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Learner-Centered Design of Online Courses: A Transdisciplinary Systems Engineering Case Design

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Abstract. Societal shifts associated with the COVID-19 pandemic have exposed challenges associated with online engineering education.These challenges encompass both those inherent to the digital learning environment and those associated with the scalable presentation of content to learners with a range of different backgrounds, learning goals, and user attributes. Universal design principles can be applied to benefit all learners in some cases (e.g., modularized content, captioning of audiovisual material). However, some interface configurations for content presentation and contextualization may benefit one type of learner at the expense of others (e.g., the expertise-reversal effect). Such examples of conflicting user needs indicate a demand for adaptable interfaces that inform the information architecture and user experience interface design. A case design approach applied to a transdisciplinary systems engineering course identifies three primary interface components to target for adaptation: (1) the initial topical "entry point" into the course content, (2) the preferred presentation medium (e.g., text notes, presentation slides, or video), and (3) the navigation mechanisms supporting exploration of the learning environment and highlighting interconnections amongst the material. These adaptations address diversity in backgrounds, learning priorities, presentation preferences, and levels of expertise to appropriately scaffold the learning process for the diversity of learners experiencing transdisciplinary courses.

Keywords. Online engineering education; instructional design; user-centered design; nonsequential information organization structures

Introduction

Online transdisciplinary engineering education is associated with both challenges pertaining to the course configuration and the content itself. Online learning has been an increasingly relevant topic in higher education institutions over the last few decades, but online learning environment usage was still inconsistent across undergraduate and graduate courses [1]. The COVID-19 pandemic drastically altered the dynamics around online learning, transforming it from an available but optional alternative to the only means of instruction as schools worldwide were shut down [2]. Although online education has benefits, including greater access to the content and temporal flexibility [2], this rapid shift to fully online instruction also revealed significant challenges. A subset of these challenges can be addressed through course design. These include supporting learner motivation [3] and attention while engaging with the content [4],

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especially in the case of passive content interaction such as watching lecture videos. Server and bandwidth limitations were also widely reported to negatively influence the online learning experience [5].

Transdisciplinary engineering education is critical to developing engineering students, both at undergraduate and graduate levels [6, 7]. Transdisciplinary engineering is an approach that draws on the concepts, principles, methods, and tools of multiple disciplines and not only integrates them but transcends traditional disciplinary boundaries [8]. Effective transdisciplinary learning requires students to acquire knowledge of concepts and methods from different disciplines, recognize and understand the connections between them, and apply and build upon this understanding in a specific problem context.

Systems engineering (SE) is a broad, complex domain that emphasizes consideration of a diverse array of factors (i.e., components and interactions) that impact system dynamics in order to monitor, manage, and alter system behavior. The learning environment must accommodate a range of learners with different backgrounds, needs, and goals by considering both universal design principles and potentially conflicting individual needs and preferences. SE is widely considered a transdisciplinary domain, and SE education must contend with three primary resulting challenges [9]. The first is that learners can encounter difficulties with identifying and synthesizing the connections between content in highly interconnected information spaces. Second, there is an emphasis on developing a mindset rather than simply acquiring skills and knowledge associated with methodologies, tools, or theories. Finally, SE's applied, practical nature means that learning occurs primarily through experience, which is impossible to transfer directly from instructor to learner. These challenges indicate the importance of deliberate course design to support learners in accomplishing their learning tasks.

This paper describes a prototype design for an online, asynchronous graduate-level SE course based on an existing course taught at Purdue University. The course was originally titled Perspectives on Systems Engineering (PoSE) and focuses on the five "systems languages" (or SE sub-domains) referred to as SE1 through SE5 (for more detailed descriptions, see [10]). Although course design encompasses both content (including real-world SE case studies) and learning environment design, the learning environment is the system of interest in this case design. To facilitate this, the content utilized in the design process was previously created and recorded material from multiple previous semesters of successful delivery of the course.

This design is proposed as an alternative to the ways in which educators currently approach teaching highly complex, transdisciplinary subjects in an online, asynchronous configuration. It is not meant to represent a definitively superior method of instruction compared to in-person learning but instead to offer an alternative (and moderately scalable) method of disseminating SE / transdisciplinary knowledge. As such, the evaluation of this course design is considered out of scope of this paper. Further, a comparative evaluation of either interface design preferences or learners' knowledge retention is similarly considered out of scope.

1. Methodology

1.1. Metaframework of Universal Online Course Design

Universal design approaches in education have roots in accomodating disadvantaged learners such as those with disabilities, limited language fluency, or disparities in prior knowledge. However, the interventions that come from the application of universal design tend to benefit all learners. There are three domain-specific universal design frameworks: Universal Design for Learning (UDL), Universal Design of Instruction (UDI), and Universal Instructional Design (UID) [11]. Each of these frameworks considers the education system from a slightly different perspective (e.g., learner, instructor, and course designer), but there is significant overlap in terms of the core principles of each approach. Therefore, in order to develop a single list of important principles to consider during course design and implementation, highly similar principles across UDL, UDI, and UID were aggregated into "metaprinciples" consisting of one or more of the original principles.

Not all of these metaprinciples are relevant to the case design's purpose. All three frameworks were initially designed for application to face-to-face learning. Therefore, some of the metaprinciples do not apply to an online, asynchronous course design and could be discarded. Similarly, other remaining metaprinciples exclusively emphasized elements beyond the scope of learning environment design by describing either content design (including assessment design) or course implementation, both of which were considered out of scope. The relevant metaprinciples are shown in Table 1 and the original principles they drew from.

Table 1. Metaprinciples drawing from at least one UDL, UDI, or UID principle relevant to learning environment design. The framework of the orginal principle is denoted in bold. Adapted from [9].

Metaprinciple	Child Principles
1. An instructional environment should provide multiple, accessible means of representing the course information	**UDL**: Multiple means of representation **UDI**: Utilize multiple, accessible means of content delivery **UDI**: All course materials should be accessible, engaging, and flexible **UDI**: All materials should be physically accessible and usable by all learners **UID**: Consider a distribution of learner individual differences
2. An instructional environment should support multiple means of engaging learners with the content	**UDL**: Multiple means of engagement **UID**: Consider a distribution of learner individual differences
3. An instructional environment should provide a diverse, inclusive, welcoming climate	**UDI**: Diverse and inclusive class climate **UID**: Create welcoming classrooms **UID**: Consider a distribution of learner individual differences
4. An instructional environment should utilize natural learning supports	**UID**: Consider and integrate the use of natural learning supports, including technology **UID**: Consider a distribution of learner individual differences
5. Instructors should identify essential course components	**UID**: Identify the course's essential components

1.2. User Personae Development

User personae are fictional descriptions of exemplar users with different goals, behaviors, abilities, and attitudes meant to represent subsets of the intended user population. These concrete examples support the analysis of design decisions in the context of different users with different attributes, facilitating the identification of universally beneficial design decisions as well as those that may be beneficial to one group at the disadvantage of another. When disparate design decisions arise from conflicting user needs, dynamic interfaces offer a solution to a "one-size-fits-all" approach that may ultimately impair some users.

For the case design, there were five learner personae developed through an iterative and collaborative discussion between three subject-matter experts (including the authors), each of whom was able to represent the perspective of a key stakeholder (i.e., students, instructors, industry professionals). The personae are amalgams of observed student characteristics from the 2017 and 2019 iterations of PoSE.

1.2.1. Personae Characteristics

Helpful learner personae describe the prospective user in terms of relevant characteristics that can inform design; too much excess description can become cumbersome to deal with. Learners were described in terms of characteristics that impact their learning outcomes, approach to the information space, and the quality of their online experience. These characteristics were identified by consulting the literature and considering observed student behavior and self-reported goals (captured through a PoSE discussion board assignment).

Many individual differences have been shown to impact learning and academic outcomes. Only a subset of these suggest design interventions at the level of the learning environment, including achievement motivation (i.e., the internal factors driving pursuit of success) [12], extrinsic motivation [13], attention regulation abilities [14], learning styles (more accurately described as instructional presentation preferences within the Felder-Silverman model) [15], and prior domain knowledge or expertise [16].

Levels of prior domain knowledge are especially important due to the transdisciplinary nature of the class resulting in learner interest from different disciplinary backgrounds. Due to the nature of the PoSE content, this attribute must be described multidimensionally by considering prior experience with each "systems language." The expertise-reversal effect further emphasizes the importance of this attribute, as it reveals that design interventions that are support novices may be detrimental to more experienced learners (and vice versa) [17]. Therefore, the ways in which the learning environment is designed to support learning are not constant for all learners across all experience levels.

In addition to these, it has been observed that learners vary in terms of their current role and their objectives when it comes to the class. Learner roles include (1) traditional students (i.e., on-campus graduate and upper-level undergraduate students), (2) working professionals (i.e., part-time, off-campus graduate students who are taking classes while working in industry), and (3) executives (i.e., members of upper management in a company who are not seeking a degree but want to learn about systems engineering to apply it within their institution). Additionally, different learners will have different objectives, or priorities, when approaching the course, which may be related to the above roles. For example, some students may be primarily concerned with earning a good grade, while others may want to learn the information to apply to their current or future job or simply to master the content. These may relate to the motivation factors discussed above.

Finally, access to sufficient bandwidth is critical for a high-quality online learning experience and was one of the major technological barriers highlighted by the COVID-19 pandemic [5]. Bandwidth access may vary across learners due to a number of factors, including socioeconomic status and location (e.g., rural, urban, or suburban community). Although expanding bandwidth for learners is not within the scope of this case design, lower bandwidth connections do represent a constraint on accessible system design.

1.2.2. Dynamic Interfaces

Virtual learning environments have one major benefit associated with them that other design alternatives do not: computers are inherently adaptable and can be designed to provide different users with different experiences. These dynamic interfaces offer a potential solution to situations where learners have conflicting needs that cannot be resolved into a single design. In an educational context, dynamic interfaces have been designed to accommodate factors including learning styles, achievement motivation, and prior knowledge [18]. Although they exist on a continuum, two types of dynamic interfaces are adaptable and adaptive interfaces. The primary difference is the locus of control for the adaptation behavior; in fully adaptable interfaces, users have control, whereas in fully adaptive interfaces, the interface system has absolute control. Generally, providing the user with some measure of control is encouraged [19].

1.3. Learner Task Analysis

Learners would perform two primary tasks within an online learning environment: learning tasks and information-search tasks. Learning tasks are defined as any task that contributes to the acquisition or expression of knowledge (e.g., watching a lecture video, taking a quiz, etc.). Learning transdisciplinary SE content is challenging due to the transdisciplinary thinking needed to connect topics across different disciplinary contexts and the emphasis on developing a "systems mentality" that facilitates application of the material to systems outside the course boundaries.

Cognitive flexibility theory (CFT) is an instructional theory that is meant to be applied to highly interconnected and complex domains like SE [20]. CFT argues that in order to deeply learn in such a domain, it is necessary to explore an information (or content) space from multiple perspectives to develop a holistic mental network of knowledge. In service to this goal, CFT is frequently discussed along with non-sequential information and navigation structures (NSINSs), which serve as an alternative to hierarchical organization systems that impose nested structures and tend to emphasize sequential information access. In contrast, NSINSs, commonly referred to as hypertext or hypermedia systems, support contextual navigation that emphasizes the connections between different pieces of content by providing a navigable link that can be explored. The effectiveness of these structures is partially related to the expertise level of the student (as noted in the expertise-reversal effect), with more experienced learners expressing a stronger ability to reap the benefits and avoid the challenges associated with NSINSs [21].

The systems mentality that is ideally developed by SE students is characterized primarily by the ability to apply SE concepts and perspectives to real-world systems outside of the context of the PoSE course. This can be conceptualized as learning transfer.

Although content design (including the use of case studies) and environmental variables influence learning transfer, these are considered out of scope, so the emphasis must be placed on the two principles associated with learning environment design. These include modularized content delivery and multiple, variable methods of representation of the material (which relates back to the universal design metaframework) [22].

2. Results

2.1. Universally Applicable Design Decisions

There were two major design decisions to support learners that were universally applicable throughout the learning environment: (1) captioning of video content and (2) topical and temporal content modularization.

Providing captions is one means to address the first principle listed in Table 1, stating that all content should be accessible and be represented through multiple means. The addition of text to the auditory information is an additional way of representing the material. This benefits learners with auditory challenges, non-native English speakers, and students who simply prefer to read. Captions can also support learners who are situationally disabled due to a noisy environment or issues with the recording's audio quality.

Content modularization was applied to recorded lecture material at multiple levels, as shown in Figure 1. Other existing content, such as paragraph and PowerPoint-style lecture notes, were not modularized at a finer grain size than the module level, but do tend to relate to the thematic topics and individual segments. Several design requirements were applied in order to identify thematic topics from original, 75-minute lectures as well as to parse the individual segments within each thematic topic as necessary.

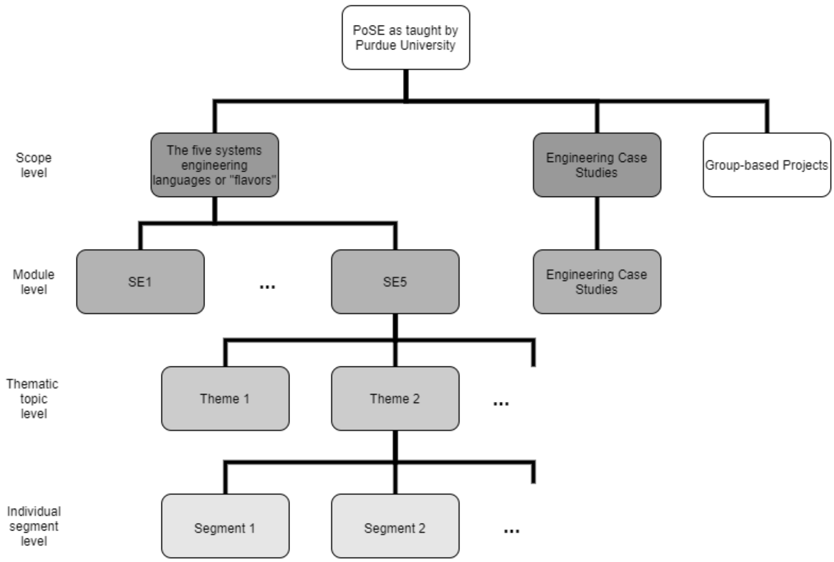

Figure 1. Diagram showing the modularization of PoSE content at different levels. Adapted from [9].

At the scope, module, and thematic topic levels, topical modularization, or parsing based on subjects being discusses, was applied. Topical modularization was implemented to support learning transfer. To support NSINSs, the thematic topics should not necessarily need to be viewed in a particular sequence. References to material beyond the thematic topic do not need to be entirely removed, but they should represent reasonably independent segments where the content within the segment must be presented sequentially to support understanding of the topic of interest.

The individual segment level is the lowest level and is applied to restrict the length of individual videos. This type of modularization is meant to accommodate learner attentional demands and bandwidth quality variations. This temporal modularization targets learner self-regulation of their attention, which can be especially difficult during long-lasting, passive activities like watching full-length lecture videos or even attending in-person lectures. There is significant variability and discourse regarding the ideal length of an individual segment, ranging from a maximum of six minutes to ranges of 12-20 minutes [23]. Temporal modularization impacts bandwidth requirements through decreasing the file size without impacting the video quality itself, therefore providing robust access to the content regardless of access to high-speed internet. Therefore, a target length of less than 15 minutes with an upper limit of 16 minutes was applied to all video content. Additionally, individual video segments should be segmented so that they end at natural transition points between sub-topics and do not cut the instructor off mid-sentence.

Regardless of amount of content, all modules required at least one rewatch of the material to finalize the thematic topics and identify transitional timestamps. From there, temporal modularization was performed as described above. If an individual segment was extremely short (under 5 minutes), it was evaluated in the context of other, possibly temporally displaced segments associated with the same thematic topic and the same recording semester. If the summation of the two segments was under 16 minutes and the transition did not result in confusion, the two segments were combined. (See [9] for additional details regarding the modularization process.) .

2.2. Adaptable Interfaces: Accounting for Conflicting Needs

A "one-size-fits-all" design is not always desireable due to conflicting learner needs. Three design decisions were identified where user personae characteristics suggested different solutions that could not be simultaneously implemented. These design decisions consisted of the sequencing of the systems language modules, the "default" presentation medium (i.e., text or video), and the implementation of nonsequential information and navigation structures. Adaptable interfaces were designed in order to support dynamic user experiences while maintaining learner control.

Due to the transdisciplinary nature of the course, the user personae are representative of a number of different backgrounds; they also represent varying degrees of "fluency" in each of the systems languages. Building upon existing knowledge and providing sufficient learner control to explore interests are approaches that can increase learner engagement with the material. There is no singular module sequence that will do this for all learners. As such, it was decided that an adaptable interface should be utilized to allow users to determine the sequence in which they access and complete the systems languages modules.

Learners also vary in terms of their instructional presentation preferences (also described as learning styles within the Felder-Silverman model). For example, some learners may learn better or simply prefer watching video lecture content, while others may prefer reading text. In many cases, both paragraph-style lecture notes and the lecture videos cover broadly the same topics, though the recorded lectures contain more detailed discussions. As such, the default means of presenting information represents an opportunity for customization of the learning experience to better suit a user's preference. An adaptable interface is most appropriate in the case of user preference that would be best known to the user themselves and was implemented to allow the learner's to indicate their ”default” presentation preference. It is worth noting that due to the greater detail in the lecture videos, it is still recommended that these be reviewed at some time.

Finally, an NSINS was implemented in the context of an adaptable interface. As noted previously, NSINSs can support learning of complex, interconnected material by making those connections navigable and thus highlighting them, as well as allowing the learner to explore the information space from multiple different perspectives. The designed NSINS for this case design relied on tags connecting instances of a keyword throughout the content, providing a rich network of navigable links. The keywords were identified through a content analysis of the existing PoSE content. Critically, NSINSs impact different types of users (especially novices and experts) differently. Novices can easily become disoriented and cognitively overloaded within NSINSs, whereas experts are better able to manage the additional cognitive load and are more likely to benefit from the NSINS. As such, it is critical to support both experts and novices through an adaptive interface that influences the primary active navigation system. Novices will be able to navigate through a more structured, hierarchical, and sequential system, and though the tags will still be visible to them, they will not have to interact with the tags in order to navigate. In contrast, experts can experience the system where the primary navigation mechanism is the tags, allowing a deeper exploration of the information space. The adaptable nature of this dynamic interface is critical, because it allows users to decide when they are experienced enough to navigate primarily with the tags and enables them to return to a hierarchical structure via an omnipresent adaptation trigger (i.e., toggle) in case of disorientation or cognitive overload.

3. Discussion

The content modularization process is important because it highlights several important takeaways that should be considered before applying it elsewhere. Both topical and temporal modularization are literature-supported approaches to providing learner support to address attentional challenges and facilitate learning transfer, but come at a non-trivial cognitive workload cost to those responsible for organizing the modules. This process cannot be applied well in a short timeframe, as it requires multiple iterations of watching the lecture material in order to identify the transitional timestamps, and the actual editing process requires even further rewatching. Content modularization is a process that could be applied more widely to online course design, regardless of the characteristics of the subject domain.

Computer-based, asynchronous environments provide significant design flexibility in a way that cannot be supported within an in-person course design. For example, the digital medium allows for multiple versions of the learning environment to coexist, where the learner will be presented with the iteration that best supports their individual needs, goals, and experiences. It is important to note that this case design was intended to provide a viable interface design alternative, not to test a hypothesis of “superior” delivery. Adaptable interfaces are one method of implementing individualized, learnerfocused instructional design and allow for consideration of all types of users in situations where there are conflicting characteristics present.

It is also worth noting that identification of thematic topics and transition points between individual segments is subjective. It is highly unlikely that two different "modularizers" would ultimately present identical outputs. However, the degree and impact of these differences is unclear and would depend on the nature of the material and clarity of any agreed upon requirements; this may merit investigation if the modularization process is more widely applied.

Finally, it is worth remarking that although there is generally corresponding "text" content for each lecture video, the depth of the explanations are not constant. Although paragraph-style lecture notes present the concepts in a well-contextualized manner that might resemble a book chapter, the PowerPoint-style lecture notes lack context, depth, and clarity [24]. However, these concerns could be addressed through supplemental content design, although that is out of the scope of this case design.

Future work may include the implementation of this course interface design and comparison to other asynchronous, online course designs and synchronous, co-located course designs. Outcomes of such comparisons would help describe effects and interactions between learning modality, interface, and environmental context on learning outcomes for the PoSE course.

4. Conclusion

Online, asynchronous courses represent an opportunity to expand the reach of transdisciplinary education to a wider audience. Through revisiting our assumptions about the foundations of online learning in context of its universal challenges as well as domain-specific needs, novel learning environments can be designed to support learners. Some of these challenges can be met through implementation of universal design and consideration of individual differences in a way that ultimately benefits all users, including captioning and content modularization. However, it is critical to recognize the limitations of a "one-size-fits-all" design approach, as the learner diversity may be associated with conflicting needs that suggest mutually exclusive designs. This is especially true in the context of transdisciplinary engineering education, which is prone to attracting learners from a variety of disciplinary backgrounds and experiences. The disparities in prior domain knowledge and expertise raise challenges associated with the expertise-reversal effect, which emphasizes the dangers of designing with only novices in mind. Adaptable interfaces offer an alternative to a single, universally-applied design through allowing different learners to interact with different designs depending on their own self-reported characteristics while still maintaining learner control. Implementation of adaptable non-sequential information and navigation structures in particular offers a solution to many of the complex issues associated with the complex, highly-interconnected domains associated with transdisciplinary engineering education.

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