Addressing the challenges of online and blended STEM learning with grounded design

Yunjeong Chang
The State University of New York at Buffalo

Eunbae Lee
Kyung Hee University, Seoul

During the COVID-19 pandemic, online learning became a major alternative to college science, technology, engineering, and mathematics (STEM) courses in postsecondary education. Faculty members, although subject matter experts, often lack pedagogical knowledge and training on how to effectively teach new generations of students online, or incorporate appropriate technologies. Faculty teaching online courses needed a new guiding framework to balance domain goals and emerging technologies. We present grounded design for STEM courses to align domain goals and instructional methods and technologies while reflecting instructors' pedagogical beliefs and addressing cultural and pragmatic issues. It is critical to provide students with aligned STEM learning experience and engagement via defensible theories and research-evidenced pedagogy in online and blended courses while technological, cultural, and pragmatic considerations are also addressed. We suggest grounded design as the conceptual and design framework for designing online and blended courses and discuss the assumptions, approaches, and examples. We provide practical guidelines to apply grounded design to online and blended learning environments and suggest future research. This article can assist both novice and seasoned STEM faculty to connect theory and research to teaching practices and optimise their online and blended courses.

Implications for practice

- University STEM instructors can use grounded design framework for online, blended, and technology-enhanced teaching.
- Instructors should begin the course design by aligning the domain goals with optimal psychological and pedagogical foundations.
- When choosing technology to support online learning, instructors should align it with learning goals and needs of students, and consider cultural and pragmatic foundations.

Keywords: online learning, blended learning, STEM, grounded design, technology integration, learning systems design, faculty development

Introduction

When the COVID-19 pandemic first swept the world in 2020, colleges converted to online to keep their members safe and continue to provide education. This abrupt emergency transition granted faculty and students little time to thoroughly design online learning experiences and receive adequate training (Sedaghatjou et al., 2021). Instructors were expected to apply different pedagogical strategies suited for online settings. However, faculty with little previous online teaching experience had to improvise (Johnson et al., 2020). Due to urgency, online learning efforts were mainly focused on the digital transformation. Vital factors in teaching and learning such as domain goals, appropriate methods, and cultural and pragmatic considerations were often neglected or misaligned (Adedoyin & Soykan, 2020; Dhawan, 2020).

Some courses are harder to convert to the online mode of delivery due to lack of in-person interactions. Specifically, science, technology, engineering, and mathematics (STEM) fields, which require both laboratory and hands-on experiences, face additional challenges (e.g., no laboratory access, the impossibility of having hands-on experiment) in the transition to online teaching (Tigaa & Sonawane, 2020). This is mainly because the goal of STEM is not to simply impart content knowledge but to guide students to develop scientific thinking, critical-thinking, problem-solving skills (Kuhn, 1993). While STEM faculty were encouraged to incorporate technologies to develop the aforementioned skills, an online mode of delivery added challenges to STEM faculty.

Previously, Garrison et al. (1999) guided the design of online learning in higher education to form a community of inquiry that promotes cognitive, teaching, and social presences in asynchronous text-based online courses (Garrison et al., 1999). However, asynchronous, text-based online learning environments allow no real time interactions or just-in-time support. Online courses have evolved to employ multi-modal media and technologies that afford unimagined opportunities for synchronous interactions, content engagement, and expansion (Mayer, 2009). Using online, mobile, and wearable devices, teaching and learning are no longer defined or confined within fixed periods of time and location (Khaddage et al., 2016). Students have seemingly unlimited options for using, manipulating, and creating resources through a myriad of technologies (Cronin, 2017). Faculty members who teach online courses need a new guiding framework to balance the domain goals and emerging technologies.

Since 1997, the grounded design framework has been adopted to create aligned learning environments with domain goals, teaching methods, and emerging technologies. Grounded design is a design framework for student-centered, technology-enhanced learning environments that focuses on the alignment of domain goal, methods, and strategies in the psychological, pedagogical, cultural, technological, and pragmatic areas of teaching and learning (Hannafin et al., 1997). After two decades of technological advancement and societal changes, it is meaningful to reexamine how this framework could optimise contemporary online learning, and this study posed the research questions:

1. What are the challenges STEM faculty and students face in online teaching and learning?
2. How can grounded design provide the framework and guiding principles to overcome the challenges in online and blended courses?
3. What STEM online and blended courses can be used as examples of grounded design?

To address these questions, we first reviewed the challenges in online, blended, and technology-enhanced college teaching and learning. Then by applying the grounded design framework, we proposed optimised online learning that aligns the learning goals with instructors' beliefs about teaching and learning, as well as contemporary learning theories and strategies. We then reviewed studies conducted in STEM areas to identify online, blended, and technology-enhanced courses that fitted the ground design framework while presenting solutions to previous challenges.

Literature review: Challenges in online teaching and learning

Students underprepared for learning online

While college students are expected to exercise self-regulated learning in online learning environments, contemporary college students may be unprepared, unable, or unwilling to engage in self-regulated learning. Previous research reported that self-regulated learning skills such as goal setting, planning, monitoring, and reflecting on the learning process (Zimmerman, 2008) affect online learning experience and academic performance (Cho et al., 2017). However, students often lack the requisite self-directed learning skills. Prior to college, students are accustomed to memorising, following external directions, and taking standardised tests (Zimmerman & Kulikowich, 2016). Moreover, when they lack self-regulatory strategies, students rarely seek assistance or consult additional resources, and tend to give up when encountering difficulty (Kilis & Yıldırım, 2018).

A meta-analysis study by Broadbent and Poon (2015) delved into the correlation between self-regulated learning strategies and student academic achievement in online higher education learning environments. Analysing studies published between 2004 and 2014, the study found a number of self-regulated learning strategies were associated with higher academic achievement in an online setting (e.g., time management, metacognition, effort regulation, peer learning, elaboration, rehearsal, critical thinking, and help seeking). Dörrenbächer and Perels (2016) found that levels of self-regulated learning strategies were individually different because the strategies are dynamically associated with other learning constructs such as motivation, emotion, or personality. Alghamdi et al. (2020) further identified the associated construct of self-efficacy on learning with technology.

Faculty unfamiliar with teaching online

Domain expertise is widely expected of instructors, yet the majority have received minimal preparation for teaching, or online teaching, particularly in mathematics and science fields (Bathgate et al., 2019). Some institutions provided instructors with resources to transition in-person courses to online, yet over generalised resources are insufficient to meet the various learning goals or pedagogies in STEM disciplines (Alexander et al., 2019). Moreover, misaligned technology integration practices are distressingly common (Koehler & Mishra, 2009). For effective teaching and learning with technology, Koehler and Mishra (2009) proposed aligning and meaningfully integrating technological, pedagogical, and content knowledge. Few college faculty members have experienced or observed effective teaching with technology when they were students. Rather, many are apathetic toward technology integration (Kebritchi et al., 2017). Koehler and Mishra (2009, p. 62) argued:

> [M]any teachers earned degrees at a time when educational technology was at a very different stage of development than it is today. It is, thus, not surprising that they do not consider themselves sufficiently prepared to use technology in the classroom and often do not appreciate its value or relevance to teaching and learning.

Technologies could be integrated to meaningfully externalise thinking processes and encourage learners to visualise complex concepts and scientific phenomena (Krist et al., 2019). For example, complex topics, such as the water cycle in physical geology or the human circulatory system in biology, pose challenges to learners because they contain multiple layers of information that often interact in abstract, counter-intuitive, and unobservable ways (Akçayır et al., 2016). Well-designed learning environments provide powerful tools for complex learning by presenting multiple representations of information. Despite their potential, many technologies in online or blended learning environments are unused or misused.

Misalignment among domain goals, pedagogical beliefs, and online teaching practices

When pedagogy is misaligned with domain goals, online teaching becomes challenging and inhibits student learning. In science, for example, the goal remains to guide students to develop scientific reasoning, inquiry, problem solving, and critical thinking skills. Inquiry-based learning has been widely applied in science, however, barriers are common due to misalignment among domain goals, pedagogical beliefs, strategies, and technology. For example, lack of effective scaffolding (i.e., supporting sense making or strategic decision making during) has been detrimental during inquiry-based learning (Mamun et al., 2020).

Practical barriers such as teaching large student cohorts leave instructors few opportunities to enable students to conduct inquiry and develop reasoning skills. Peer collaborative learning, where students work in small groups of three or four members to accomplish shared goals, exchange reasoning, and observe patterns of thought, is harder to achieve online (Chang & Hannafin, 2015). While online learning management systems and online tools have been widely used to facilitate collaboration and communication, incorporating online tools has not been proven effective in promoting the learning of students with differing learning preferences and prior knowledge of using online tools (Oh & Kim, 2016). To address aligning domain goals with pedagogical beliefs and strategies, technology can be used to optimise support across STEM faculty and students to enable them to succeed in their roles online. A variety of design frameworks for technology-enhanced learning environments have been introduced and examined (Bower & Vlachopoulos, 2018). Yet, researchers have rarely balanced students' learning issues, pedagogical issues, and epistemological differences and strategies for online teaching and learning. Besides, the extent to which the framework can be applied in online or blended learning environments has not been examined.

In the following section, we examine grounded design as the conceptual and design framework for STEM online learning. We argue that contextual factors must be differentiated, weighed, and addressed to reflect both key epistemological differences and strategies. We then review the grounded design based online instructions that demonstrate well-aligned epistemology, learning goals, strategies, and technology use. Finally, we suggest ways to optimise online college STEM learning environments. The key is to align instructor beliefs surrounding teaching and learning within domain learning goals, theories, and strategies, across current technology-enhanced college STEM courses.

Conceptual design framework: Grounded design

Grounded design is a framework for student-centered, technology-enhanced learning environments that focuses on the alignment of domain goals, methods, and strategies in the psychological, pedagogical, cultural, technological, and pragmatic areas of teaching and learning (Hannafin et al., 1997). No given strategy can be universally applied to all types of learning independent of overarching epistemological goals, learning requirements, and varied contextual demands. Strategies must adapt to and reflect different epistemological and philosophical assumptions of a given domain to accommodate varied learning goals, contexts, and requirements. The foremost principle for design a grounded learning environment is the alignment of domain goals, pedagogical beliefs, and teaching strategies. To design a grounded learning environment, instructors first reaffirm the domain goals. For example, the domain goals of science are thinking like a scientist and performing the processes of science (Next Generation Science Standards, 2013). Instructors then examine whether their own pedagogical beliefs are consistent with the domain goals and if their teaching practices are designed to address the learning goals. One instructor’s teaching methods and practices should not be particular to their own pedagogical belief, but rather reflect values and beliefs relevant to the domain (Land et al., 2012). Next, five foundations of learning environments should be considered and aligned: psychological, pedagogical, and cultural, technological, and pragmatic (Figure 1).

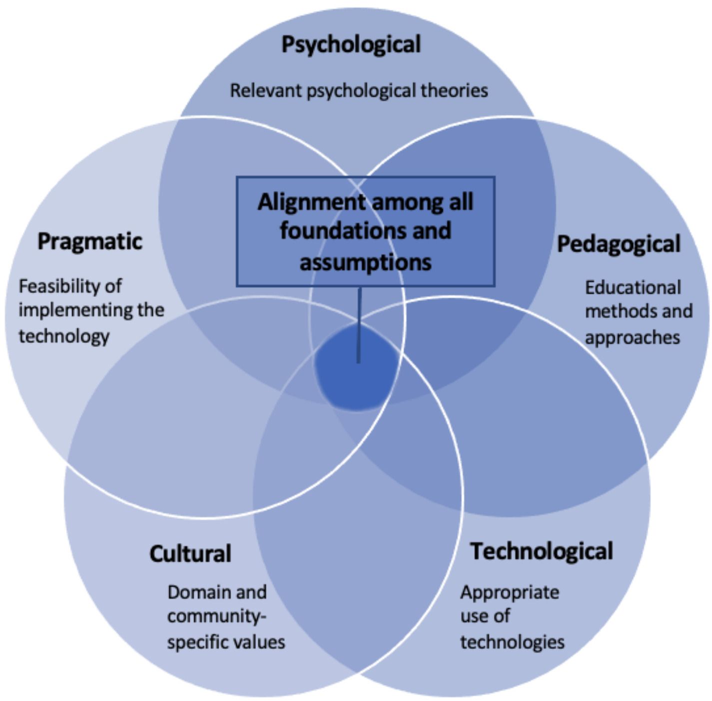

Figure 1. Five foundations of grounded design adapted from Hannafin et al. (1997, p. 106)

Psychological foundations refer to the relevant psychological theories that inform how people learn. For example, behavioural psychology is the foundation of direct instruction based on stimulus/response associations (Schunk, 2012). Cognitive psychology introduced cognitive load theory in relation to information processing theory to explain how people store and recall memories and build schema, and therefore help design multimedia learning materials (Sweller, 2011). Pedagogical foundations refer to educational methods and approaches that evolved from learning psychology. For example, behaviourist assumptions introduced stimuli-response-feedback instructional activities, while cognitivist suggested information processing strategies (i.e., highlighting the information to be learned, chunking the relevant information, step-by-step guidance) to process, learn, and recall the information efficiently. Cultural foundations reflect the domain and community-specific values. For example, some higher education institutions value community engagement as the most important mission of the institution, while the field of computer science recently has given more attention to equality and diversity issues (e.g., the Computer Science for All initiative). Alternatively, engineering education has valued design thinking (Dym et al., 2005), and medical education has valued a problem-based learning approach (Barrows, 1986). Technological foundations address the appropriate use of technological resources for the domain goals, content, context, and students. Cutting-edge technologies are not always the best option and can bombard students with unessential media and tools and interferes with cognitive processing (De Jong, 2010). The selection of the right tools for the right purpose is essential to address the domain goals and issues. Pragmatic foundations suggest to check the feasibility of implementing the technology in reality. For instance, if an activity requires the synchronous login of more than 100 students in the system, will the wi-fi connection be stable enough for all students, or is the budget enough to provide equitable learning experiences for students with different mobile devices and data plans?

Additionally, grounded design poses four conditions: a defensible theoretical framework, research-supported decision, iteratively validated design, and generalisable practice (Hannafin et al., 1997). With regard to a defensible theoretical framework, a well-established theoretical framework provides a sound and sustainable ground for building learning environments. Case-based reasoning theory, for instance, informs case-based learning. Case-based learning provides learners with sequencing experiences that afford concrete, authentic, and timely feedback where learners can confront their conceptions and misconceptions, identify gaps in their understanding, and progress iteratively to refine their knowledge and skills. For example, web-based case collections (case libraries) were created to support professional graphic and web designers as they learned about computer programming (Dorn & Guzdial, 2010).

Regarding research-supported decisions, research should be carried out to defend the efficacy of applied teaching practice. For example, graphic organisers (i.e., concept mapping tools) are presumed to activate prior knowledge structures and depict visual relationships between new and prior information before learning textual material. However, little empirical research has examined their effects on retention and transfer. Shaw et al. (2012) examined the effects of using graphic overviews on 111 undergraduates but reported no support for overviews over graphic organisers. Rather, the researchers concluded that graphic organisers actually provided greater benefit than overviews. Students who viewed graphic organisers after the text, outperformed those who viewed them, when tested on information application, not just retention.

In terms of iteratively validated design, varied teaching practices and associated frameworks need to be validated iteratively through successive implementations. This may be accomplished through design-based research to optimise effectiveness in a given setting and assess the generalisability to similar problems and contexts while simultaneously refining the theory upon which the design is based (Wang & Hannafin, 2005). Based on Mayer and Moreno’s (2003) cognitive overload scenarios, multiple studies have been conducted to refine strategies for arranging multimedia objects to reduce cognitive load. Nelson and Erlandson (2007) explored the interface of multi-user virtual environments to minimise cognitive overload. In addition, by investigating the effect of communication modality on cognitive load and inquiry learning, Erlandson et al. (2010) found a highly effective way of communication through voice-based chat in order to reduce cognitive load in a multi-user virtual environment based inquiry curricula. These efforts were both informed by, and contributed to, the refinement of Mayer’s cognitive theory of multimedia learning (Mayer, 2009).

Finally, regarding generalisable practice, the broader applicability of a given learning design needs to be demonstrated. However, researchers rarely provide empirical evidence to document the generalisability of a learning design. Hays (2005) examined the potential of gaming for military training and educational applications. He reported that among 270 published reviews of instructional games, only 48 provided supporting empirical data to document the effects as follows:

> The empirical research on the effectiveness of instructional games is fragmented, filled with ill-defined terms, and plagued with methodological flaws. Some games provide effective instruction for some tasks some of the time, but these results may not be generalisable to other games or instructional programs. (Hays, 2005, p. 3).

These four conditions of grounded design inform the selection, design, and pedagogy of evidence-based instruction, especially in the relatively new territory of technology-enhanced online and blended learning.

Methods

We reviewed and selected grounded STEM online and blended learning examples following a systematic review process (Petticrew & Roberts, 2008). The Web of Science database was used to conduct the review. The selected terms were searched in the title, keywords, and abstract of the paper. The search strings were as follows: TS=[("stem" OR "science" OR "technology" OR "math*" OR "engineering" OR "comput*" OR "biology" OR "physics" OR “chemistry”) AND (“online*” OR “hybrid” OR “blended” OR “MOOC”) AND ("college*" OR "university*" OR "undergrad*" OR “faculty” OR “teacher” OR "higher education") AND ("teaching" OR "instruction*" OR "learning" OR "professional development")].

The study selection was iterative and divided into several stages. We ran several rounds of reviews by establishing inclusion and exclusion criteria (Table 1). Using criteria 1 to 5, the initial search round resulted in 8144 articles through title. In the second round, we selected 403 studies that met criteria 6 and 7 through title and abstract. The third-round review included analysing the articles’ full-text with grounded design’s five foundations (i.e., psychological, pedagogical, cultural, pragmatic, technological) by using inclusion criteria 8 to 11.

Table 1
Systematic review process

Round	Inclusion criteria
1	1. Studies must be conducted in STEM fields.
	2. Studies must be conducted in online, hybrid, or blended settings.
	3. Studies must be conducted in higher education settings.
	4. Studies must be conducted between 2010 to 2021.
	5. Studies must be published in peer-reviewed journals or proceedings.
2	6. The full version of the publication is available at the authors’ institutions.
	7. Studies must include empirical evidence.
3	8. Studies must address learning or teaching challenges in the real-world context (e.g., classroom, course, professional development).
	9. Studies must describe a course topic and domain/learning goals.
	10. Studies must describe theoretical framework.
	11. Studies must describe how technology was used in the study.
Round	**Exclusion criteria**
1	1. Studies are not conducted in STEM fields.
	2. Studies are not conducted in online, hybrid, or blended settings.
	3. Studies are not conducted in higher education settings.
	4. Studies are not conducted between 2010 to 2021.
	5. Studies have been published without a peer review process.
2	6. The full version of the publication is not available at the authors’ institutions.
	7. Studies do not include empirical evidence.
3	8. Studies do not address learning or teaching challenges in real-world contexts.
	9. Studies do not describe a course topic and domain/learning goals.
	10. Studies do not describe theoretical framework.
	11. Studies do not describe how technology was used in the study.

For the third round, two authors first analysed entire full texts independently and then discussed their findings using a template (Appendix A) generated based on the grounded design framework . The analysis process adopted document analysis procedure which involved a deductive process that allows researchers to collect objective and unaffected data by the research process in a cost-effective way (Bowen, 2009). The first author intensively analysed studies within engineering, mathematics, and professional development contexts. The second author intensively analysed within the science and technology domain. From a total of 403 articles, we selected 42 studies for the third round. By creating an Excel file similar to Appendix A, the authors shared their findings to be discussed and select the most appropriate examples: those that demonstrated the grounded design approach. The included studies described the aligned domain goals, psychological and pedagogical foundations and addressed technological, cultural, and pragmatic considerations. In addition, the four conditions of grounded design were examined. Most studies were research-evidenced and defensible but not all were iteratively validated or generalisable. When there was a disagreement between two authors, an agreement was reached through discussion. As a result, 10 examples were included in this paper.

Findings and discussion: Grounded STEM online and blended learning

While online learning has allowed contemporary education to be more accessible, interactive, and reflective, multiple concerns have been remained in STEM education such as high cost, competency demonstration for safety issues (e.g., learning a case with radioactive samples, toxic chemical substances) and ethical issues (e.g., experiments on human subjects), and students' lack of self-directed learning skills. To address these concerns, we highlighted several examples that demonstrated grounded design, to discuss how the previously indicated challenges were addressed (Appendix A).

Addressing the discrepancy between domain goals and teaching practices

Multiple studies have been carried out using the grounded design approach to enhance college students' online learning experiences. Augmented reality assisted science learning is also emerging as a supplementary aid to online and blended learning through which students can individually interact outside the classroom or in groups within the classroom. In Akçayır et al. (2016) study, Turkish university students conducted physics experiments in augmented reality using videos, animations, and images via mobile devices and demonstrated better laboratory skills, completed the experiment in a shorter time, and reported positive attitudes toward the physics lab. This augmented reality enabled learning environment was designed under the multimedia learning theory (Mayer, 2005) and adopted multimedia learning principles. Previous research informed its application design as to how augmented reality can enhance learning (Chiang et al., 2014; Santos et al., 2014). The use of technology was meaningful in that students were able to watch events that could not be observed in a real laboratory setting, for example watching molecules move (Akçayır et al., 2016). This study exhibited grounded design and could be reiterated and replicated in other settings to provide further evidence of its broader application.

Similarly, Geneticus Investigation is designed to enhance undergraduate biology students' hypothetico-deductive reasoning and can be used as a cost-effective virtual lab in an online or blended course (Deep et al., 2015). This system allows students to reason at each step of science experiments, from choosing different hypotheses for a given problem, designing experiments, predicting outcomes, running simulations of the experiment, comparing outcomes, and accepting or rejecting the hypothesis. The system is grounded with constructivist learning theories and inquiry-based learning and provides model-based reasoning and agent-based modeling, and utilises technological affordances like variable manipulation in simulation, immediate and customised feedback and self-paced learning. However, pragmatic assumptions to generalisability could be further demonstrated.

Problem-based learning is a popular approach for STEM. Facilitating a collaborative problem-based learning in an online setting calls for integrating scaffolding and appropriate technologies in a grounded approach. Synchronous web conferencing such as Zoom is suggested as an alternative tool to provide immediate interactions between instructor and students and among students for discussion and group work (Correia et al., 2020; Wenzel, 2020). Arena et al. (2021) reported that a large number of biomedical engineering students in the United States engaged in problem-based learning via Zoom and showed a positive satisfaction with the course design. The learning activities were designed under the guidelines of constructivist learning theories, and students were engaged in solving an open-ended science problem in a small group. Using breakout rooms, screenshare, chats, video and audio calls, and other functions embedded in Zoom, students were able to communicate and coproduce a solution.

Applying grounded design framework to this study, culturally, the biomedical engineering field is interdisciplinary in nature and thus students are exposed to a wide range of expertise and diverse perspectives Pragmatically, there was a challenge because one noted instance of unstable wi-fi connection occurred. This was eventually resolved with a mobile hotspot using the cellular service. Reported case studies using video conferencing in other domains are mounting (Lieux et al., 2021), yet defensible research evidence of its validity remains scarce. More empirical studies need to be conducted to validate and generalise the design guidelines of using web conferencing in STEM.

To increase the awareness of ethical issues that arise in scientific practice, Nadolny et al. (2013) integrated an ethics training 3D virtual world, SciEthics Interactive, into undergraduate science and engineering courses. In science and engineering, the importance of ethical training has garnered increasing attention to assist in avoiding misconduct in scientific research (e.g., falsification, fabrication, and plagiarism) (Steneck, 2006). In response, Nadolny et al. (2013) used the TransGen Island program within SciEthics Interactive as a supplement to the course curriculum. Their study, involving 53 university students in the United States and South Africa, found the simulation significantly increased learning motivation and awareness of ethical issues and promoted science knowledge. Nadolny et al. (2013) demonstrated grounded design as it situated learners in an interactive online environment to increase awareness of ethical issues in science. Nonetheless, the study could be further iterated to be generalisable in a wider academic setting.

Supporting students' deeper learning and engagement online

Online platforms enabled educators to pragmatically ground the course design to promote the retention of marginalised populations in STEM. An online mode of delivery enabled personalised learning and, in turn, demonstrated high retention rates in the subject areas that traditionally recorded high drop-out rates like computer science and engineering. Given the challenges of teaching large student cohorts, massive open online courses (MOOCs) have been used as a cost-effective supplement. For example, Van den Broeck et al. (2020) used a MOOCs platform to support engineering students who transferred from a smaller college to a larger public university, and experienced difficulties with basic mathematics. Their study found the MOOC positively promoted the mathematics diagnostic test scores of the participating students. Additionally, within constructivist pedagogy, Rae and Samuels (2011) examined the effectiveness of an online personalised system of instruction for first year students in computer science in the United Kingdom. Their self-paced online personalised system of instruction provided video clips (e.g., lecture, summary, solution) and online tests for first-year students in large introductory mathematics courses. Analysing a decade of data, the study found online personalized system of instruction promoted deeper learning for students.

Several studies have been designed in a grounded approach to support college students' engagement in online learning. To promote motivation in online learning, game-based learning has been used. Alien Rescue, for example, incorporates game elements and simulates a playing experience for students to learn the language of science through role-play in a science fiction fantasy setting. Liu et al. (2014) examined the theory, design, and research behind Alien Rescue and proved its effects on motivation and science learning. Huang et al. (2013) provided an open online instructional game that incorporates research-validated motivational instructional design models such as Malone and Lepper (1987)'s four motivational factors (i.e., challenge, curiosity, rules, and fantasy) and Keller's (1987) attention, relevance, confidence, and satisfaction (ARCS) model. The study found that the game features, perceived motivational support and cognitive learning levels, and final satisfaction with the learning process are meaningfully correlated to each other. The program is grounded with cognitive-constructivist pedagogy and cognitive and motivational theories to design optimal learning environments.

Technological applications are developed to support learners' self-regulated learning. Azevedo et al. (2010) used MetaTutor, the artificial pedagogical agent, in a college biology course by adopting the theoretical assumptions of self-regulated learning to emphasise the role of cognitive, metacognitive, motivational, and affective processes. In MetaTutor, pedagogical agents guide college students learning of complex science topics and prompt students to engage in planning, monitoring, and strategic learning phases. By allowing learners to type their thoughts and content summaries, the system supports learners' expression of metacognitive monitoring control processes. Among components of grounded design framework, MetaTutor is designed on solid theoretical foundations, incorporated defensible theory (i.e., self-regulated learning), iteratively validated through empirical research within the design-based research framework and can be generalisable in a variety of subjects for promoting self-regulated learning.

The use of pedagogical agents to promote self-regulated learning has been replicated and refined through multiple studies. In an online remedial mathematics course at a community college, Kim and Bennekin (2013) used the pedagogical agent to help students perceive the value of math knowledge and skills, set personal goals, and plan for their subsequent exercises. The students in their study who interacted with the virtual agent exhibited more positive changes in recognising the intrinsic value of the mathematics course than those who did not have access to the agent.

Professional development to design grounded online learning environments

To develop online teaching strategies, it is necessary to provide faculty with sustainable professional development. The effectiveness of a short duration (e.g., 2 days, a week) professional development is also questionable, because without continuing or follow-up support for teaching, misunderstood teaching strategies could be applied. Hayward and Laursen (2018) provided continuing support through an email Listserv for an inquiry-based learning professional development workshop. Participants continuously interacted with each other and received support from the professional development facilitators. After a year of online support, the study found more professional development participants (30 out of 35) incorporated inquiry-based learning than before they attended a professional development. Analysing the online interaction patterns of 35 participants and facilitators through social network analysis, Hayward and Laursen (2018) found the participants began using inquiry-based learning in their classes in the year following the workshop with the help of the online Listserv. By creating a sustainable learning community, this study results could be strengthened.

To train college instructors to provide more inclusive learning environments, the LIGHTHOUSE CC project team provided online professional development to community college computer science instructors. Professional development has often been unsuccessful because it has failed to take teachers' existing knowledge, beliefs, and attitudes into account (Darling-Hammond et al., 2009). To achieve lasting changes in teachers' practical knowledge (Van Driel et al., 2001) and to make it sustainable, the programs focused on building a community of practice (Vescio et al., 2008). Instead of providing a lecture-driven (i.e., a combination of multimedia-based lectures and quizzes) course format in a MOOC platform, the course could be designed to provide multiple channels to engage faculty learners with authentic problem settings. In Chang et al.'s (2018) study, each learning module in the online course was designed with a project-based learning approach based on situated cognition theory. Involving 86 faculty learners, the study found the online course increased faculty learners' motivation and engagement and a sense of belonging in professional development. While this online professional development was designed within grounded design framework, its long-term impact in the classroom may need to be iteratively examined and validated.

Implications: How to apply grounded design

Grounded design for online and blended STEM learning environments could be achieved by following the guidelines suggest in Figure 2.

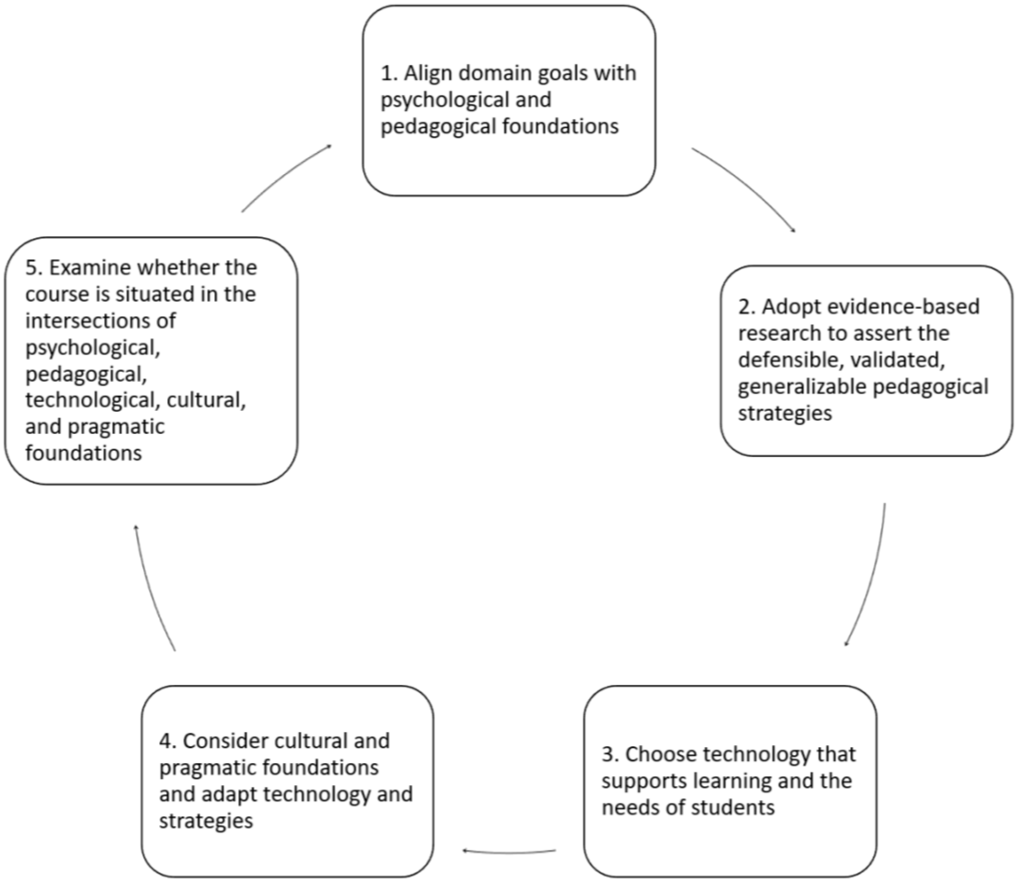

Figure 2. Guidelines for ground design

First, instructors begin by aligning the domain goals with psychological and pedagogical foundations. Instructors should begin the course design by reviewing and determining the domain goals and standards, then selecting psychological and pedagogical foundations that support the domain goals. If the domain goals involve achieving critical thinking or problem solving, constructivist psychological foundations of learning may fit. Constructivist foundations allow for individual meaning making, and ill-structured problem solving can be facilitated by inquiry-based, problem-based, project-based, or case-based learning pedagogies (Kuhn, 2007; Mamun et al., 2020). If the domain goals are focused on declarative knowledge acquisition and skillful procedural behaviours, cognitive and behaviourist psychology could inform the learning design (Ertmer & Newby, 2013). As domain goals become increasingly diversified and interdisciplinary, different psychological and pedagogical grounds should be considered.

Second, based on the defined domain goals and psychological and pedagogical foundations, instructors should adapt related literature and empirical research evidence to assert the defensible, validated discipline specific pedagogical approaches for online learning. Repeated applications in varied contexts and with different audiences could inform generalisability and best practice, thereby mitigating pitfalls (Brinkley-Etzkorn, 2018). Furthermore, this requires that faculty members in all subject areas should be informed users of educational research. A community of practice and sustainable professional development should become an integral part of the scholarship of teaching and learning (Philipsen et al., 2019; Trust & Horrocks, 2017).

Third, when choosing technology to support online learning, be sure to align the educational goals and needs of students and consider cultural and pragmatic foundations. Technology integration is no longer a choice in online and blended learning. To assure all students access and use the technology for the benefit of learning, instructors must examine the technological affordances to the extent that they support productivity, accessibility, and scholarship (Boyle & Cook, 2004; Kilis & Yildirim, 2018). For example, requiring a "bring your own device" policy to integrate an augmented reality enhanced laboratory using personal smartphones should be implemented with caution as it could be burdensome to students of various socioeconomic backgrounds (Tawfik et al., 2016). Also, fast and reliable wi-fi connections need to be available on campus and at home. Likely, using cloud-based tools among distant students for collaborative knowledge building in a developing country can be achieved through technological support (Ghazal et al., 2019). Moreover, students' abilities to use technology should not be automatically assumed. Supporting students in online and blended learning should be accompanied by a variety of channels and manners (Rennar-Potacco & Orellana, 2018).

Finally, at the final stage of course design, instructor needs to examine the intersections of psychological, pedagogical, technological, cultural, and pragmatic foundations. The essence of grounded design is the alignment and optimisation through domain goals, pedagogy, strategies, and practices (Land et al., 2012). If any of the foundations and conditions are not met, then the instructor should follow the process again to rectify the discrepancy.

Conclusion and future directions

This study centered around the question of how instructional challenges for online and blended STEM courses can be resolved given the framework of grounded design. COVID-19 brought instances of emergency online and blended learning methods in higher education. Even before the COVID-19 pandemic, higher education institutions worldwide had increasingly integrated technologies and offered online courses to extend learning opportunities (Organisation for Economic Cooperation and Development [OECD], 2018; Sursock et al., 2010). In the evolving landscape of online, blended, and technology-enhanced learning environments, college educators confront increasingly dynamic and varied demands from contemporary students and societal advancements. Faculty members and students are underprepared for teaching and learning online, in terms of course design and pedagogy, student engagement, and self-regulation. Technology is often misused and misaligned with epistemological and pedagogical groundings. These challenges can be achieved through adopting grounded design practice.

Grounded design provides a design framework for the design and implementation of STEM online and blended learning while keeping domain goals and instructional practices aligned. To achieve domain learning goals, courses must address evolving needs while aligning with varied instructional strategies and technological capabilities. We reviewed several examples from university STEM courses to see how they have addressed evolving needs and challenges in terms of psychological, pedagogical, technological, cultural, and pragmatic foundations, while maintaining the defensible, iterative, research-evidenced, and generalisable conditions of grounded design. These examples depict how to practice grounded design for online and blended learning courses.

When technologies are used in teaching and learning without the grounded assumptions of theories and psychology, without instructors' solid understanding of pedagogy and strategies, they become merely another example of bells and whistles. When the instructor selects a technology tool to incorporate into teaching, the instructor should be able to defend their selection with validated research evidence. It is critical to provide students with aligned STEM learning experiences and engagement via designing defensible, research-evidenced online and blended courses with grounded design framework. While innovations may have been researched in one setting with a particular group of students, generalisability should be established in different contexts. Subsequent research is required to validate and generalise the use of specific technologies in broad settings.

Additionally, recent studies have asserted the importance of incorporating culturally relevant pedagogy to provide inclusive online learning environments. Each student possesses different accessibility, affordability, technical infrastructure, or digital literacies in online learning (Irvin & Macklin, 2007; Tawfik et al., 2016). Individually different prior online learning experiences and affordances in learning technologies are potential variables that may affect the learning confidence or academic performance of the student (Irvin & Macklin, 2007). Cultural (e.g., race or ethnicity) or socioeconomic (e.g., parental income or occupation) backgrounds may also affect the online learning experiences of the student. For example, Ke and Kwak (2013) reported that compared to white Caucasian students, Hispanic/Latino students benefited less from online learning. Another study (Du et al., 2015) found that African American female students tended to prefer to lead during collaborative learning while having a timid attitude toward online discussion. Therefore, providing inclusive learning environments is essential to engage learners who have had different levels of experience in online learning.

Clearly, continued advances in theory and research will inform the design of college STEM learning environments. While progress has been made, further research and supporting evidence is needed to ground our practices to assist learning and performance in online learning. Students perceive that student-centeredness and instructor-centeredness are reciprocal in high-quality education (Elen et al., 2007). We advocate grounded strategies that account for relevant, critical epistemological goals rather than a preference of one over the other. Grounded design is a responsible practice expected of STEM faculty who are both new and seasoned in teaching online.

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Corresponding Author: Eunbae Lee, elee@khu.ac.kr

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Appendix A
Grounded design practices with five foundations and four conditions

		Akçayır et al., 2016	Arena et al., 2021	Azevedo et al., 2010	Chang et al,. 2018	Deep et al., 2020	Hayward & Laursen, 2018	Nadolny et al., 2013	Rae & Samuels, 2011	Van den Broeck et al., 2020
Domain		Physics	Biomedical engineering	Biology	Computer science education	Genetics education	Teacher professional development	Science and engineering	Computer science	Mathematics
Foundations	**Psychological**	Constructivist	Cognitivist	Constructivist	Constructivist	Constructivist	Constructivist	Cognitive-constructivist	Cognitivist	Constructivist
	Pedagogical	Problem-based learning	Metacognitive scaffolding prompt	Situated learning, Project-based learning	Inquiry-based learning	Community of Practice and Inquiry-based learning	Situate in interactive learning environments	Provide personalised system of instruction	Using multimedia learning principle	Provide a personalised learning platform
	Technological	Synchronous web conferencing (Zoom)	Hypermedia pedagogical agent	Online professional development course	Question prompts, simulated manipulation, customised feedback, self-paced learning	Online interaction with facilitators	3D virtual world	Using online system	Augmented reality	Using MOOCs platform
	Cultural	Interdisciplinary nature and collaborative problem solving	Self-regulatory skills	Communities of practice	Complex learning through problem solving	Build sustainable learning community for teachers	Increase awareness of ethical issues in science	Promote deeper learning of first year students in computer science	Laboratory skills	Promote retention rates of marginalised population
	Pragmatic	Rotating facilitator model, de-localised physical location	Scaffolding and feedback	Using MOOC	Hypothetico-deductive reasoning	Transition from in-person workshop to e-mentoring	Using virtual environment	Using virtual learning environment	Using augmented reality and smart phones	Using MOOC platform
Conditions	**Defensible theoretical framework**	Constructivist model of learning	Self-regulated learning	Situated learning theory	Technology-enhanced learning	Instructional change theory and social network theory	Situated learning theory	Theoretical foundation of personalised system of instruction framework	Multimedia learning theory	Framework for effectiveness
	Research supported decisions	Empirical study	Empirical study	Empirical study	Empirical study	Empirical study	Empirical study	Empirical study	Empirical study	Empirical study
	Iteratively validated design	Not presented	A synthesis of research on self-regulated learning and hypermedia	Iteratively designed and developed	Iteratively designed and developed Design based research	Not presented	Iteratively designed and developed	Used case studies	Not presented	Not described
	Generalisable practice	Facilitator recruitment	Adaptation of MetaTutor for complex science topics to foster self-regulated learning	Propose practical guidelines	Operational in a self-paced or face-to-face or blended learning mode	Not presented	Provided practical guidelines	Suggested testing in various disciplines	Not presented	Suggested to conduct follow up study with larger samples