cognitive constructionism (*THRY-COGCONSTR—individual knowledge construction*) social constructionism (*THRY-SOCCONSTR—mediating artifacts, tools, and technologies*), and transformative learning (*THRY-TRNSF—changing ways of knowing, thinking*).

Because the difficulties students faced were so numerous and diverse, focus was given to nodes representing what worked well when determining design moves, which included intentionally increasing design thinking process-related content into laboratory and lecture elements and explicitly connecting these concepts to assignments, activities, and their steps. To support faculty who were new to ANSC 498 and to DTEL, three meetings for lab instructors were held throughout the semester—at the beginning, midpoint, and end—to discuss progress within their lab sections and ensure alignment of the cohorts. Templates containing guidelines and objectives for each lab session were also provided. An extra lecture on wicked problems and the design thinking process was included in the schedule and a DTEL expert was invited to each lab session to discuss and assist with the development of each group's wicked problem statements.

To leverage the schema building, an assignment for groups to share their design thinking processes, rather than only the final product, was implemented. This design move was associated with a more consistent and deliberate explanation of each assignment objective by instructors during the laboratory sessions, aiming to improve student understanding of activities performed and to stimulate a more engaged and active learning process.

Additionally, to support the course structure established in the design moves from the previous iteration, one instructor who was familiar with the course was assigned as the role of "course coordinator." This individual was tasked with overseeing the lecture portion of the course and mentoring other faculty members in laboratory instruction, with special attention to the DTEL process. The goal for this design move was to improve consistency in laboratory instruction and student experience.

Finally, to address issues identified in the teamwork arena, a lecture by an expert on teamwork and leadership was included in the following semester to better equip students to deal with conflicts and improve team-building skills. This lecture was strategically scheduled within the first weeks of the semester, typically before group conflict was observed.

Iteration 4 (Fall 2022)

The fourth iteration of the network map from fall semester of 2022 is presented in Figure 5. Four clusters were identified at the $P < 0.01$ level of significance, at the confidence of $Q = 0.625$, comprising a total of 55 linked nodes.

In the red cluster, with square-shaped nodes, no struggle-related node was identified. Similarly, in the gray cluster with down-triangle-shaped nodes, only one struggle-related node was identified (*STRUGGLE—Peer-review—quality, quantity of peer feedback*). This indicates students' experiences were consistently positive and strongly aligned with various learning theories (*THRY—CONSTRUCTINIST—generativity, making, and creativity; THRY-SOCCONSTR—mediating artifacts, tools, and technologies; THRY-SIT—communication in community (or team); THRY-SIT—community of practice OR local community (team); THRY-CONSTRUCTIONIST—pride in your work, products*). The data suggests the learning environment fostered high levels of collaboration and creativity (*WORKED—Teamwork—communication, dialog, and understanding; WORKED—Sharing project, observing other groups, and rehearsing*). The results show engagement and mutual support among peers, allowing ideas to flourish, and diverse perspectives to be valued (*WORKED—Learner agency, freedom, flexibility, and creativity; WORKED—Build Confidence, growth*).

Both the black cluster with diamond-shaped nodes and the blue cluster with triangular-shaped nodes were dominated by nodes representing difficulties faced by students. Similar to previous iterations, in the black cluster, struggles are primarily related to the early stages of the design thinking process (*STRUGGLE—Problem understanding—researching, conceptual understanding; STRUGGLE—Problem framing—problem statement, wicked problems*), while in the later stages positive experiences are demonstrated (*WORKED—Identify a solution, prototype, and issue; WORKED—Adapting, changing goals; WORKED—Relevance—real-world impact—come to life*). Concerns were mainly related to vagueness of certain assignment rubrics and instructions, leading to confusion and uncertainty regarding how to meet the assignments criteria (*STRUGGLE—Ambiguity (want clarity, not open-ended); STRUGGLE—Want* *examples, template, feedback by instructor*). Conversely in the blue cluster, many of the struggles encountered were related to collaboration and teamwork (*STRUGGLE—Teamwork—irresponsible team members, lack commitment; STRUGGLE—Teamwork, prefer to work individually; STRUGGLE—Teamwork—roles, role negotiation, and accountability; STRUGGLE—Teamwork—perfectionism, control; STRUGGLE—Teamwork—communication, dialog, and misunderstanding; STRUGGLE—Teamwork—relationships, trust, and interaction*).

Design moves included review of assignment rubrics and instructions to improve clarity. Additionally, at each stage, groups were asked to initiate discussions of upcoming tasks and objectives to ensure clarity and alignment before proceeding with their work. To further improve collaboration experience, a mid-semester reflection on teamwork was added in which students graded their teammates and the instructors privately shared averages of these grades with each student. This approach allowed groups and students to identify shortcomings so that they were able to address them in a timely manner.

Iteration 5 (Spring 2023)

The network map of the fifth and last iteration corresponding to spring semester 2023 is presented in Figure 6. Seven clusters were identified at the $P < 0.001$ level of significance and at the confidence of $Q = 0.453$, comprising a total of 90 linked nodes.

In the light green cluster with diamond-shaped nodes, there is significant dissatisfaction expressed towards teammates, with various nodes denoting areas such as time management, collaboration, logistics, fulfilling roles, communication, and incorporating ideas alignment among team members (*STRUGGLE—Procrastinating in work and collaboration; STRUGGLE—Time management—team; STRUGGLE—Teamwork—irresponsible team members, lack commitment; STRUGGLE—Teamwork—meetings, collaboration; STRUGGLE—Teamwork—roles, role negotiation, and accountability; STRUGGLE—Teamwork—communication, dialog, and misunderstanding; STRUGGLE—Teamwork—relationships, trust, interaction, and alignment*). However, there were nodes in this cluster indicating that some aspects of the learning experience were positive (*WORKED—Learning with design thinking is more active, engaging; WORKED—Relevance—general*), including aspects of teamwork such as the diversity of student backgrounds, thought processes, points of view (*WORKED—Teamwork—diversity, difference*).

In the red cluster with circular-shaped nodes, an overall positive learning experience is depicted with nodes describing elements perceived as successful by the students comprising approximately 80% of the cluster. The most notable struggles were related to between-group feedback, where students found it challenging to evaluate others' works while expressing dissatisfaction with the feedback they received (*STRUGGLE—Peer-review—giving feedback, evaluating peer work; STRUGGLE—Peer-review—quality, quantity, and contradicting feedback*). Within groups, problems related to perfectionist and controlling behaviors were described and seem to be related to the preference of work individually (*STRUGGLE—Teamwork—perfectionism, control; STRUGGLE—Teamwork—prefer to work individually*). Despite these setbacks regarding teamwork, social constructivism (Vygotsky, 1978) appears as a learning theory strongly aligned with students' experiences in this cluster, being represented by various nodes (*THRY-SOCCONSTR—mediating artifacts, tools, and technologies; THRY-SOCCONSTR—zone of proximal development; THRY-SOCCONSTR—collaborative knowledge; THRY-SOCCONSTR—scaffolding*).

The remaining clusters (gray, with square-rounded-shaped nodes; pink with down-triangle-shaped nodes; blue with square-shaped nodes, dark green with triangular nodes and black with hourglass-shaped nodes) did not show significant new findings compared to the previously described clusters in this and previous iterations.

Learning Theory Association Across Iterations

In the first iteration of the study (spring 2021; Figure 2), only 4 nodes out of the 35 (11.4%) in the network map represented principles from learning theories, and in the following iteration (fall 2021, Figure 3), this number decreased to only 2 nodes out of the 24 (8.3%). The most marked increase (1.14-fold increase as a percentage) is then observed, as 15 nodes out of 84 (17.8%) represented different principles from multiple learning theories in the network map of the third iteration (spring 2022, Figure 4). The fourth iteration had a slight decrease in the number of nodes representing learning theories, but a slight increase considering their representation within the map (10 theory-related nodes out of 55, 18.2%, Figure 5). In the fifth and last iteration, representing the spring of 2023 (Figure 6), the number of theory-related nodes reaches a total of 22 nodes, representing almost a quarter of the entire network map (24.4%).

Discussion

Course Trajectory

Course trajectory regarding the network maps resulting from all five iterations demonstrates an increasing level of complexity from the first iteration (Figure 1) to the fifth (Figure 5). Based on their own experiences with ANSC 498 in these five semesters as well as the findings supported by the data presented herein, the authors identified the increased richness and depth of reflections produced by students each semester as a factor contributing to the evolution of those results. This is not surprising in design-based research, and it may be seen as a positive outcome, as embracing the complexity of learning is a foundational principle of learning sciences (Kolodner, 1991). The sequential analysis of data at the end of each semester provided insight into the student learning process and helped to either reinforce existing assumptions or expand perspectives to include additional considerations.

For example, analysis of students' reflections in iteration 1 included the presence of a somewhat isolated and small representation of the preference of students to work individually could be related to previous unsuccessful teamwork experiences. Students' frustration or feeling of unpreparedness towards teamwork has been reported in the literature, corroborating these findings (Wilson et al., 2018). While the challenge of teamwork is familiar to those in education (Vass

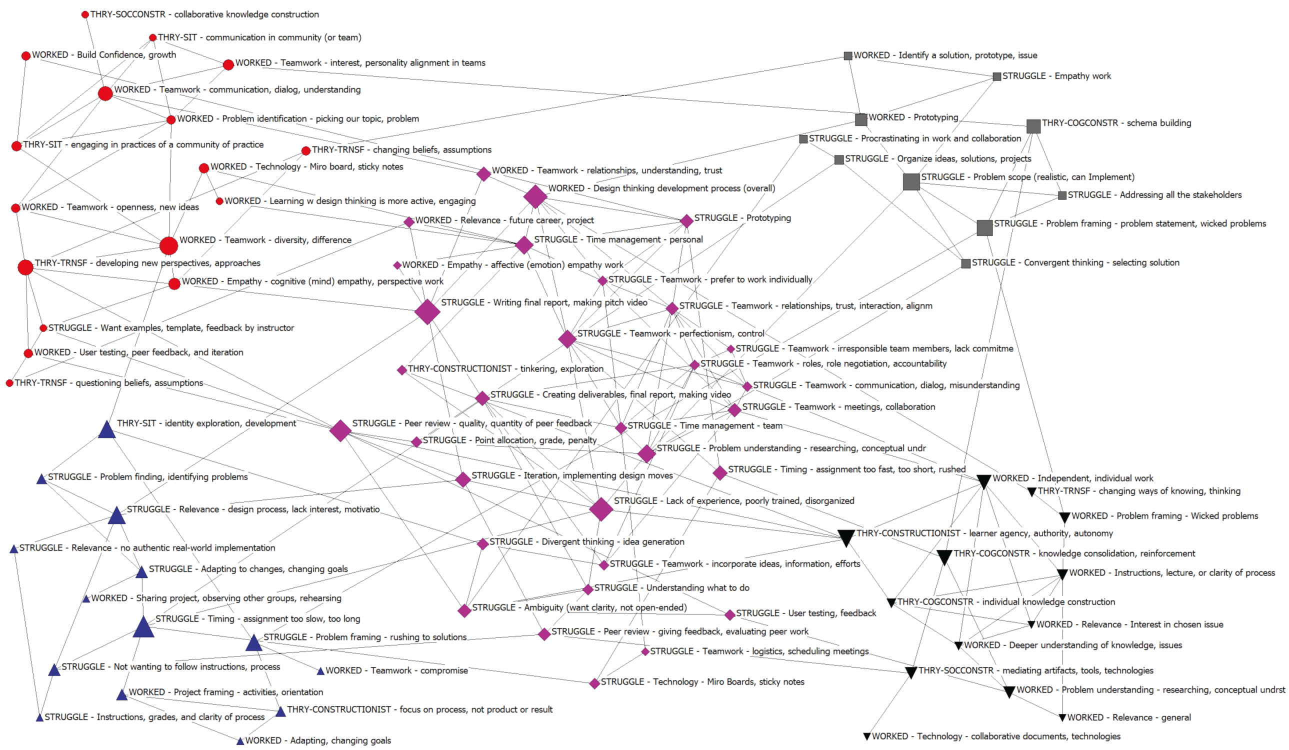

Figure 4. Network analysis map generated from the symmetrical correlation of the codes from student-generated reflections submitted by the end of the third iteration (spring 2022) of the designed-based research study ($P \leq 0.001$; $Q = 0.519$). Color and shape of nodes represent different clusters ($n = 5$), according to Girvan-Newman algorithm (Girvan and Newman, 2002). The number of clusters within the map was determined using the highest Q value as the deciding criterion. Betweenness was elected as the centrality measure for each individual variable, which is reflected by node size, reflected by the reported resulting Q-value. A version of this network map containing the betweenness values for each individual node is presented in Supplementary Material.

and Littleton, 2010), additional findings from the first iteration helped to illustrate the importance of team projects in learning. Specifically, as described in the results section, student reflections revealed that divergent thinking appeared as both something that worked and a struggle. These findings reflect the complexity of learning, as a single aspect that can be seen as both positive and negative by a similar cohort of students and it also corroborates the importance of effective collaboration to foster positive learning experiences (Collins et al., 2016). Learning experiences in this cluster were also moderately associated with the constructivist approach that emphasizes knowledge consolidation, learner agency, and generativity (Piaget, 1977). This suggests that the individual student's ability to generate and process knowledge independently is also a component of the collaborative process (Vass and Littleton, 2010).

The inclusion of learning theory-related content in student reflections was notable. As learning theory informed the changes made after each iteration and were communicated to the instructors, education on the specific theories was not a course learning outcome or an associated priority of information conveyed to students. Without the formal inclusion of this content, it is particularly interesting that not only the number of theory-related nodes, but their location in the maps, and thus their role, also evolved throughout the five-iterations. The nodes representing principles from learning theories observably "moved" from peripheral areas of the maps in the first four iterations (Figures 2 to 5) to a very central region in the fifth iteration, more specifically, the red cluster with circular-shaped nodes (Figure 6). Because each of these theory nodes represents a code that was identified in students' reflections, their frequency of appearance in the map, their location and how they connect to other nodes (representing other codes) is useful for understanding changes across iterations. The location of these theory nodes is important as they are often connecting nodes to each other, making them an integral part of the network structure compared to when located in the more peripheral parts of the map. In other words, student experiences were becoming increasingly aligned with principles from learning theories.

This alignment supports that the design changes implemented in each iteration were based on theory. This concept is further reflected and confirmed by the comparatively greater size of the theory-related nodes, which denotes greater betweenness centrality values, which is a measurement deployed in network analysis (Freeman, 1977). Increasing levels of betweenness indicates that there is a shorter path of connectivity between others suggesting increased influence on the data that it is connecting. As relevant to this study, betweenness indicates that principles from theory played a more central role in connecting other aspects of student experiences.

Realizing that early iterations of the course displayed an increase in the number and the importance of struggles as perceived by students, it is not a negative outcome. Rather, this result was crucial for the development of important design moves, as it allowed the authors to understand the issues that needed to be addressed. As a reflection of the design moves developed and implemented after an iteration that was densely represented by struggles, the following semesters showed clear

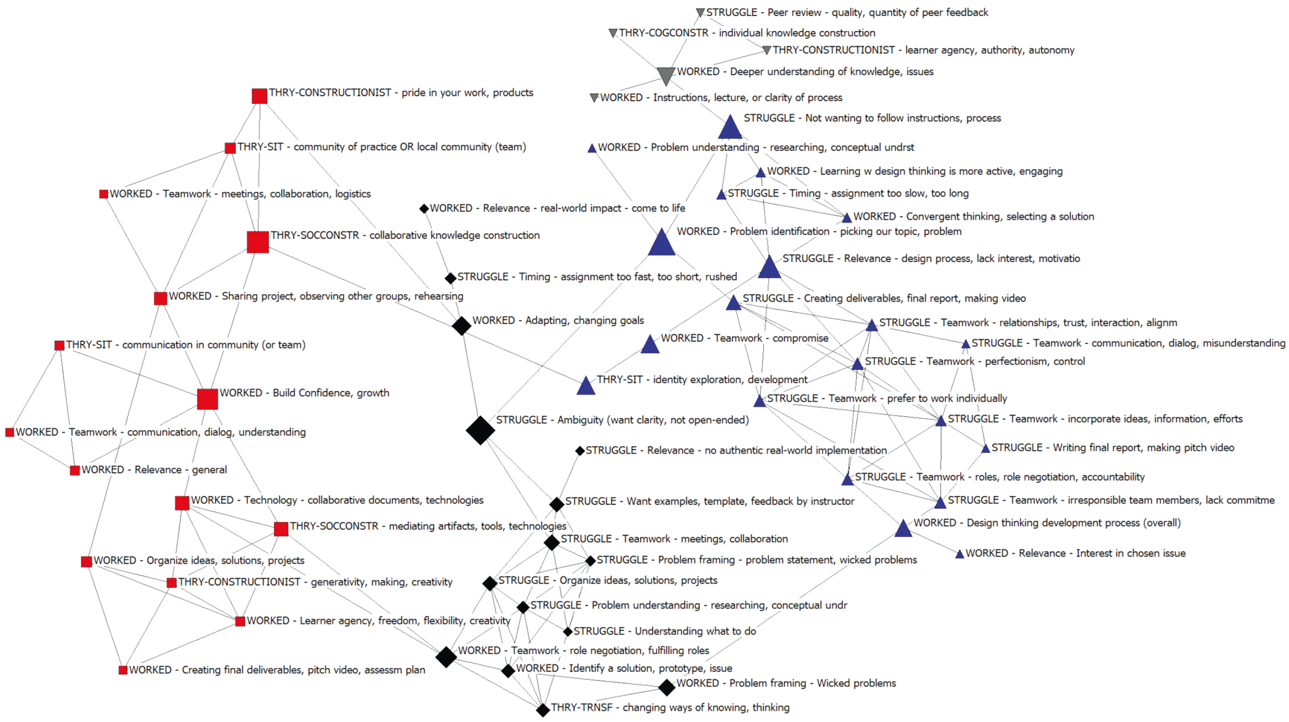

Figure 5. Network analysis map generated from the symmetrical correlation of the codes from student-generated reflections submitted by the end of the fourth iteration (fall 2022) of the designed-based research study ($P \leq 0.01$; $Q = 0.625$). Color and shape of nodes represent different clusters ($n = 4$), according to Girvan-Newman algorithm (Girvan and Newman, 2002). The number of clusters within the map was determined using the highest Q value as the deciding criterion. Betweenness was elected as the centrality measure for each individual variable, which is reflected by node size, reflected by the reported resulting Q-value. A version of this network map containing the betweenness values for each individual node is presented in Supplementary Material.

signs of improvement. The progress and positive response to these changes were translated as a smaller representation of challenges and difficulties perceived by students (22 nodes labeled as *STRUGGLES*, representing 40% of the network map for iteration 4, shown in Figure 5). It is also possible to observe a trend for the *Struggle* nodes to become less centralized and more peripheral to the network map's entire structure, when compared to iteration 3 (Figure 4). This tendency of decentralization of the *struggle* nodes can be more clearly observed in the network map representing the fifth iteration (Figure 6), in which the perceived challenges and difficulties are more densely present in the peripheral light green cluster with diamond-shaped nodes, on the left-hand side of the map. This again corroborates the complexity of learning, in which positive and challenging experiences may, together, yield an effective and constructive learning environment, conducive to student growth (Collins et al., 2016). The impact of the students' relationships within their team remained a key component of aspects of the design thinking process across each iteration and highlights the importance of the social setting in student learning (Jaramillo, 1996). The relationships within and between clusters are examples of this complexity. For example, divergent thinking appears as a strength relating to outside-the box thinking and brainstorming and yet divergent thinking as it relates to idea generation was a struggle when associated with teamwork, particularly related to meetings and collaboration. These data present examples of authentic contextual learning via relationships between students as is seen in situated learning (Lave, 1991).

With each iteration instructors implemented specific courses suggested by the student data evaluated, thereby it is not surprising that in later iterations, there was a notable presence of codes related to student engagement, clearly indicating the separation between knowledge construction, and learning culture (Kafai, 2006). The increased student engagement with the reflection assignments can be interpreted as an expression of an overall increased engagement with the course and its processes as the changes from each iteration were successively implemented. It could also be associated with increasing faculty familiarity with the assignment and thus being able to better instruct students on how to write effective reflections.

A positive outcome of the increased complexity and depth of both students' reflections and network maps is the appearance of more layers to similar categories of codes, adding interesting nuances to each cluster and, consequently, each map. Interestingly, data suggested that that identifying solutions and prototyping were not perceived as issues by students, on the contrary, these aspects were part of their positive experiences (*WORKED—Identify a solution, prototype, issue; WORKED—Prototyping*). There is also evidence to support successful schema building by students (*THRY-COGCONTR—schema building*), which aligns with the cognitive constructivism theoretical framework (Piaget, 1977). This suggests that struggles mainly revolved around the initial states of the design thinking process, such as problem framing and scope, not necessarily the experiences gained during the constructive process.

Collectively, assessment of clusters at the later iterations shows a mixed representation of difficulties, enjoyable experiences, and learning theories, showing that, perhaps, eliminating all struggles is not possible or desirable in a

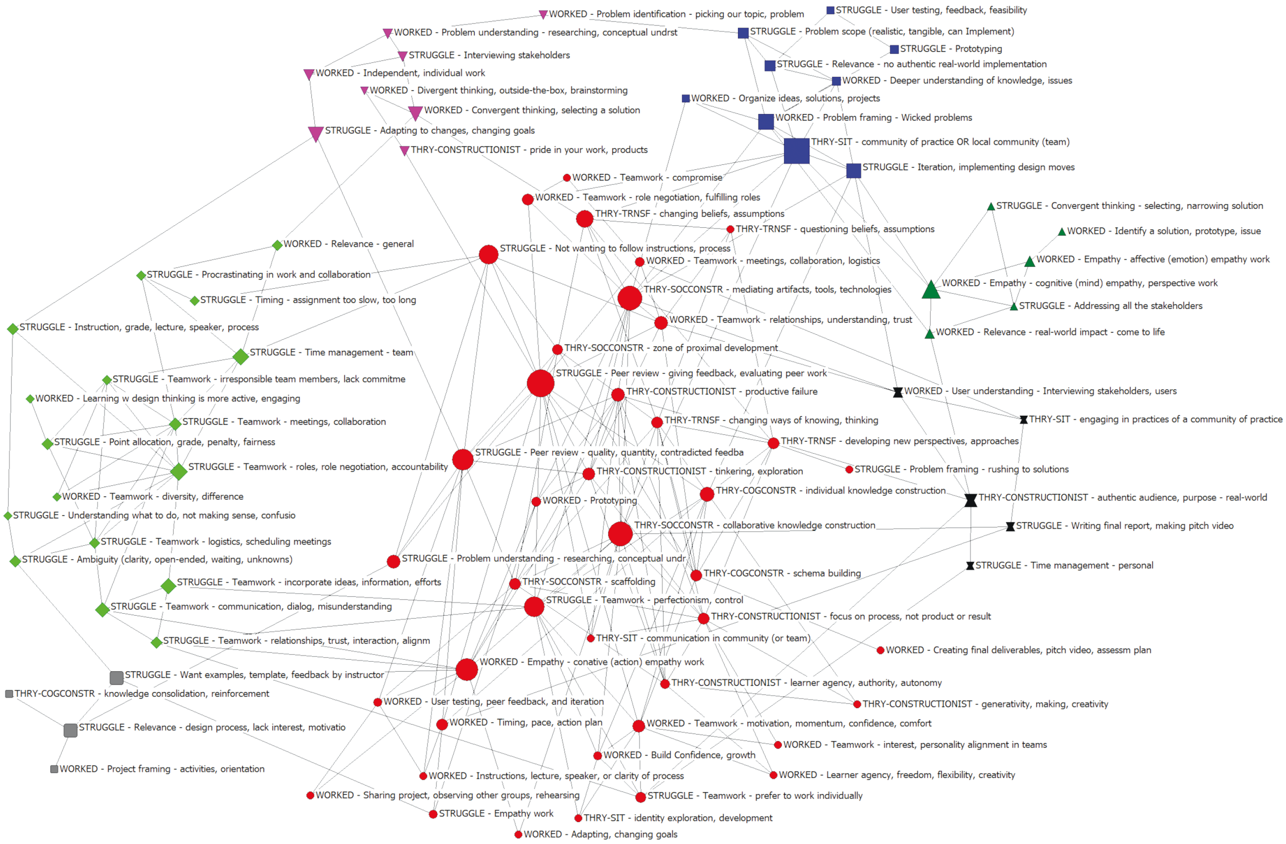

Figure 6. Network analysis map generated from the symmetrical correlation of the codes from student-generated reflections submitted by the end of the fifth and last iteration (spring 2023) of the designed-based research study ($P \leq 0.001$; $Q = 0.453$). Color and shape of nodes represent different clusters ($n = 7$), according to Girvan-Newman algorithm (Girvan and Newman, 2002). The number of clusters within the map was determined using the highest Q value as the deciding criterion. Betweenness was elected as the centrality measure for each individual variable, which is reflected by node size, reflected by the reported resulting Q-value. A version of this network map containing the betweenness values for each individual node is presented in Supplementary Material.

healthy and constructive learning environment. Learning is a complex process that may require students to face certain challenges, which, once overcome, can yield enjoyable and fulfilling experiences (Collins et al., 2016).

While changes implemented with each iteration are, by design, limited in scope (Razzouk and Shute, 2012) emergence of specific content such as struggles with the creation of the initial problem allows for data-driven changes to address the identified struggle (Donaldson and Smith, 2017). Furthermore, these nuances allow researchers and educators to gain better understanding of students' perceptions and how to leverage positive learning experiences in a very specific context and discipline—graduating seniors in animal science—which have not yet been explored in the current literature.

Implications and Future Directions

From the detailed analysis of this five-iteration study it was possible to extract five design principles that may be applicable to other courses implementing DTEL. These principles are based within the discipline of animal science, but they may also benefit other higher education areas of agriculture and life sciences.

The first design principle is based on the distribution between lecture and laboratory credit hours. This study has shown that allocating 75% of credit-hour time under laboratory instruction is more effective and appears necessary for the successful implementation of DTEL in a team-project-based learning course. The remaining 25% of the time allocated to lectures should be utilized as a support to the laboratory activities, student understanding of those activities, and even overall student personal and professional development and not as an avenue for "profession of knowledge" by the instructors.

In alignment with this first principle, the second principle includes the designation of an individual instructor to be the course and lecture coordinator. Universities frequently face challenges with faculty workload and a limitation of this study was that faculty experience in teaching and in using DTEL was not included as a variable for examination. Yet, these findings support the value of a course and lecture coordinator. Ideally, this individual should be familiar with the course structure and the DTEL processes as their role will be to assist and mentor other faculty members in this style of teaching, as well as ensure consistency across multiple laboratory sections.

To accomplish this task more effectively, the third design principle identified is instructor scaffolding. Instructors for each laboratory section, particularly those who are teaching the course for the first time, should be provided with meetings, discussions, and other resources such as publications, laboratory templates, and guidelines to support their understanding of DTEL, its objectives, and to foster effective and consistent teaching within its framework.

Consistency is also the core of the fourth design principle, identified as clarity and consistency in assignments, instructions, processes, and rubrics across laboratory sections. This principle is relevant especially when students and new instructors are not familiar with the DTEL framework. Excessive and exclusive focus on grades and final deliverables can deter students and instructors from engaging in the *processes* of DTEL, which is a vital aspect of the learning value in this format of instruction.

The last and fifth design principle identified is fostering effective teamwork. Collaboration is one of the most important elements of many learning theories. However, it is not uncommon for students in higher education to be ill-prepared and even adverse to teamwork in academic activities (National Academies of Sciences and Medicine, 2018, 2022), which greatly impairs successful collaborations and may even lead group projects to failure. Hence, providing students with proper and intentional preparation for effective teamwork is vital for the success of the DTEL in team-project-based learning. It is also reasonable to consider the impact of students' previous experiences with these constructs as well as the influence of demographics; however, these were beyond the scope of this study. Inclusion of such information will likely more precisely inform design-based changes and may provide a basis for predictive design, which would be an important step in this area of study.

The data presented herein shows that the implementation of DTEL in an animal science senior capstone course was successful in improving students' perceptions of their experiences associated with the process. The successive refinement of the course through data-oriented design moves also increased the alignment of these experiences with empirically grounded learning theories (Fischer et al., 2018; Sawyer, 2022).

It is important to emphasize, that learning is a complex process highly influenceable by a variety of uncontrollable, and often unidentifiable elements (Collins et al., 2016). Thus, the methodology of design-based research, including aspects of data collection, analysis, and interpretation, utilized in this study represents a novel and promising path for research in teaching, learning, and extension in the discipline of animal science. Future investigation in closely related fields is likely to reveal nuances unique to those disciplines.

Time, perseverance, and patience are required for the exploration and implementation of DTEL. Although the design principles identified herein should be applicable and effective in a universal context, each learning environment has its own unique limitations, issues, and strengths. Future research on the efficacy of the inclusion of DTEL in the revision of traditional disciplinary content-based courses such as physiology, nutrition, and reproduction may offer valuable insights into the role of DTEL implementation throughout an animal science curriculum. Being intentional about identifying failure and successes in each context is necessary for overall effectiveness of DTEL and its processes. Nonetheless, the universal design principles for DTEL implementation identified in this study identify a first step to the application within the discipline of animal science.

Supplementary Data

Supplementary data are available at *Translational Animal Science* online.

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Conflict of Interest Statement

The authors Alice Poggi Brandão; Jeffrey Glennon Wiegert; Sushil Paudyal and Kathrin Anson Dunlap served as instructors for Animal Science Capstone (ANSC 498), during the data collection period. None of the authors have any potential conflict of interest to disclose.

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