Teaching and Designing Online STEM Courses to Support Self-Directed Learning Skills

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Contents

Introduction

The COVID-19 pandemic gave college faculty and instructional support staff a crash course in online teaching and course design. Educators and students alike discovered certain benefits of online courses, but the shift to "online all the time" bore out the warning in past research that online learning—particularly asynchronous, self-paced courses that lack live interaction between faculty and students—puts more demands on students to manage their own learning and is associated with lower pass rates.[1] The shift also revealed that many faculty have not been adequately prepared for the challenges of teaching and learning online, and that faculty often lack access to resources and institutional support for using technology effectively to foster student learning.[2]

The pandemic showed that online learning is here to stay and underscored the need for STEM faculty to incorporate instructional strategies to help their students to manage their learning

While postsecondary institutions have reopened campuses and resumed in-person teaching, many have expanded online course offerings in response to strong student demand.[3] This pivotal moment offers an opportunity for researchers and educators to build on the lessons of the pandemic and address gaps in the research about how colleges can support students in managing their learning. Developing and testing easy-to-use online tools to help students become more self-directed learners is a key mission of the Postsecondary Teaching with Technology Collaborative, a national research and capacity building center focused on strengthening teaching and learning with technology (See box 1 for background).

In this paper, we provide practitioners with guidance around how to build students' self-directed learning mindsets and skills. We also review the theory and scientific evidence on instructional strategies that can be integrated into STEM courses and have been shown to help students understand and use self-directed learning processes. We present an initial attempt at translating these ideas and evidence into an actionable framework to guide the design of instructional strategies in online and hybrid courses.

The Postsecondary Teaching with Technology Collaborative, funded by the U.S. Department of Education, brings together educational researchers from SRI International and the Community College Research Center at Teachers College, Columbia University; technical assistance staff and coaches from Achieving the Dream; educators, staff members, and administrators from nine broad-access higher education institutions across the nation; and several developers of online course systems and courseware. This team is conducting research into how broad-access postsecondary institutions can leverage technology—along with other tools of teaching, advising, and tutoring—to help students manage their learning in introductory online STEM courses that are mostly or entirely technology mediated, including those that are asynchronous, synchronous, and hybrid with some face-to-face activities.

How did the pandemic affect equity in STEM education?

STEM courses need more equitable approaches to online learning and teaching

While the challenges of supporting online student success crop up in all kinds of courses, they are of particular concern for gateway science, technology, engineering, and mathematics (STEM) courses, which have chronically disappointing success rates. These courses are required for credentials in fields that serve as key pathways to economic mobility, such as information technology, advanced manufacturing, and allied health occupations (e.g., nursing, audiologist, physical therapist).

STEM programs have struggled for years to provide more inclusive environments. Recent research suggests that inequitable institutional structures, policies, and environments contribute to underrepresentation of some populations in degree attainment. Such structural factors receive scrutiny because data indicate that Black and Hispanic students are as likely as other students to enter college intending to pursue STEM majors but are far less likely to attain STEM degrees—even when controlling for academic preparation.[4] Indeed, research has identified systemic issues, including the low representation of faculty of color in STEM departments and alienating instructional cultures that emphasize meritocracy, “weeding out,” and competitiveness.[5]

STEM education reformers have advocated several strategies to make systems and policies more equitable. For example, past reforms include replacing non-credit developmental courses with co-requisite supports, revising curriculum to emphasize depth over breadth, increasing mentorship and undergraduate research opportunities, embedding supports to counter stereotype threat and increase sense of belonging, and using instructional methods designed to elicit more active ways of learning.[6]

The pandemic indicated that online modalities counter some of these equity reforms by exacerbating feelings of isolation and exclusion. Mindful of such challenges that online settings pose to effective, equitable learning, we seek to build on past research and practice by identifying online instructional strategies that faculty can use to build a more supportive online learning experience for all their students.[7]

What is self-directed learning?

Key ideas from learning science can inform the design of online support strategies

Given the association of online college courses with lower student success rates,[8] we looked to research to find instructional strategies that could better support students in this modality.[9] To develop our approach, we drew on insights from research that discusses how instructors can help students build positive emotions, beliefs, mindsets, and skills. We are grouping these varied processes under the umbrella term **"self-directed learning."** [a,10]

Self-directed learning is a collection of emotions, beliefs, attitudinal mindsets, and cognitive or behavioral processes used to manage learning tasks. Building such mindsets and skills can improve students' academic and career outcomes.[11] In concept, when instructors create inclusive conditions that feature the use of instructional supports targeting self-directed learning, students can achieve in courses better.[12]

Our definition of self-directed learning groups the various processes into three categories: motivation, metacognition, and applied learning skills. This definition:

- Underscores the importance of helping college students take an active, directive role in managing their online learning.[13]
- Draws from relevant research literatures on self-regulated learning, motivation, self-determination theory, growth mindset, and sense of belonging.
- Includes varied but complementary processes that researchers have linked either to the brain's "executive functions" or to "non-cognitive" processes closer to affective states, beliefs, and attitudes.

[a] We use this term with a nod to several decades of past adult learning theory and research into self-directed learning (For review, see Merriam, 2001). We situate our work as following a research strand suggested by Merriam and Caffarella (1999) that focuses on how contextual factors can be designed to support the development of these skills.

- Elevates the importance of supporting postsecondary students' sense of belonging and beliefs about the personal relevance of academic study to their lives to better address the needs of historically marginalized students.

How do postsecondary institutions currently support self-directed learning skills?

Many postsecondary institutions have aimed to teach these skills and mindsets through stand-alone student success courses taught by study skills experts.[14] While this approach has contributed to improved grade point averages, retention, and graduation rates,[15] it also puts the burden on students to transfer these self-directed learning processes to their academic courses. As found in surveys of online students, transferring and sustaining these skills and mindsets can be especially difficult in fully online courses, particularly asynchronous courses with limited social interaction.[16]

How does self-directed learning work?

Learning and motivational theories offer a foundation to develop new instructional supports for learning

In this section, we present a way of understanding the theoretical foundations of self-directed learning that aims to provide a bridge to practice. Then, we turn to empirical studies that get us closer to understanding which instructional strategies have been shown to make a difference in both academic outcomes and students' use of these processes. We also discuss ways to integrate instructional strategies into online and hybrid courses—an approach that can complement teaching students self-directed learning mindsets and skills through stand-alone courses.

Research has underscored the importance of helping college students coordinate three types of processes: motivational, metacognitive, and applied learning.

In the following paragraphs, we define the processes. Then, we describe the instructional strategies that help students engage in these three types of processes in a timely and strategic fashion.[b]

[b] Note that these processes coincide with a cyclical process observed by scholars in the field of self-regulated learning. In their framing, students begin academic tasks by establishing self-motivation and analyzing learning needs, then by managing their performance through practices of self-control and self-observation, and, finally, by reflecting on progress by examining personal self-reactions and self-judgments.

Motivational processes energize and direct behavior,[17] **and they build on students' beliefs—such as their sense of control, self-efficacy, and belonging.**[18] Positive beliefs correspond with academic persistence and resilience, even when students face setbacks and failures. Students from historically marginalized groups may have developed negative beliefs, including "STEM imposter syndrome" and stereotype threat, which correspond with avoidance of academic challenges and drop-out.[19] Through their instruction, faculty can help students develop the following motivational emotions, beliefs, and mindsets:

- Embrace a growth mindset to develop and maintain a sense of self-efficacy
- Build and maintain a personal sense of belonging
- Assess and identify the personal value of a course

Equity researchers have noted that any of these motivational mindsets will be influenced by students' experiences in both the classroom and the larger institutional context. A competitive, unsupportive, impersonal, or "sink or swim" culture may compromise student motivation. By contrast, a context with supportive faculty, advisors, and administrators that reinforces students' belief in their ability to learn and their sense of belonging can bolster their motivation to succeed in courses delivered in any modality.[20]

Metacognitive processes help students manage their learning. When effectively performed in a cyclical manner around each task or assignment, these processes help students actively adjust to the demands of any learning task.[21] However, many college students have had limited experience with the kinds of learning activities believed to develop such metacognitive habits. Often, students' past school experiences have taught them to rely on their teachers for most decisions about what, when, and how to study. Teaching first-year college students about such metacognitive processes can improve their academic success and have positive effects on motivation and confidence.[22] Through their instruction, faculty can help students use the following metacognitive processes around every assignment:

- Identify learning needs based on reflection on past performance
- Set goals and monitor progress toward them
- Plan time for studying
- Select learning strategies and adjust them as needed
- Reflect on learning progress and performance

These metacognitive processes help students shift from the motivational phase of assessing one's feelings, beliefs, and attitudes about learning to laying out the specific actions that will help them manage the learning process.

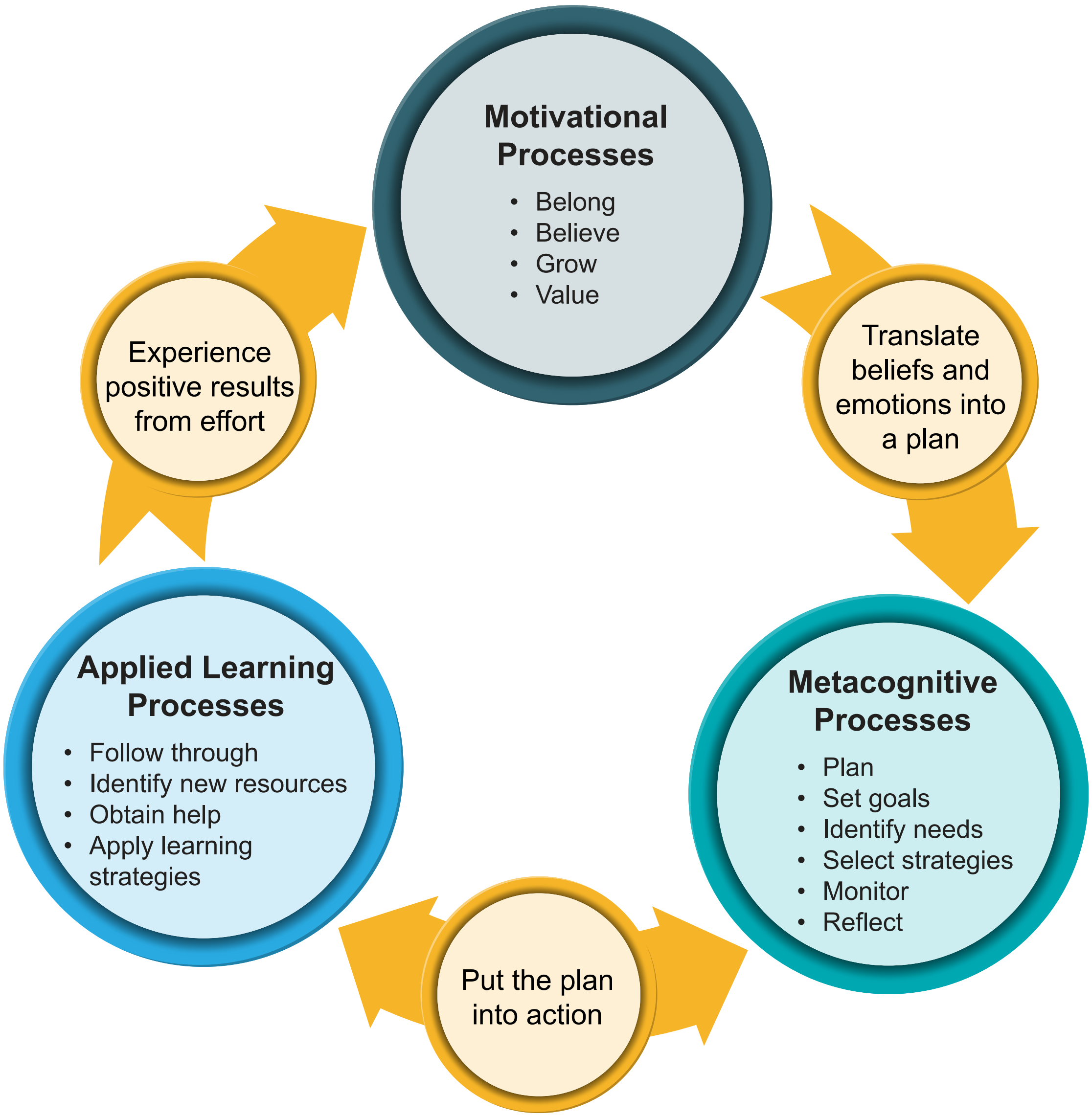
Applied learning processes comprise learning techniques and management strategies that help students take greater ownership for achieving their learning goals. Distinct from domain-specific study skills, these processes work across multiple domains but differ by domain in how frequently or intensively they are applied. They reflect the types of strategies that learners can use to implement and refine learning plans. Researchers have developed various ways to design learning technologies used in online and hybrid courses to engage students in these processes. Faculty can help students learn and use the following applied learning processes:

- Set up the study environment and enact time management plans
- Identify additional resources to support learning and obtain help
- Use learning strategies such as spacing practice, self-quizzing, note-taking, and problem-solving heuristics

While faculty may see providing such supports as unrelated to their content-focused work, research has found that having faculty encourage students to use active learning techniques early in college has positive impacts on students' academic success.[23] Taking steps to equip students with these techniques may reduce the resistance that instructors report when they ask students to engage more independently in learning than they have in previous educational experiences.

To conclude this summary of the theoretical foundations of self-directed learning, it is important for faculty to support these three types of processes through their instruction because they mutually reinforce one another (Figure 1). The **motivational processes** provide the foundational emotions and beliefs that energize students' approach to learning. The **metacognitive processes** translate those emotions and beliefs into an action plan in a cyclic manner, serving to manage the overall learning process around each task or assignment. The **applied learning processes** put students' metacognitive learning plans into action and help them to adjust their learning approach as needed. By engaging in these processes, students have a positive experience of taking control of their learning, which can enhance motivational beliefs.

Figure 1. Mutual Reinforcement of the Three Processes



In the next section, we share findings from our reviews of recent empirical studies. We focus on instructional strategies that can use technology to support students' understanding and use of self-directed learning processes.

What do we know about supporting self-directed learning?

In reviewing past research, we set out to capture the current state of knowledge about how faculty can support online and hybrid STEM students' self-directed learning processes (See box 2 for the methods of the research review).[24] We wanted to identify rigorous empirical studies that indicated some promising approaches.[25] As we reviewed the evidence, we appreciated that fostering greater use of self-directed learning processes can support and reinforce related major STEM education reform efforts of the past two decades. These reforms draw on the learning sciences and socioculturally anchored approaches for advancing students' STEM learning.[26]

Studies of online and postsecondary STEM learning shed light on effective instructional strategies

While we found that researchers have focused on supporting students to engage in self-directed learning processes since well before the pandemic, most of this research has taken place in different contexts from online courses in broad-access, postsecondary institutions (for example, much research has taken place in face-to-face courses in secondary education and international settings). Thus, insights into the strategies that instructors can use to support students remain largely buried within the research.

In the post-COVID19 era, many faculty report feeling overwhelmed. Consequently, our search focused on practices that place a limited burden on faculty. We also prioritized use of technology features to reinforce and/or scaffold the development of these processes in online and hybrid courses.[27]

Overall, we found that researchers engaged faculty in using varied approaches to helping students to use self-directed learning processes. They integrated support for these processes into their courses in ways that did not require a full redesign of their courses. The approaches varied by type of STEM course and sometimes by when and how many times students were asked to use the processes in a course. Usually, researchers asked faculty to integrate some technology-based presentations, tools, or reminders into their courses that supported students in applying self-directed learning processes.

We organize selected findings below according to our three categories, focusing on those findings that seemed salient across the studies and lent themselves to course integration. For each of the three categories of processes, we summarize the overall research findings and then we list the key elements of the instructional strategies.

Strategies to support motivational processes

Research has identified several instructional strategies that faculty can use to influence students' emotions and beliefs and positively affect both students' motivation to study and the total time they spend studying. Studies also show potentially positive impacts on academic achievement—either for all students or specific student subgroups—when faculty share information about the malleability of intelligence through effort, present success testimonials from prior students representing historically marginalized groups, engage students in connecting what they are learning to personal and practical values, and provide ways to build online community and self-efficacy. Because some of these strategies require more time

Methods

We consulted four recent literature reviews of instructional strategies intended to develop two types of self-directed learning processes (motivational and metacognitive), and we conducted a systematic database review of recent empirical studies. In these complementary reviews, we aimed to identify instructional strategies that (1) showed promising evidence of improving STEM college students' academic success or increasing their reported use or awareness of self-directed learning processes, and (2) had the potential to be adapted to online courses.

Focusing on articles published since 2011, we employed queries in our database review featuring terms related to "self-regulated learning," a term commonly used by researchers, and related constructs, as well as STEM domains, technology use, and postsecondary and secondary contexts. We initially found 4,263 studies. Researchers screened these studies to include those that featured self-regulated learning as an outcome or predictor variable, specific classroom interventions, and a high school or college population. This secondary screening brought the sample to 209 studies. Researchers then screened these studies to include only those with treatment and comparison groups with baseline equivalence and outcomes related to course grades, domain knowledge, and self-regulated learning skills. The final sample included 15 studies.

In examining these 15 studies, we noted that the instructional strategies employed showed significant positive impacts on academic outcomes or self-reported use of self-directed learning skills. We also found many of the instructional strategies were brief and relatively easy to incorporate into classes. Several of the instructional strategies that researchers implemented in face-to-face settings appeared to be adaptable to online courses or facilitated by using technology. We synthesized these strategies with those described in the four recent literature reviews that showed promising results for either all students or historically marginalized populations.

and effort to implement than is likely feasible for most faculty members, we have looked for opportunities to streamline them for practical integration within courses.[28] Specific supportive strategies include:

- Foster students' sense of belonging by providing students from historically marginalized groups with access to either video-based or written testimonials created by prior students of similar backgrounds about their personal journeys; these began with challenges and struggles and transformed into successful development of a sense of belonging in college over time.[29] (See Sharing Stories of Belonging for an example.)

Sharing Stories of Belonging

Students: Second-semester Black students in their first year of a 4-year university

Process Support: Researchers had students read narratives presented as having been written by upper-level students. In these narratives, the upper-level students described their experiences in their first year, in which they worried if they belonged in college. They also framed this feeling as commonplace to first-year college students. Study participants then wrote their own essays describing their own experiences.

Results: Researchers found that this hour-long intervention resulted in increased grade-point averages and cut the achievement gap of Black students in half.

- Present all students with an **online module** about how intelligence is not fixed, but increases through effort (i.e., cultivating a growth mindset).[30]
- Engage students in **writing down two or three of their most important personal values** and why they are so important, or **assessing the practical utility** to their own lives of learning a skill or concept in class.[31]
- Offer learners ways to **help each other online** to reduce isolation and build a sense of belonging.[32]
- Introduce students to basic course content using a **flipped learning environment that requires them to use Internet resources**, developing their self-efficacy as online learners.[33]

Strategies to support metacognitive processes

Several studies show that helping online college STEM students engage in multiple metacognitive processes had positive impacts on their academic performance (e.g., course or unit exam grades) and/or their self-reported motivation, confidence, collaboration skills, or use of self-directed learning processes. Most studies engaged students in reflecting on their past performance and then guided them in selecting applied learning strategies to use in upcoming courses or assignments. One study focused on asking students in an online course to plan when they would watch video lectures. Key instructional strategies include:

- Give students an **online lesson** early in a course that explains metacognitive processes and includes activities to check students' understanding of these processes.[34] (See SDL Instructional Modules for an example.)

SDL Instructional Modules

Students: Students in an anatomy and physiology course at a 4-year university

Process Support: Researchers presented online lessons to students about the challenges of college learning and the importance of using effective study strategies. One module introduced students to mnemonic techniques (e.g., retrieving information, spacing memorization) and conceptual learning techniques (e.g., elaborating and explaining). Another module taught students metacognitive techniques (e.g., how to plan their studies, monitor progress, adjust strategies, and evaluate performance). The final module advised students to establish and maintain study routines, including how to reduce distractions in their study environment. Each module took 60 to 90 minutes to complete.

Results: Students who completed this training made better use of resources and had higher test scores on exams.

- Ask students to complete a **plan** at the beginning of a course or a project, which they can either upload or complete as an online form; in the plan students identify the factors that have limited their performance in the past and articulate a specific plan to overcome these obstacles in the future.[35]
- In the first two weeks of the college term, require online students to go to an **online link** to set a time to watch daily lectures.[36]
- Alert students to their learning progress using formative assessments (e.g., through a concept map task or low-stakes quiz), and then **provide opportunities for peer support** through an activity (e.g., debate or online support network) in which students can discuss the content with each other.[37]
- **Structure online learning environments** to help students plan tasks or evaluate how a task went. This might involve providing online learning logs or administering online forms both before and after a project or research task that include questions intended to help students with planning (e.g., "How do you plan to ensure coordination and cooperation between the group members?") and to evaluate results.[38]

- **Prompt students** every two weeks during a course, sometimes through reminders and sometimes through a "learning log," to describe their goals, needs for help, and time management. Prompts might also ask students to reflect on their performance (e.g., comparing progress on different assignments, identifying best learning strategies); and/or describe planned adjustments to their learning strategies for future assignments.[39]
- **Provide individualized feedback** on students' metacognitive goals, plans, and self-judgments; this kind of feedback helps students refine their metacognitive approaches. For example, in one study, instructors commented on the quality of students' metacognitive plans and reflections within 48 hours.[40]

Strategies to support applied learning processes

Several studies showed that providing supplemental instruction—or embedding support into lessons—can help students engage in applied learning approaches as they study. These strategies had positive impacts on college STEM students' course grades or self-directed learning awareness and engagement. Key instructional strategies were:

- Give students **online lessons** that explain how to find help, practice spaced memorization, self-quiz, and take notes. It helps to follow such lessons with an assessment of students' understanding of these resources and practices.[41]
- Integrate **support for seeking help**—such as online help from peer tutors—within a learning management system or by using a student-driven lesson design, such as project-based or problem-based approaches.[42] (See Peer Helping Activities for an example.)

Peer Helping Activities

Students: University students taking chemistry

Process Support: After lesson, instructors distributed a concept test. If students did not meet the threshold of 70% accuracy, students were directed to debate their responses with their peers in the classroom and resubmit their answers. The instructor repeated this process three times in the course, with each concept test becoming progressively more challenging.

Results: After participating in this course, students had improved conceptual understanding and problem-solving as well as improved use of learning strategies.

- **Structure online environments** to support note-taking or self-quizzing or using online resources not specifically mentioned in the course.[43]

The review of empirical studies revealed gaps and limitations

Our review of empirical studies offers many potential instructional strategies for supporting online students in building self-directed learning mindsets and cognitive or behavioral processes. However, existing literature leaves open questions about how to design and deliver those strategies and measure their impacts in online STEM courses in broad-access postsecondary institutions. Further, while some studies report differential impacts on different groups of students, the strategies are rarely grounded in principles of culturally responsive and sustaining practices.

Lack of focus on broad-access institutions

First, most of the studies took place in large, 4-year institutions in both international and U.S. contexts. With one exception, studies that described students' racial and ethnic demographics took place in institutional or course contexts where the majority or plurality of students were White or Asian. None of the studies explicitly focused on broad-access postsecondary institutions, and only a handful identified the promise of instructional strategies that can support self-directed learning mindsets for students who have been historically marginalized in higher education and STEM fields.

Blending of different instructional strategies

Second, the studies tended to combine multiple self-directed learning processes and associated instructional strategies. As a result, it was difficult to evaluate how or when to combine specific instructional strategies, when to use them, or how to assess the relative impacts and "active ingredients" that lead to change in outcomes when faculty members implement instructional strategies or assign students to engage in self-directed learning processes.

Lack of application in a fully online learning context

Third, relatively few studies examined self-directed learning instructional strategies within a fully online learning context, which raises questions about ways to deliver these strategies. For example, many studies tested instructional strategies delivered face-to-face or outside of class (e.g., supplemental instruction). Also, studies of motivational instructional strategies often involved students in face-to-face courses participating in extended readings or student-to-student interactions followed by extended writing or speech-making tasks. Given course time limitations, such extended tasks that require students to reflect on topics not directly related to course content are likely not feasible for STEM faculty.

High reliance on self-report measures of growth in skill awareness and engagement

Finally, the studies typically relied on self-report questionnaires to determine how instructional strategies and student engagement in self-directed learning processes affected students' reported use of self-directed learning skills. A variety of instruments have been developed and validated to measure students' self-directed learning awareness and engagement, but self-report questionnaires have certain limitations and cannot, on their own, demonstrate changes in the academic behaviors that lead to improved student outcomes. Fortunately, online learning platforms generate process data that can provide more insight into those behaviors, such as whether students are following a regular schedule for completing their assignments or whether they are seeking help from peers.

How findings from the literature can help college STEM faculty build supportive online classes

The Collaborative's examination of the literature uncovered much information about self-directed learning instructional strategies that faculty can consider and apply in practice. It also raised questions about how to appropriately deliver these instructional strategies in the context of online STEM courses in broad-access institutions, a question that is an active area of research.[44]

Our review did not reveal a set of tried-and-tested instructional strategies that address all three self-directed learning processes and that can simply be replicated in online settings. Many studies tested interventions outside of academic courses and provided limited information about implementation. However, despite these limitations, existing research provides clues for how faculty can support students' capacity to manage their learning throughout an entire STEM course. (See examples in How to Integrate Self-Directed Learning Supports in an Online Course.)

How to Integrate Self-Directed Learning Supports in an Online Course

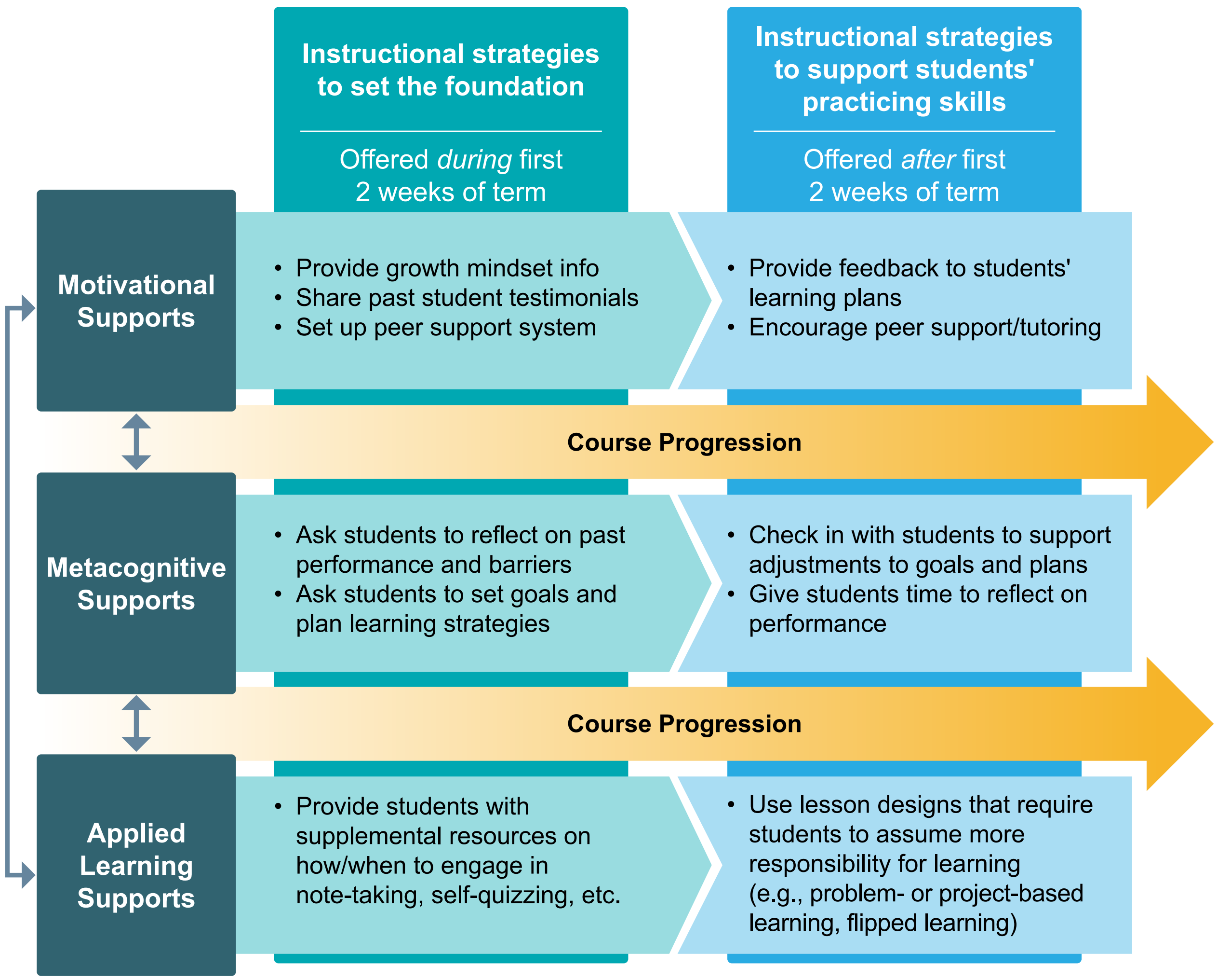
Staging your strategies to support students' self-directed learning: The strategies described above represent brief activities intended to present low logistical difficulty for faculty. You can consider how to schedule these strategies for optimal benefit, and how these strategies might be used in combination to amplify their impact. For example:

- **During the first month of the course:** Try using motivational instructional strategies to welcome students to the course and to lay the groundwork for students to use metacognitive processes throughout the course.
  - If you are teaching a course with historically low pass rates, consider providing students with some written or video-based testimonials from past students who initially struggled in your course, but found their way. Consider reinforcing students' learning from these testimonials by having them reflect on personal experiences that developed their resilience.
  - To introduce students to metacognitive processes, share a brief online video module that reviews the different types of metacognitive processes and when to apply them. Reinforce students' understanding by asking them to develop a study plan that features specific times to study and lists their personal achievement goals, and then quizzing them about their understanding of the various self-directed learning processes.

- **During the course:** Continue to help students develop regular habits of using motivational and metacognitive processes and continue to introduce them to useful applied learning approaches.
  - Consider giving students supportive structures for metacognitive processes, such as using technologies to deliver periodic reminders or asking students to complete an online learning log. These instructional strategies can help build students' habits of setting goals for each assignment, setting aside time for studying, monitoring their learning progress, and evaluating their performance.
  - Support students' applied learning approaches by including some places in the online environment where they can self-quiz, take notes, and find links to helpful online information resources for each assignment.
  - Build students' experience with motivational processes by establishing social supports for them. This might include connecting students who score low on online quizzes to an online peer mentoring group or tutoring services.

To summarize our research-based approach, Figure 2 presents our hypothetical perspective on when in a course faculty members can most productively use supportive self-directed learning instructional strategies. This figure encapsulates the instructional strategies we describe earlier in this paper. Faculty members might use this graphic to make choices about which strategies they want to integrate into their online courses.

Figure 2. When Faculty Can Use Instructional Strategies for Online College STEM Courses



What does the Collaborative aim to learn?

Broad-access postsecondary institutions in the United States will continue to adjust to the experience of the COVID-19 pandemic and increase their understanding of online learning. Given the promising research evidence, we believe that relatively simple instructional enhancements—such as setting an inclusive, supportive context, prompting students to plan, set goals, monitor their progress, seek help, and reflect on how to adjust their applied learning processes—can improve students' course grades in STEM, their use of self-directed learning processes, and their confidence and motivation as learners.

As we partner with broad-access postsecondary institutions, we anticipate learning more about the instructional strategies and student learning supports that are most important to integrate into online STEM courses. Although it is too soon to know the direction such learning will take, some findings may emerge around the following:

- What past experiences do students attending broad-access postsecondary institutions draw on to establish their practices for managing online STEM coursework?
- What does testing faculty use of supportive instructional strategies in broad-access postsecondary institutions contribute to the field's knowledge of how to support students' capacity to manage their learning?
- Will some of these instructional strategies and practices be particularly beneficial for students from historically marginalized groups? How could these strategies center equity in their design and implementation?
- How can faculty use of such instructional strategies support other teaching methods to strengthen undergraduate STEM instruction, such as active learning?
- What professional development practices,[45] institutional supports, policies, and conditions facilitate or hinder the effectiveness of these instructional practices?
- What terminology can help faculty and students understand and adopt these instructional strategies and learning processes? We acknowledge that the research field lacks a precise term for the collection of beneficial processes we aim to support. As we work with postsecondary professionals and students, we expect our terminology describing these processes to evolve.

We invite others to try out the strategies presented in this framework and to share what you learn.

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Appendices

Appendix A: Summary of references

Systematic Database Review

We conducted a systematic database review of recent empirical studies. Focusing on articles published since 2011, we employed queries related to self-regulated learning, STEM subject domains, technology-supported activities, and college or high school populations. We screened the initial resulting set of 4,263 to focus on those featuring self-regulated learning as an outcome or predictor variable and/or academic outcomes. This secondary screening brought the sample to 209 studies. Researchers then screened these studies to include only those with treatment and comparison groups with baseline equivalence on an academic variable and outcomes related to course grades, domain knowledge, and self-regulated learning skills. The final sample included 15 studies. The following three tables disaggregate these studies by category of self-directed learning process (metacognition, applied learning, or a mix of these) and summarize each study by the context, treatment condition, and key outcomes.

Metacognitive processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Vallejo-Valencia, N., Lopez-Vargas, O., & Sanabria-Rodríguez, L. (2019). Effect of a metacognitive scaffolding on self-efficacy, metacognition, and achievement in e-learning environments. *Knowledge Management & E-Learning, 11*(1), 1-19.	**Institution type:** 4-year public university (international – Colombia) **Subject:** Introductory Course to Mathematics **Participants:** 67 first semester students, 19% female, ages 16 to 38	All students were enrolled in an online math course. **Treatment students** received metacognitive scaffolding, including prompts around goal setting activities and self-evaluation modules. **Comparison students** participated in the online course without scaffolding.	**SDL skills and mindsets** Treatment students reported higher levels of metacognitive ability and academic self-efficacy. **Academics** Treatment students experienced higher scores on their unit evaluations.
Lewis, J. P., & Litchfield, B. C. (2011). Effects of self-regulated learning strategies on preservice teachers in an educational technology course. *Education, 132*(2), 455–465.	**Institution type:** 4-year public university (College of Education) **Subject:** Microcomputing **Participants:** 71 students, 72% white, 25% African American, 3% other	All students completed a WebQuest, which is an inquiry-based online activity lasting a few class periods to a month. **Treatment students** were assigned to one of two groups. The first completed a WebQuest training on self-directed learning that divided assignments into manageable amounts paired with goal setting and reflection activities. The second completed a WebQuest on technology and a survey on SDL skills focused on students' use of goal setting and monitoring of learning progress twice per semester coupled with weekly monitoring and evaluation forms on learning progress. **Comparison students** completed a technology WebQuest and a survey on technology-use.	**SDL skills and mindsets** Students who completed the survey on SDL skills increased their self-reported SDL (e.g., positive learning motivation, use of cognitive and metacognitive strategies, and management of test anxiety) as compared to the students who completed the WebQuest on SDL. There was no statistically significant difference between students who completed the WebQuest on SDL from comparison students. There was no statistically significant difference in final course grades between either treatment or comparison groups.

Metacognitive processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Yilmaz, R., & Yilmaz, F. G. K. (2020). Examination of the effectiveness of the task and group awareness support system used for computer-supported collaborative learning. *Educational Technology, Research and Development, 68*(3), 1355–1380.	**Institution type:** Public university (international - Turkey) **Subject:** Computing II **Student sample demographics:** 42 first-year political science students, 35.7% male, 64.3% female, ages 18 to 20	All students formed groups of 3-5 and were asked to submit collaborative weekly digital citizenship assignments in a computer-supported collaborative learning (CSCL) platform over 8 weeks. **Treatment students** were administered an awareness tool via the online pedagogical agent in Moodle to assist students in planning tasks and group work at the beginning of each week, before they started working in groups. An assessment followed at the end of each week, asking them to evaluate tasks and group work. **Comparison students** only completed the collaborative assignments, without the added pedagogical agent support.	**SDL skills and mindsets** The experimental group had higher online collaborative learning attitude scores than the control group. There was no statistically significant difference on self-regulated learning scales focused on forethought, self-regulation, self-observation, and self-reflection.
Baker, R., Evans, B., Li, Q., & Cung, B. (2019). Does inducing students to schedule lecture watching in online classes improve their academic performance? An experimental analysis of a time management intervention. *Research in Higher Education, 60*(4), 521–552.	**Institution type:** 4-year public university **Subject:** STEM course **Participants:** 145 freshmen, sophomore and junior students, 56% female; 68% Asian American, 13% Hispanic, 9% White, and 2% Black, with 10% not indicating their race/ethnicity, 50 % first generation students	All students were enrolled in an online 5-week STEM course during summer term. **Treatments students** received an email from a course instructor with a link asking them when they planned to watch daily lectures in the first 2 weeks of the course. **Comparison students** received the same number of emails from the course instructor, asking them which web browser they play to use and if they plan to use headphones.	**Academics** While treatment students had a positive increase of initial quiz grades, there was no difference in overall course scores.

Applied Learning processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Bagheri, M., Ali, W. Z. W., Abdullah, M. C. B., & Daud, S. M. (2013). Effects of project-based learning strategy on self-directed learning skills of educational technology students. *Contemporary Educational Technology, 4*(1), 15–29.	**Institution type:** 4-year public university (international - Iran) **Subject:** Systems-based education technology course **Participants:** 78 third-year students	All students were enrolled in a required face-to-face course for educational technology majors. **Treatment students** were taught using a teaching approach aligned with project-based learning principles. Over the course of 6 weeks, students developed a plan for a project, implemented, and presented their results. **Comparison students** were taught using a conventional teaching method.	**SDL skills and mindsets** Treatment students performed better in on a self-directed learning readiness scale focused on the motivational desire for learning, and cognitive self-management and self-control around the learning process.
Guarcello, M. A., Levine, R. A., Beemer, J., Frazee, J. P., Laumakis, M. A., & Schellenberg, S. A. (2017). Balancing student success: Assessing supplemental instruction through coarsened exact matching. *Technology, Knowledge and Learning, 22*(3), 335–352.	**Institution type:** 4-year public university **Subject:** Psychology **Participants:** 598 students, 63% female, 52% first-generation, 4% African American, 5% Asian, 35% White, 23% Mexican-American	**Treatment students** were offered 18, 90-minute weekly face-to-face supplemental instruction (SI) sessions during a 15-week semester. SI leaders provided support around developing learning strategies, such as note taking and questioning techniques, as well as tutoring support. **Comparison students** were matched using a Coarsened Exact Matching procedure and did not attend any SI sessions.	**Academics** Treatment students experienced higher final course grades.

Applied Learning processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Wen-Li, C., Shen, P.-D., Yi-Chun, C., Lin, J.-B., & Tsai, C.-W. (2017). Exploring the effects of online academic help-seeking and flipped learning on improving students? Learning. *Journal of Educational Technology & Society, 20*(3), 11–23.	**Institution type:** University (International - Taiwan) **Subject:** Applied Information Technology: Office Software **Participants:** 27 male, 75 female, two classes from the department of Finance, one from the department of Law	All students were enrolled in a face-to-face first-year university, one-semester course. **Treatment students** were in two groups. The first class (G1) received two treatments—online academic help-seeking and flipped learning simultaneously. The second class (G2) received only the flipped learning treatment. **Comparison students** received a traditional teaching approach in a blended learning environment	**SDL skills and mindsets** Both treatment groups demonstrated significant increases in student cognitive and affective involvement in the course, student self-efficacy, and self-directed learning (e.g., cognition, metacognition, and self-management).
Yaniawati, R. P., Kartasasmita, B. G., & Saputra, J. (2019). E-learning assisted problem-based learning for self-regulated learning and mathematical problem solving. *Journal of Physics: Conference Series, 1280*(4).1-8. http://dx.doi.org/10.1088/1742-6596/1280/4/042023	**Institution type:** 4-year public university (International – Indonesia) **Subject:** School Mathematics III **Participants:** 100 students	All students were enrolled in a second-semester face-to-face course, School Mathematics III. **Treatment students** used Moodle to engage in 7 e-learning sessions to engage in mathematical problem-based learning activities (e.g., angles and distances); these activities presented a problem and then students engaged in small-group collaboration with flexible tutor guidance to solve these problems. This activity was added to the regular face-to-face course. **Comparison students** received conventional, expository instruction.	**SDL skills and mindsets** Treatment students reported higher self-directed learning skills. **Academics** Treatment students had improved math problem solving ability.

Multiple processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Bernacki, M., Vosicka, L., Utz, J., & Warren, C. (2020). Effects of digital learning skill training on the academic performance of undergraduates in science and mathematics. *Journal of Educational Psychology, 113*(6), 1-43. https://doi.org/10.1037/edu0000485	**Institution type:** 4-year public university **Subject:** Anatomy and Physiology **Participants:** 137 students, 76% female, 31% African American and/or Latino/Hispanic, 58% first generation students	All students were in a face-to-face class with some online assignments. They were enrolled in a series of tasks in the first two weeks of the semester for which they would receive course credit (<1% of final grade). **Treatment students** completed two "Science of Learning to Learn" online modules including readings and activities. Readings introduced an applied learning strategy (spaced practice) and the phases of self-regulated learning (e.g., goal setting, developing plans, monitoring their learning, and evaluating their performance) and activities tested student understanding. **Comparison students** completed the same number of learning activities based on the content of the course.	**SDL skills and mindsets** Treatment students implemented more resources for planning, monitoring progress, and cognitive strategy use (i.e., learning and retrieval practice). **Academics** Treatment students had higher test scores on initial and final exams.

Multiple processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Bowman, N. A., Nayoung, J., Martin, K. D., Schneider, N., & Xiaomeng, Y. (2020). The impact of a goal-setting intervention for engineering students on academic probation. *Research in Higher Education, 61*(1), 142–166.	**Institution type:** Large, public Midwestern university in the United States **Subject:** Engineering **Participants:** Total sample: 3164 students; Effective sample for regression discontinuity analysis varied from 22 to 114 to the left of the cut off and 293 to 805 to the right of the cut off. 24% female, 77% White/Caucasian, 6% Latinx/Hispanic, 4% Asian American/Pacific Islander, 4% international, 2% Black/African American, 2% multiracial, and 4% other; 20% of students with valid data were first-generation college students; the average weighted high school GPA was 3.78.	All students started as engineering majors in face-to-face classes. **Treatment students** first reflected on prior academic performance and then completed a performance improvement plan worksheet focused on planning and reflection that helped them reflect on prior performance, identify barriers to their success, set concrete goals, and develop strategies for moving forward; following this, students met for 30 minutes with an academic advisor to discuss responses. **Comparison students** did not receive the goal setting intervention.	**SDL skills and mindsets** The intervention increased the grades of engineering students on probation who are beyond their first year of college.

Multiple processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Gok, T., & Gok, O. (2016). Peer instruction in chemistry education: Assessment of students' learning strategies, conceptual learning and problem solving. *Asia - Pacific Forum on Science Learning and Teaching, 17*(1), 1–21.	**Institution type:** University (Turkey) **Subject:** Chemistry **Participants:** 47 total students; 22 in the experimental group, 25 in the control group, ages 18-22.	All students were enrolled in an introductory face-to-face general chemistry course. **Treatment students** received peer instruction. Teachers provided a lesson and then distributed a concept test. If students did not meet the threshold of 70% accuracy, students debated their responses with their peers and resubmitted their answers. The instructor repeats this process three times, with each concept test becoming progressively more challenging. **Comparison students** received conventional instruction.	**SDL skills and mindsets** Peer instruction had positive effects on students metacognitive and management strategies. **Academics** Peer instruction had positive effects on students' conceptual learning.
Lang, G. (2018). Using learning journals to increase metacognition, motivation, and learning in computer information systems education. *Information Systems of Education Journal 16*(6), 39-47.	**Institution type:** University **Subject:** Computer information systems **Student demographics:** 98 total participants; 71% were male, 29% were female; 0% were freshman, 12% were sophomores, 35% were juniors, and 53% were seniors.	All students were enrolled in a face-to-face computer information systems undergraduate elective course, which emphasized experiential, hands-on learning. **Treatment students** were tasked with writing five journal entries related to metacognitively evaluating their strategies throughout the semester. Every 2 weeks (5 times per term), students responded to the same prompts asking them to compare coding projects, identify best strategies, and describe their plans for future adjustments to strategies. **Comparison students** completed five non-metacognitive writing prompts.	**SDL skills and mindsets** Learning journals increased metacognitive awareness and intrinsic motivation.

Multiple processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Sas, M., Bendixen, L. D., Crippen, K. J., & Saddler, S. (2017). Online collaborative misconception mapping strategy enhanced health science students' discussion and knowledge of basic statistical concepts. *Journal of College Science Teaching, 46*(6), 88–99.	**Institution type:** Large southwestern urban university in the United States **Subject:** Health sciences basic statistics **Student demographics:** 106 undergraduates. **Treatment group** – 24 students; average age of 22.3; average GPA of 3.39; 12.5% male, 87.5% female; 4.2% African American, 4.2% Asian, 8.3% Asian/ Pacific Islander, 50.0% Caucasian, 20.8% Filipino, 8.4% Other **Comparison group** – average age of 24.5; average GPA of 3.41; 31.1% male, 69.0% female; 13.7% African American, 3.4% Asian, 10.3% Asian/ Pacific Islander, 51.7% Caucasian, 10.3% Filipino, 6.9% Other	All students participated in online dyad discussion for three weeks. **Treatment students** were tasked with searching for two errors in a concept map individually, then seeking help from a peer who had a correct version of the map as a means of fostering meaningful discussions. **Comparison students** responded to discussion questions posed by instructor. Instructor engagement is limited to counting discussion posts.	**SDL skills and mindsets** The treatment students received higher discussion meaningfulness scores (as reflected in counts of discussion threads for disagreements, agreements, and evidence of conceptual change), regardless of their self-reported self-regulation ability. **Academic outcomes** The treatment group experienced higher learning outcomes compared to the comparison group.

Multiple processes			
Article	**Context**	**Treatment and Comparison Condition**	**Key Outcomes**
Stephen, J. S. & Rockinson-Szapkiw, A. J. (2021). A high-impact practice for online students: The use of a first-semester seminar course to promote self-regulation, self-direction, online learning self-efficacy. *Smart Learning Environments, 8*(1),1-18. http://dx.doi.org/10.1186/s40561-021-00151-0	**Institution type:** 4-year public university **Subject:** First-Semester Seminar **Participants:** 48 rising freshman, 88% female, 50% Black or African American, 38% White, and 12% Hispanic or Latino	All participants enrolled in an 8-week online class delivered synchronously and asynchronously using an LMS and video conference application. **Treatment students** had additional biweekly learning logs to encourage continuous student engagement and reflection. Learning log assignments included prompts for time management, goal setting, help seeking, and reflection. Instructors provided feedback on the logs within 48 hours, providing further resources as needed. **Comparison students** participated in the online class without the learning logs.	**SDL skills and mindsets** Treatment students reported higher levels of self-directed learning (e.g., SDL awareness, learning strategies, learning activities, evaluation for progress monitoring, and interpersonal skills) and online self-regulated learning. There was no statistical significance between treatment and comparison conditions on measures for online learning self-efficacy.
Zumbach, J., Ortler, C., Deibl, I., & Moser, S. (2020). Using prompts to scaffold metacognition in case-based problem solving within the domain of attribution theory. *Journal of Problem-Based Learning, 7*(1), 21–31.	**Institution type:** University **Subject:** N/A – intervention outside of specific course **Student demographics:** 40 volunteers; 27 university students, 13 nonacademic participants; average age was 25.90 years; 30 participants were male, 30 were female.	All students participated in a case-based, computer-based learning scenario about a high school student who has recently started to struggle academically. Three video files supplemented the scenario, each providing different explanation of the struggle based on attribution theory (locus of control, stability, and controllability). **Treatment students** had access to online prompt with information about metacognitive strategies five times, one on each page within the learning environment which presented information on motivational attribution theory. They were required to choose a strategy and apply it to their learning. The total treatment across all five prompts was around 45 minutes. **Comparison students** completed the case-based problem without prompts.	Results are not statistically significant for SDL (e.g., cognitive strategies, metacognitive strategies, and resource-oriented learning strategies).

Literature Review

Few studies identified in our systematic database review provided instructional strategies intended to develop postsecondary students' motivational emotions, beliefs, attitudes, mindsets and skills—a key area of relevance to students in broad-access postsecondary institutions. Also, few studies in our review examined technological modalities for delivery of supports for self-directed learning. For these reasons, we also consulted four recent literature reviews: three focused on instructional strategies intended to develop motivation and one that included a section on ways to use technology to support post-secondary students' self-regulated learning processes. The following table summarizes the study inclusion criteria of these reviews and study findings relevant to self-directed learning.

Article	Literature Search	Strategies	Key Findings	SDL processes
Dabbagh, N., Bass, R., Bishop, M., Costelloe, S., Cummings, K., Freeman, B., Frye, M., Picciano, A., G., Porowski, A., Sparrow, J., & S. J. Wilson, S. J. (2019). *Using technology to support postsecondary student learning: A practice guide for college and university administrators, advisors, and faculty* (WWC 20090001), U.S. Department of Education, Institute of Education Sciences, National Center for Education Evaluation and Regional Assistance, What Works Clearinghouse https://ies.ed.gov/ncee/wwc/practiceguide/25.	**Process:** Researchers conducted an extensive literature search across several databases and supplemented with studies recommend by the expert panel. **Number of studies:** 29 eligible studies. **Criteria:** • Used a comparison group design, • Included a technology-based intervention to support student learning, • Had a sample of college students in the United States, • Was published in 1997 or later, • Reported on one or more outcomes in the following domains: 1. academic achievement; 2. college attendance; 3. credit accumulation and persistence; 4. attainment of a degree, certificate, or credential; 5. post-college employment and income; 6. student engagement and motivation	• Online note-taking with periodic prompts for self-reflection and -monitoring • Text-based reminders and metacognitive prompts to provide tips and coach students • Individualized emails sharing student goals and performance • Campus-wide learning support sites to share resources related to studying • Adaptive learning environments with pedagogical agents aligned with different SDL processes such as help-seeking and reflection • Tool embedded in the LMS to provide students with benchmarks of their own activity level in the LMS as compared to their peers	The report shared five recommendations: 1. Use communication and collaboration tools to increase interaction among students and between students and instructors. 2. Use varied, personalized, and readily available digital resources to design and deliver instructional content. 3. Incorporate technology that models and fosters self-regulated learning strategies. 4. Use technology to provide timely and targeted feedback on student performance. 5. Use simulation technologies that help students engage in complex problem-solving	Metacognitive processes Applied learning processes

Article	Literature Search	Strategies	Key Findings	SDL processes
National Academies of Sciences, Engineering, and Medicine. (2017). *Supporting students' college success: The role of assessment of intrapersonal and interpersonal competencies,* National Academies Press https://doi.org/10.17226/24697.	**Process:** Researchers conducted extensive search of Google Scholar and other websites related to social-psychological interventions. They reviewed all references listed within relevant intervention studies. **Number of studies:** 27 eligible studies **Criteria:** • Used random assignment, with clearly defined treatment and comparison groups of at least 10 students each • Had a sample of college students or individuals who were about to matriculate in a college • Was published after 2010 • Explored impact of intervention's impact on an SDL competency of interest	Interventions related to our framework (noted in asterisks in next column) fell into two main categories: 1. Students see recorded testimonials (video, audio, written) from prior students that focus on how to develop a sense of belonging, and then write down how they might apply the ideas (9 studies) 2. Students see an educational module or video on a coping or study strategy, and then either take a quiz and/or summarize how they might apply these insights	The authors found there are 8 intrapersonal competencies that can be impacted by interventions and are correlated with persistence and success in undergraduate education: • conscientiousness, • sense of belonging*, • academic self-efficacy*, • growth mindset*, • utility goals and values*, • intrinsic goals and values, • prosocial goals and values, and • positive future self *denotes competency aligned with our framework	Motivational processes
What Works Clearinghouse. (2022). *Growth mindset interventions for postsecondary students* (NCEE 2022-006), U.S. Department of Education, Institute of Education Sciences, National Center for Education Evaluation and Regional Assistance https://ies.ed.gov/pubsearch/pubsinfo.asp?pubid=WWC2022006.	**Process:** WWC reviewers investigated studies under the WWC Standards 4.0 and the Supporting Postsecondary Success topic area protocol. **Number of studies:** 15 eligible studies, 6 met standards **Criteria:** • Employed a randomized controlled trial, quasi-experimental design, regression discontinuity design, or single-case design • Had a sample of postsecondary students in the United States or Canada • Include growth mindset interventions intended to impact academic achievement, college enrollment, and progression in college	Interventions typically include two components: • Exposure to information around how intelligence can grow when a student exerts efforts towards something new or challenging • Application of growth mindset components through reflection and planning	Growth mindset interventions: • May increase academic achievement, • May result in little or no change in college enrollment, • May result in little or no change in progressing in college.	Motivational processes

Article	Literature Search	Strategies	Key Findings	SDL processes
What Works Clearinghouse. (2022). *Social belonging interventions* (NCEE 2022-005), U.S. Department of Education, Institute of Education Sciences, National Center for Education Evaluation and Regional Assistance https://ies.ed.gov/pubsearch/pubsinfo.asp?pubid=WWC2022005	**Process:** WWC reviewers investigated studies under the WWC Standards 4.0 and the Supporting Postsecondary Success topic area protocol. **Number of studies:** 14 eligible studies, 7 met standards **Criteria:** • Employed a randomized controlled trial, quasi-experimental design, regression discontinuity design, or single-case design • Had a sample of postsecondary students in the United States or Canada in less advantaged or underrepresented groups • Include social belonging interventions intended to impact academic achievement, college enrollment, and progression in college	Interventions typically include two components: • Exposure to other students' experiences with concerns about social belonging • Reflection on their own futures.	Social Belonging interventions: • have inconsistent effects on academic achievement • have inconsistent effects on progressing in college • may result in little to no change in college enrollment	Motivational processes

Appendix B: Methodology

We read literature reviews conducted since 2011 that related to college learners' use of motivational strategies to support academic success and technologies to support self-regulated learning (See references on pages 32-34).

We also conducted a search for articles since 2011 in Google, ERIC, and the PsychInfo/Education ProQuest databases using systematic search terms that reflected key parameters of interest (See Table 1).

As we embarked on the search process, we initially aimed to find studies that concurrently addressed self-regulated learning AND STEM college coursework AND online technologies. However, these parameters eliminated most studies. Consequently, we adjusted the search parameters so that studies could include those that tested a self-regulated learning intervention AND/OR STEM college coursework AND/OR online technologies. We entered the search terms in sequence, leading with terms focused on self-regulated learning and technology, and then followed by student grade level, STEM domain, and study terms.

Table 1. Search terms

Self-regulated Learning (15 terms)	Technology (13 terms)	Domain (3 terms)	Study Design Terms (13 terms)	Population (10 terms)	Instructional Improvement (13 terms)
(self-regulat* OR self-direct* OR metacogniti* OR plan* OR analyz* task* OR goal-setting OR motivat* OR organiz* OR persist* OR self-control OR "attention to detail" OR "progress monitor*" OR belonging OR "growth mindset" OR reflection")	(online OR virtual OR distan* OR hybrid OR blended OR "learning management system" OR adapt* OR courseware OR computer OR tech* OR apps OR "intelligent tutoring systems" OR telelearning)	(STEM or science OR math*)	(comparison OR control OR experimental OR randomized OR treatment OR correlational OR intervention OR longitudinal OR theor* OR "program effectiveness" OR pre OR post OR quasi-experimental)	(postsecondary OR "post secondary" OR "post-secondary" OR secondary OR faculty OR instructor OR professor OR "high school" OR college OR "higher education"	(instruction* improve* OR "professional development" OR curicul* improve* OR "teaching practice" OR "academic achievement" OR pedagogy OR feedback OR "application of learning" OR culturally-relevant OR "professional learning" OR "inclusive pedagogy" OR "faculty development" OR "curricular redesign")

Originally, we included instructional improvement terms as well but decided to eliminate them to ensure the focus of the articles remained on students' development of self-directed learning skills.

We initially found 4,263 studies. A team of four researchers conducted an initial screening of the abstracts of the articles to ensure they focused on the following criteria:

- Self-directed learning: The article addressed self-directed learning skills, including as an outcome or a predictor variable
- Intervention: The article had to include a specific intervention to improve self-directed learning skills or improve student outcomes through a self-regulated learning intervention
- Sample: The article focused on secondary and postsecondary (including graduate) grade levels
- Student-focused: To focus on interventions that supported students, we excluded those that were practitioner-focused (e.g., how nurses utilized self-directed learning skills in their practice) or focused on teacher development or not in academic settings (e.g., in co-curricular activities or sports)
- Evaluative: We excluded purely descriptive or theoretical articles

This screening resulted in 209 articles. The team then conducted a more thorough screen of the full articles to ensure they met the What Works Clearinghouse (WWC) standards of having two comparison groups with baseline equivalence and provided information on outcomes relevant to our study (e.g., course grades, content or domain knowledge, metrics for self-directed learning skills, retention). The team initially included meta-analyses to inform the team's analysis but ultimately excluded them as they did not meet WWC standards.

Of these remaining studies, 15 were included to inform the description of self-directed instructional strategies for this paper. The remaining were excluded as they did not include a comparison group that permitted researchers to attribute outcomes to the use of self-directed learning interventions.

The 15 that met standards included 11 randomized controlled trials and five quasi-experimental studies. Of these:

- Nearly all were done in STEM courses, with a few offered through supplemental activities.
- Half were done in the United States.
- More than half employed some form of online technology.

- Interventions supported the use of strategies either at different time points in a course, or different time points around an assignment, ranging from before students began an assignment to during an assignment to after they completed one.
- Most interventions engaged students in repeatedly using one or more self-directed processes of the three core types: motivational, metacognitive, or applied learning.
- Interventions were used for most, if not the entire, academic term.
- Significant positive results in academic outcomes and/or self-directed strategy awareness or use were achieved for both small and large groups of students.

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