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Work in Progress: Re-Interpreting Engineering Laboratory Literature Through the Lens of Cognitive Load

Gregory Wickham, Harvey Mudd College
Matthew Spencer, Harvey Mudd College

Matthew Spencer is an associate professor of engineering at Harvey Mudd College. His research interests include hands-on learning, MEMS, ultrasound imaging and circuit design.

Re-interpreting Engineering Laboratory Literature Through the Lens of Cognitive Load

Abstract -- This WIP theory paper argues laboratory and engineering project classes can produce high cognitive load by pursuing many learning objectives at the same time. It further argues that courses where students work in teams are particularly prone to producing high cognitive load because the interdependence required to produce positive group dynamics necessarily creates higher cognitive load.

This argument is rooted in literature that articulates the learning objectives of laboratory classes. The literature suggests that laboratory activities can pursue many learning objectives at once. This is salient because a review of cognitive load literature suggests that pursuing many learning objectives can contribute to cognitive load. Other literature on engineering group projects reveals that group work can produce cognitive load in its attempts to foster interdependency, and that this can result in maladaptive team behaviors like specialization and attentional narrowing.

In response to these observations, this paper seeks to articulate features of laboratories that can trigger this cognitive-load-based loss of learning. It suggests future experimental and theoretical work to refine the features that have been articulated.

1 Introduction

Laboratory activities, defined here as "instructor-led, hands-on experiences in which students characterize or prototype an engineering artifact or measure natural phenomena," are a cornerstone of engineering pedagogy, with some estimates predicting that as many as 50% of engineering classes include a laboratory activity [1]. Other work shows that there are more published papers on laboratory activities in engineering education literature than other discipline-based education literature [2]. However, literature affirms that laboratory instruction is valuable [3], not least because it serves many learning objectives at the same time [4].

Because laboratory activities are so widespread in engineering education, improvements in laboratory pedagogy would affect many students. However, multiple publications bemoan the lack of assessment in laboratory activities and note that where assessment is present, it is not standardized [4], [5]. This history of weak assessment may originate with instructors' conception of laboratory activities: Instructors often describe the importance of laboratory activities using non-specific learning goals – e.g. "relating theory to practice" – instead of learning objectives [4], or occasionally insist that they can't articulate learning objectives at all [5].

This work analyzes how laboratory activities are described by three theories: laboratory categorization, cognitive load, and teamwork. Laboratory categorization refers to a collection of theories about the best way to describe laboratories. Cognitive load theory is a branch of educational psychology that argues that any learning task has some intrinsic difficulty called “cognitive load,” that cognitive load is borne by the learner’s working memory, that learning is limited by the learner’s ability to absorb cognitive load (i.e.: their available working memory), and that activities that tax working memory can interfere with learning [6]. Teamwork refers to a body of literature on undergraduate engineering teams that shows that teamwork can have unintended side effects [7], like affective losses when dealing with non-contributing team members [8], [9] or specialization of knowledge [10].

These theories are elaborated below. Sections 2-4 provide literature background on the definition of laboratories, laboratory categorization, cognitive load, teamwork and specialization. Section 5 combines these theories to provide a logic model of cognitive-load-related learning loss in laboratories, and section 5 further posits future theoretical and experimental work.

2 Definition of Laboratories and Theories of Laboratory Categorization

Despite the ubiquity of laboratories in engineering curricula, laboratory activities are rarely defined in literature. Byrnes et al elucidated a difference between “hardware laboratories” and “software laboratories,” which are described respectively as “laboratories in which students were asked to interact with an external piece of equipment or measure a natural phenomenon” and “laboratories that consisted entirely of simulation or programming” [1]. This work expands on that definition, arguing that laboratories are “instructor-led, hands-on experiences in which students characterize or prototype an engineering artifact or measure natural phenomena.” This definition does not specify a duration for a laboratory activity, so it can encompass both one-off experiments and sprawling engineering projects. Notably, most capstone and cornerstone experiences fit the definition. However, the definition does insist on hands-on activities, so it is designed to exclude activities that are purely computer-based.

Other works have other implicit definitions of laboratory activities. Some works center the idea of constructivism in discussing laboratories, and argue that a laboratory activity is one that provides rich information for constructing knowledge [11]. Others simply lament the lack of specificity in defining laboratory activities [12].

Consequently, categorizing laboratory activities or describing universal features of laboratory activities is a challenge. Fesisel and Rosa attempt to describe learning objectives broad enough to encompass all laboratories [4], so it may be possible to categorize laboratory activities by the number of Feisel & Rosa learning objectives that the activities pursue. Buck, Bretz and Towns provide a categorization based on “level of inquiry,” a measure of how many steps of the inquiry process are provided to students [13]. Usefully, Buck Bretz and Towns provide a rubric for evaluating the level of inquiry in an inquiry-based activity, but it isn't clear how well this categorization generalizes to laboratory activities that are not specifically inquiry-based, like design and build exercises.

An ideal laboratory categorization would be widely generalizable and would be predictive of properties of a laboratory, like its difficulty or how well students learn in the activity. Neither of the aforementioned laboratory categorizations are ideal: both ignore prior student experience, which affects learning and perception of difficulty, and Buck, Bretz and Towns may not generalize well to all laboratory activities. Defining a good set of core descriptive features for laboratory activities is an open problem.

3 Cognitive Load

Modern cognitive load literature has its roots in observations of the differences between novice and expert problem solvers [6]. Experts solved problems more efficiently than novices because they knew a set of "schema," common problem configurations, and used those to set up problems efficiently [14]. Researchers showed that the work of solving problems could limit students' ability to understand schema, which the researchers attributed to the cognitive load of problem solving interfering with the cognitive effort required for schema acquisition [15], [16].

This observation led to the theory of cognitive load: (1) learning depends on transferring materials from short term to long term memory, (2) complex tasks place demands on the limited short term memory of solvers, so (3) complex tasks inhibit learning by preventing the transfer of novel information from short-term to long-term memory [14]. Task complexity in this description can depend on many factors, which are described as different types of cognitive load. Intrinsic cognitive load is the inherent complexity of a task or concept, extraneous cognitive load is load introduced by the presentation of an idea, and germane cognitive load is the effort required to convert knowledge from short to long term memory [17].

Cognitive load is related to laboratory activities. At minimum, the presentation of laboratory manuals can affect extraneous cognitive load. For instance, laboratory manuals that link diagrams to text poorly can introduce extraneous cognitive load [18]. Further, medical literature shows some evidence that pursuing many learning goals can affect cognitive load [19].

4 Teamwork, Interdependence, Stress and Specialization

Team or group-based work benefits student learning [8], and teamwork skills are considered essential to employment [20], [21], so teaching and learning teamwork is important work. Teamwork can occur in laboratory activities, and learning to work in teams is one of the learning objectives laid out by Feisel and Rosa [4], so it is little surprise that both instructors and students perceive laboratory activities as crucial to learn teamwork skills [20], [21].

One key to effectively teaching teamwork is ensuring that students in a team have positive interdependence, meaning each student's work supports the achievement of all of their team members [22]. There are multiple types of interdependence: goal interdependence, where students believe that their success depends on other students meeting their goals; reward interdependence, where students believe that achieving a reward is dependent on the performance of everyone in the team; role interdependence, where each student has a specific job that contributes to a shared goal; and resource interdependence, where students must pool knowledge, time or other resources because no single student can achieve a goal [9].

The conditions that foster positive interdependence can cause stress, which can negatively impact team performance and student learning. This work defines stress using a definition from Salas by way of Dietz: "a process in which perceived demand exceeds resources, and that results in undesirable physiological, psychological, behavioral or social outcomes". That definition echoes resource interdependence, which is fostered by overwhelming an individual's resources, necessarily creating a situation where "perceived demand exceeds resources" [23]. Interdependence also causes other stressors, including role ambiguity, role conflict, and increased need for coordination among team members [23].

These stressors have consequences: Dietz and Bong observe that team members narrow their attention, communicate less and behave individualistically under stress, which can interfere with the perception of goal interdependence [23], [24]. Bong also invokes cognitive load, stating that "excessive stress can contribute to cognitive overload, attentional narrowing and distractibility, all of which are associated with impaired performance" [24].

Teams under stress may opt to specialize. Specialization occurs when students deliberately divide learning objectives for a project among themselves so that each student only masters a portion of the objectives. (As an aside, specialization has not been widely reported in literature, with much of the experimental work coming from Schmidt [10].) Specialization is a natural embrace of interdependence – students are giving themselves interdependent roles (role interdependence) to improve their team performance (reward interdependence) and mitigate the time requirements of a project (resource interdependence) – but it can reduce learning because students only learn the material in their specialty. In a series of interviews with students and faculty, Schmidt documented the occurrence of specialization on student project teams and confirmed that students and faculty perceive that specialization reduces learning [10].

5 Interpretation of Background Materials and Future Work

This work suggests a plausible chain of phenomena linking ambitious instructor learning objectives in laboratory activities to diminished learning. Pursuing many learning objectives or high levels of inquiry in a laboratory activity can create a high cognitive load for students, and high cognitive load interferes with learning. Teamwork learning goals also introduce a variety of stressors, many related to cultivating interdependence, that can increase cognitive load further and cause attentional narrowing. Student teams may cope with this stress by specializing, which increases interdependence, but guarantees that students will not learn topics outside of their specialty. The proposed relationship between these ideas is illustrated in Figure 1.

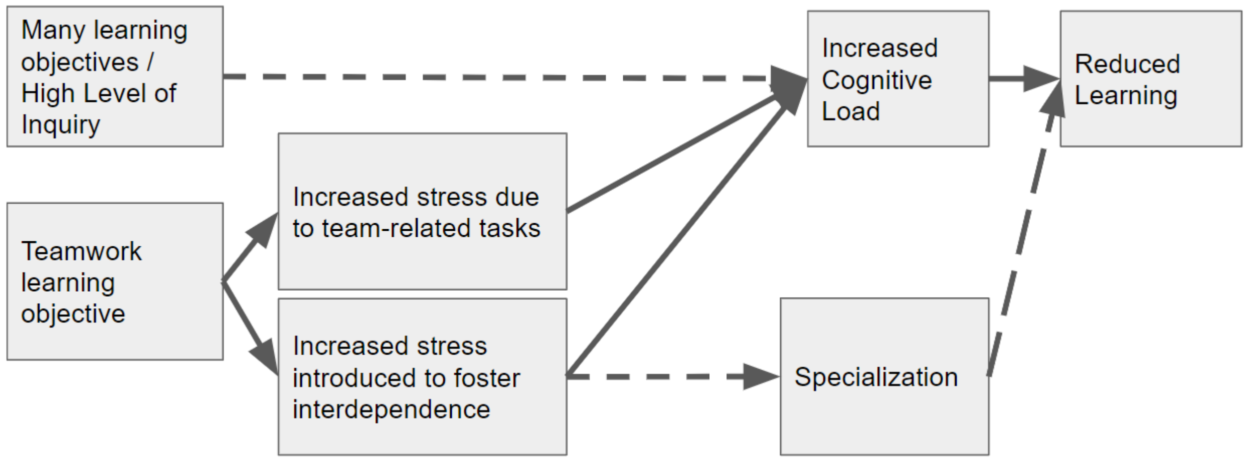

Figure 1: Proposed causal links between laboratory learning objectives and reduced learning

This logic model isn't the final word in representing cognitive load in laboratories. First, The inputs to the model are the lab categorizations described in Section 2, and per Section 2, there may be better sets of descriptive features for laboratory categorization. For example, a measure of novelty, how many learning goals in the lab are new to the students, might predict cognitive load more directly. Second, this logic model uses the same definition of reduced learning that is implicitly stated in cognitive load literature – this literature argues that learning is acquiring domain-specific schema [14] – and that definition may not effectively capture all types of learning, especially when the activity is complex or problem-based [25]. For instance, this model implies that introducing a teamwork learning goal will always result in reduced learning, but working in a team is obviously important to practicing and learning teamwork skills, and learning in small cooperative teams has a long track record of improving learning [26].

Some of the lines in Figure 1 are dashed. These dashed lines denote connections that are not well supported by literature. These include the connection between having a high level of inquiry and increased cognitive load, the relationship between specialization and reduced learning, and the relationship between learning objectives and cognitive load. Literature is also silent on how many learning objectives are pursued in a typical laboratory activity.

Consequently, relating laboratory activities to cognitive load requires more work. Theoretical and qualitative work can define better categorizing features of a laboratory, and ensure those features predict learning and perceptions of difficulty. Quantitative work can probe the unsupported relationships in the logic model. Finally, specialization is probably a widespread behavior, and more work qualitative and quantitative should document stories of specialization, the conditions that create specialization, and how specialization affects learning.

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