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This chapter provides faculty with design principles based on the How People Learn framework, as well as current best practices for designing engaged learning environments in STEM classes in the hope of continuing improvement in STEM education.

Supportive Teaching and Learning Strategies in STEM Education

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The 1996 Advisory Committee report to the National Science Foundation, *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology,* called for many changes in STEM (science, technology, engineering, and mathematics) education (George and others, 1996). The committee's overriding recommendation was that "all students have access to supportive, excellent undergraduate education in science, mathematics, engineering, and technology, and all students learn these subjects by direct experience with the methods and processes of inquiry" (p. ii). One of their recommendations for faculty was highly salient for this chapter:

> Believe and affirm that every student can learn, and model good practices that increase learning; starting with the student's experience, but have high expectations within a supportive climate; and build inquiry, a sense of wonder and the excitement of discovery, plus communication and teamwork, critical thinking, and life-long learning skills into learning experiences [p. iv].

Seymour and Hewitt's three-year ethnographic study (1997) of 335 science, mathematics, and engineering (SME) students across seven institutions indicated that there were no identifiable academic differences between students that were significant enough to explain why one group chose to leave SME disciplines while the others remain. However, both groups, regardless of race and gender, voiced greatest concern for the "chilly

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climate" and poor-quality learning environments. High rates of student attrition were more reliant on students' perception of the quality and character of education in SME and less on students' academic abilities.

Tinto's interactionalist theory of college student departure (1993) also identifies the climate as a major reason that students leave college. In exploring theories of academic and social integration, Tinto states that the extent to which students persist at an institution relates to their educational and institutional commitments. Factors that also come into play include students' background characteristics and the extent to which students are socially and academically integrated into the university culture. Students who are socially integrated are more likely to persist at an institution, demonstrating institutional commitment, and if they are academically integrated, students are more likely to graduate within their chosen majors, demonstrating educational commitment. The normative dimension of academic integration relates to students' interpretations of the academic climate at an institution and is present when students' intellectual development and the intellectual climate of an institution are aligned (Tinto, 1975; Braxton, 2000). Clearly the classroom lies at the heart of students' academic experiences.

As Nobel laureate Herbert Simon (1996) stated, "The meaning of 'knowing' has shifted from being able to remember and repeat information to being able to find and use it" (p. 1). The NSF *Shaping the Future* report (George and others, 1996) recommends a shift in the paradigm of STEM education to creating a climate of engagement and exciting all students to explore and discover the knowledge within science, technology, engineering, and mathematics.

Over ten years have passed since the *Shaping the Future* report and Seymour and Hewitt's *Talking About Leaving*. Current reports such as *Rising Above the Gathering Storm* (Augustine, 2005) indicate growing concern about STEM teaching and learning. Can the state of the learning environment in STEM classrooms change substantially? What can faculty do to design more supportive learning environments that include all students?

We think the answer to the first question is yes and provide a summary of the state of the art of thinking about the design of supportive learning environments. The key ideas are designing learning environments based on the How People Learn framework and working backward from student learning outcomes, through evidence, to planning instruction.

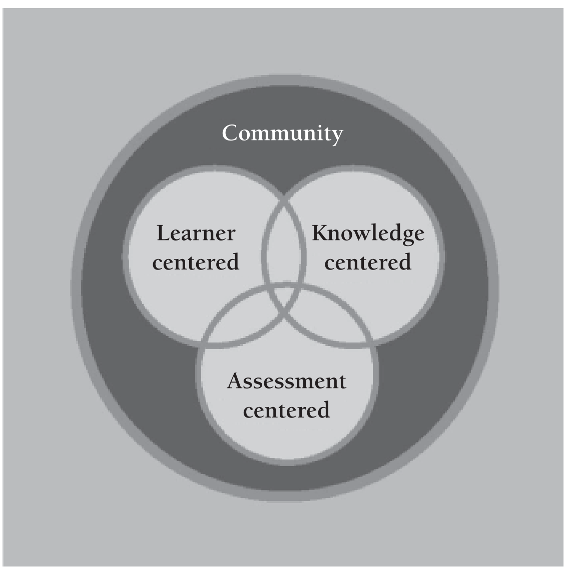
Recent reports, however, conclude that higher education in general, and presumably STEM education, is "declining by degrees" (Hersh and Merrow, 2005) and is "underachieving" (Bok, 2005). While the conclusion seems to be that postsecondary education is not performing well, there is a lack of focus on how to improve it. Sullivan (2005), in his overview of professionalism in America, highlights the problems associated with competition (negative interdependence) and advocates the cooperation inherent in "civic professionalism." He proposes that professional education may be renewed through three apprenticeships: an apprenticeship of the head that focuses on intellectual or cognitive development, an apprenticeship of the hand that focuses on the tacit knowledge and skills practiced by competent practitioners, and an apprenticeship of the heart that focuses on the attitudes and values shared by the professional community. Thus, it is not only more academic focus that is needed, but also practical skills and civic values. An instructional procedure that affects the head and hand while simultaneously affecting the heart, thereby potentially reversing the negative trends noted in higher education, is cooperative learning (Smith, Sheppard, Johnson, and Johnson, 2005; Johnson, Johnson, and Smith, 2007).

The How People Learn Framework and the Backward Design Approach

Before elaborating on cooperative learning, problem-based learning, and other forms of pedagogies of engagement, which we argue will provide substantially better learning environments, we summarize the How People Learn framework and the backward design approach because these provide compelling reasons, as well as the necessary conditions, to embrace pedagogies of engagement.

How People Learn Framework. Although the individual lenses (see Figure 2.1) represent aspects of a classroom, interdependencies of these lenses have been found to be more common within classroom environments

Figure 2.1. Four Lenses That Make Up the How People Learn Framework.



Source: Adapted from Bransford, Vye, and Bateman (2002).

(Cox, 2005). Each lens has criteria for careful consideration in the light of the subject matter, course level, and desired outcome. Lenses are complementary, and all lenses should be present and in balance to create an effective learning environment (Bransford, Brown, and Cocking, 2000; Bransford, Vye, and Bateman, 2002). A learning environment that is *knowledge centered* is designed based on an analysis of what we want students to know and be able to do as a result of the learning experience and helps students develop the foundational and enduring knowledge, skills, and attitudes needed for successful transfer of this knowledge. A learner-centered environment connects the strengths, interests, and preconceptions of learners to their current academic tasks and learning goals and helps students learn about themselves as learners. *Community centered* means providing a supportive, enriched, and flexible setting inside and outside the classroom where all students can learn, feel safe to ask questions, and work collaboratively. Finally, *assessment centered* means providing multiple opportunities to monitor and make visible students' progress from what they currently understand to the ultimate learning goals in an effort to allow students to continue working on their weaknesses and revise their thinking.

Our principal How People Learn guide for this chapter is "Creating High-Quality Learning Environments: Guidelines from Research on How People Learn" (Bransford, Vye, and Bateman, 2002). We chose this as our guide for three reasons: it was part of a National Academy of Sciences workshop, it is focused on postsecondary education, and it connects the How People Learn framework to the backward design approach of Wiggins and McTighe in *Understanding by Design* (1998).

We also note that another recent *New Directions for Teaching and Learning* volume (Number 108) applied the How People Learn framework (Petrosino, Martin, and Svihla, 2006). Petrosino, Martin, and Svihla (2006) focused more on adaptive expertise and the STAR (Software Technology for Action and Reflection) legacy cycle, and hence our chapter is complementary to their volume. Bransford (2007) stressed the importance of thoughtfully designed learning environments in his recent guest editorial in the *Journal of Engineering Education,* and Pellegrino (2006) argues for rethinking and redesigning curriculum in his paper commissioned by the National Center on Education and the Economy for the New Commission on the Skills of the American Workforce.

Backward Design Process. The idea of a backward-looking design process from student learning outcomes, through acceptable evidence, especially feedback and assessment, to planning instruction has been and is being embraced by others; Dee Fink, for example, has significant learning experiences in which he adds emphasis on situational factors that influence the design (Fink, 2003).

Identifying Desired Outcomes. The first step in the backward design model is identifying what it is you want students to know, to be able to do, and perhaps even to be as a result of the class session, learning module, course, or program. In STEM classes, learning outcomes are typically framed as cognitive outcomes: what we want the students to know. Two additional dimensions of outcome are what we want students to be able to do and who we want the students to be, that is, the values and attitudes shared by members of the community as a result of the designed learning experience. Sullivan (2005) frames these three outcome areas as the three apprenticeships.

Wiggins and McTighe (1997) recommend identifying (1) big ideas, topics, or processes that have enduring value beyond the classroom; (2) ideas, topics, or processes that reside at the heart of the discipline; and (3) ideas, topics, or processes that require uncoverage, that is, complex and difficult-to-learn ideas that require faculty guidance and insights. Finally, in planning for pedagogies of engagement, Wiggins and McTighe recommend considering to what extent the idea, topic, or process offers potential for engaging students.

Assessment. The second step in the model is determining acceptable evidence to decide whether or to what extent students have met the learning goals. Typically this is done with content-focused questions measuring outcomes at the low end of Bloom's taxonomy: Remember, Understand (Anderson and Krathwohl, 2001). To assess student learning outcomes at the mid and upper levels of Bloom's Taxonomy—Apply, Analyze, Evaluate, Create—open-ended questions and problems are typically used. Recently there has been considerable interest in using tasks that approximate practice and are more authentic and performance based.

Assessing students in groups creates additional opportunities and challenges for assessing student learning. Our recommendation for faculty who use cooperative learning groups is to design, encourage, and support students' learning in groups but assess individual learning and performance (Smith, 1998; Johnson and Johnson, 2004).

In addition to the summative assessment of student learning, it is also important to provide formative and diagnostic assessment opportunities for students (Angelo and Cross, 1993). More than summative assessments, formative assessments help teachers revise their teaching practices, identify and mitigate potential problems and hindrances to student learning, and note changes in student learning throughout a course. Related to students, formative assessments help students self-assess their understandings of academic content, support a student-centered approach to learning, and provide an additional method to document this learning (Angelo and Cross, 1993; Bransford, Vye, and Bateman, 2002). Technology such as wireless classroom communication systems also have been used extensively within both K–12 and postsecondary settings to increase the amount of formative assessment that occurs within classroom environments (Pea and Gomez, 1992; Dufresne and others, 1996; Mestre, Gerace, Dufresne, and Leonard, 1997; Wenk and others, 1997; Roselli and Brophy, 2002).

In the absence of technology, instructors may use other classroom assessment techniques to assess students formatively (Angelo and Cross, 1993). For example, the minute paper technique asks students to give a two- to three-minute response on index cards about what they are learning in the class and what questions remain unanswered. Similar to the minute paper, the "muddiest point" gives an instructor quick feedback about students' understanding. Within this technique, students are asked to identify the most confusing or most difficult aspect of a lesson. Additional techniques may be used by instructors depending on the information that they want to obtain from their students.

Plan Instruction. The third step in the backward design process is planning instruction. We focus on pedagogies of engagement—cooperative learning and problem-based learning—for learning outcomes that represent big ideas, are at the heart of the discipline, require uncoverage, and have potential for engaging students.

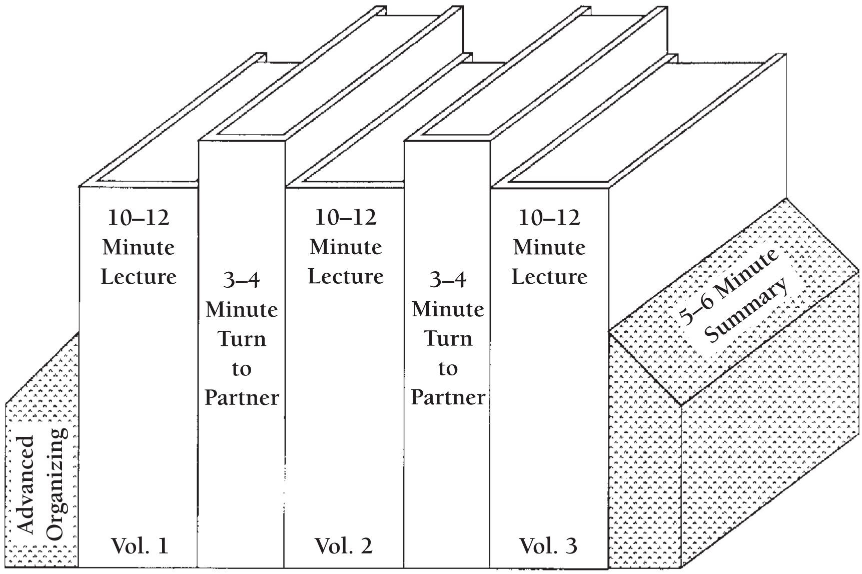
Implementation of Cooperative Learning and Problem-Based Learning

The classroom practices involved with cooperative learning and problem-based learning are complex to design, implement, and manage. In part because of these implementation challenges and many others, cooperative learning and problem-based learning are not widely practiced in STEM classrooms. Part of the reason for this may be not only their difficulty in designing, implementing, and managing, but that most faculty did not experience any form of cooperative or problem-based learning during their undergraduate or graduate education.

In this section, we highlight some well-developed and well-honed practices. Informal cooperative learning groups (often referred to as active learning), formal cooperative learning groups, and cooperative base groups are the most commonly implemented by engineering faculty. Each has a place in providing opportunities for students to be intellectually active and personally interactive in and outside the classroom. Informal cooperative learning is commonly used in predominantly lecture classes and will be described only briefly. Formal cooperative learning can be used in content-intensive classes where the mastery of conceptual or procedural material is essential; however, many faculty find it easier to start in recitation or laboratory sections or design project courses. Base groups are long-term cooperative learning groups whose principal responsibility is to provide support and encouragement for all members, that is, to ensure that each member gets the help he or she needs to be successful in the course and in college.

Active Learning. Informal cooperative learning consists of having students work together to achieve a joint learning goal in temporary, ad hoc groups that last from a few minutes to one class period (Johnson, Johnson, and Smith, 1998). Informal cooperative learning groups also ensure that misconceptions, incorrect understanding, and gaps in understanding are identified and corrected and learning experiences are personalized. In one instantiation of informal cooperative learning, every ten to fifteen minutes,

Figure 2.2. Bookends on a Class Session



students are asked to discuss and process what they are learning as shown in the bookends on a class session (Figure 2.2).

Breaking up lectures with short cooperative processing times results in slightly less lecture time but reengages the students. During lecturing and direct teaching, the instructor ensures that students do the intellectual work of organizing material, explaining it, summarizing it, and integrating it into existing conceptual networks. Common informal cooperative learning techniques include focused discussions before and after the lecture (bookends) and interspersing turn-to-your-partner discussions throughout the lecture. Although three- to four-minute turn-to-your-partner discussions are illustrated in Figure 2.2, many faculty provide one to two minutes, and some can be as short as thirty seconds.

As faculty gain familiarity with real-time assessment and informal cooperative learning, they often modify the format. For example, if most students choose the correct answer to a concept question, the faculty member might ask students to reflect on the underlying rationale for their answer and turn to their neighbor to discuss it; if most students choose an incorrect answer to a concept question, the faculty member might try to explain it again, perhaps in a different way; and if the answers to the concept question are a mixture of correct and incorrect, the faculty member might ask students to turn to their neighbor, compare answers, and see if they can reach agreement on an answer.

Many examples of the use of informal cooperative learning are available. Mazur (1997) describes the interactive aspects of a nineteen-minute lecture on Newton's laws in his book *Peer Instruction.* Darmofal (2005) has written about his use of informal cooperative learning and concept tests in aeronautical engineering, and Martin, Mitchell, and Newell (2003) have been experimenting with informal cooperative learning and concept tests in fluid mechanics.

Informal cooperative learning ensures that students are actively involved in understanding what they are learning. It also provides time for instructors to gather their wits, reorganize notes, take a deep breath, and move around the class listening to what students are saying. Listening to student discussions can give instructors direction and insight into how well students understand the concepts and material being taught.

The importance of faculty engaging students in introductory courses, using procedures such as those summarized, is stressed by Seymour's research (2002): "The greatest single challenge to SMET pedagogical reform remains the problem of whether and how large classes can be infused with more active and interactive learning methods" (p. 87).

Formal Cooperative Learning Groups. Formal cooperative learning groups are more structured than informal cooperative learning groups, are given more complex tasks, and typically stay together longer. Social interdependence theory and cooperative learning research identified five essential elements to successful implementation of formal cooperative learning groups: positive interdependence, face-to-face promotive interaction, individual accountability and personal responsibility, teamwork skills, and group processing:

- *Positive interdependence.* The heart of cooperative learning is positive interdependence. Students must believe that they are linked with others in a way that one cannot succeed unless the other members of the group succeed (and vice versa). Students are working together to get the job done. In other words, they must perceive that they sink or swim together. In formal cooperative learning groups, positive interdependence may be structured by asking group members to agree on an answer for the group (group product—goal interdependence), making sure each member can explain the group's answer (learning goal interdependence), and fulfilling assigned role responsibilities (role interdependence). Other ways of structuring positive interdependence include having common rewards such as a shared grade (reward interdependence), shared resources (resource interdependence), or a division of labor (task interdependence).
- *Face-to-face promotive interaction.* Once a professor establishes positive interdependence, he or she must ensure that students interact to help each other accomplish the task and promote each other's success. Students are expected to explain orally to each other how to solve problems, discuss with each other the nature of the concepts and strategies being learned, teach their knowledge to classmates, explain to each other the

connections between present and past learning, and help, encourage, and support each other's efforts to learn. Silent students are uninvolved students who are certainly not contributing to the learning of others and may not be contributing to their own learning.

- *Individual accountability and personal responsibility.* One purpose of cooperative learning groups is to make each member a stronger individual in his or her own right. Students learn together so that they can subsequently perform better as individuals. To ensure that each member is strengthened, students are held individually accountable to do their share of the work. The performance of each student is assessed and the results given back to the individual and perhaps to the group. The group needs to know who needs more assistance in completing the assignment, and group members need to know they cannot "hitchhike" on the work of others. Common ways to structure individual accountability include giving individual exams, self and peer assessment, and randomly calling on individual students to report on their group's efforts.
- *Teamwork skills.* Contributing to the success of a cooperative effort requires teamwork skills, including skills in leadership, decision making, trust building, communication, and conflict management. These skills have to be taught just as purposefully and precisely as academic skills. Many students have never worked cooperatively in learning situations and therefore lack the needed teamwork skills for doing so effectively. Faculty often introduce and emphasize teamwork skills through assigning differentiated roles to each group member. For example, students learn about documenting group work by serving as the task recorder, developing strategy and monitoring how the group is working by serving as process recorder, providing direction to the group by serving as coordinator, and ensuring that everyone in the group understands and can explain by serving as the checker. Teamwork skills are being emphasized by employers and the ABET Engineering Criteria 2000, and several books and articles are available to help students develop teamwork skills (Johnson and Johnson, 2000; Shuman, Besterfield-Sacre, and McGourty, 2005; Smith and Imbrie, 2007).
- *Group processing.* Professors need to ensure that members of each cooperative learning group discuss how well they are achieving their goals and maintaining effective working relationships. Groups need to describe what member actions are helpful and unhelpful and make decisions about what to continue or change. Such processing enables learning groups to focus on group maintenance, facilitates the learning of collaborative skills, ensures that members receive feedback on their participation, and reminds students to practice collaborative skills consistently. Some of the keys to successful processing are allowing sufficient time for it to take place, making it specific rather than vague, maintaining student involvement in processing, reminding students to use their teamwork skills during processing, and ensuring that clear expectations as to the purpose of processing have been communicated. A common procedure

for group processing is to ask each group to list at least three things the group did well and at least one thing that could be improved.

These five essential elements of a well-structured formal cooperative learning group are nearly identical to those of high-performance teams in business and industry as identified by Katzenbach and Smith (1993): “A team is a *small number* of people with *complementary skills* who are committed to a *common purpose, performance goals,* and *approach* for which they hold themselves *mutually accountable*” (p. 45).

Many faculty who believe that they are using cooperative learning are missing its essence. There is a crucial difference between simply putting students in groups to learn and in structuring cooperation among students. Cooperation is *not* having students sit side-by-side at the same table to talk with each other as they do their individual assignments. Cooperation is *not* assigning a report to a group of students where one student does all the work and the others put their names on the product as well. Cooperation is *not* having students do a task individually with instructions that the ones who finish first are to help the slower students. Cooperation is much more than being physically near other students, discussing material with other students, helping other students, or sharing material among students, although each of these is important in cooperative learning.

Before choosing and implementing a formal cooperative learning strategy, there are several conditions that should be evaluated to determine whether it is the best approach for the situation: there should be sufficient time available for students to work in groups both inside and outside the classroom; the task should be complex enough to warrant a formal group; and the instructor’s goals should include the development of skills of the types that have been shown to be affected positively by cooperative learning, such as critical thinking, higher-level reasoning, and teamwork skills.

The detailed aspects of the instructor’s role in structuring formal cooperative learning groups are described in Johnson, Johnson, and Smith (1998): (1) specify the objectives for the lesson, (2) make a number of instructional decisions (for example, group size and determining a method of assigning students to groups), (3) explain the task and the positive interdependence, (4) monitor students’ learning and intervene within the groups to provide task assistance or to increase students’ teamwork skills, and (5) evaluate students’ learning and help students process how well their group functioned.

Guidelines for designing formal cooperative learning lesson plans are available in many books and articles, such as Johnson, Johnson, and Smith (2006) and Smith (1996).

Implementation of Cooperative Base Groups. Cooperative base groups are long-term, heterogeneous cooperative learning groups with stable membership whose primary responsibility is to provide each student with the support, encouragement, and assistance he or she needs to make academic progress. Base groups personalize the work required and the course learning experiences. They stay the same during the course and possibly longer. The members of base groups should exchange e-mail addresses and phone numbers and information about schedules because they may wish to meet outside class. When students have successes, insights, questions, or concerns they wish to discuss, they can contact other members of their base group. Base groups typically manage the daily paperwork of the course through the use of group folders or Web-based discussion groups. Base groups are used by many engineering faculty in undergraduate courses and programs, in part because of their effectiveness and because they are easy to implement. They are also commonly used in professional school graduate programs, such as executive master's of business administration and management of technology. In this context, they are usually referred to as cohort groups and are groups of five or six students who stay together during the duration of their graduate program.

Implementation of Problem-Based Learning. Problem-based learning is as suitable for engineering and other STEM disciplines as it is for medicine, where it is used because it helps students develop skills and confidence for formulating problems they have never seen before. This is an important skill, since few STEM professionals are paid to formulate and solve problems that follow from the material presented in the chapter or have a single right answer that one can find at the end of a book.

The intellectual activity of building models to solve problems—an explicit activity of constructing or creating the qualitative or quantitative relationships—helps students understand, explain, and predict (Smith and Starfield, 1993; Starfield, Smith, and Bleloch, 1994). The process of building models together in face-to-face interpersonal interaction results in learning that is difficult to achieve in any other way.

Problem-based learning results from the process of working toward the understanding or resolution of a problem. It follows a learning cycle model: problem posed, identifying learning issues, individual and small group learning, application of learning, and reformulating the problem.

Problem-based learning and, more broadly, challenge-based learning (for example, case-based learning, problem-based learning, project-based learning, and inquiry-based learning) have been described in numerous references and are excellent ways to implement pedagogies of engagement in STEM disciplines. (See Bransford, Vye, and Bateman, 2002, for elaboration on challenge-based learning.)

Conclusion

STEM educators can apply many of the ideas in this chapter to their classroom practices. Increasing the sense of community among STEM students and between students and instructors within STEM classrooms is essential, since cooperative learning researchers and practitioners have shown that positive peer relationships are essential to success in college. Isolation and alienation are the best predictors of failure. Two major reasons for dropping out of college are failure to establish a social network of friends and classmates and failure to become academically involved in classes (Tinto, 1993). Working together with fellow students, solving problems together, and talking through material together have other benefits as well (McKeachie, 1988):

> Student participation, teacher encouragement, and student-student interaction positively relate to improved critical thinking. These three activities confirm other research and theory stressing the importance of active practice, motivation, and feedback in thinking skills as well as other skills. This confirms that discussions . . . are superior to lectures in improving thinking and problem solving [p. 1].

More supportive and engaging learning environments can help us accomplish our most important outcomes for STEM graduates: stronger thinking and reasoning skills, problem formulation and problem-solving skills, skills for working together cooperatively with others, and, especially, skills and confidence for figuring things out in complex environments and situations. We need the courage to relax our coverage compulsion and reach out to engage and involve students in their learning.

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