An Activity Framework for Fostering Reflection in Project-based Engineering Design Classes

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Abstract: Employers of engineering school graduates frequently lament that their new employees do not have adequate design abilities. Such sentiments are echoed in almost all major reports on engineering education. Two approaches for addressing this issue are to provide students with more engineering design experiences and to find ways to enhance the learning the results from existing experiences. This paper focuses on the second approach since providing students with more design experiences can be costly and, at the same time, evidence suggests that students do not always capitalize effectively on the potential learning opportunities stemming from such experiences. This paper proposes a framework for reflective activities that students can perform in order to enhance their learning from engineering design experiences. More specifically, this paper presents 1) some data suggesting that learning opportunities may arise through project based engineering design experiences but may not go unpursued, 2) a framework for reflective activities designed to facilitate students in pursuing these learning opportunities, 3) two slightly different instantiations of that activity, and 4) the proposed evaluation.

1. Reflection in Project-Based Engineering Design

Recent interviews with and surveys of the employers of engineering graduates demonstrate a strong feeling that graduates lack adequate design skills [John 1995; McMasters & Ford 1990; Todd, Sorensen, & Magleby 1992]. This perception is not new; almost all reports created to guide engineering education since the turn of the century have recommended an increased focus on design in engineering education (e.g. [ASEE 1994; Grinter 1955; Mann 1918]). This call seems to be becoming more frequent and more central to the re-engineering of engineering education, as evidenced by the increasing number of reports in recent years.

One approach for addressing the issue is to provide students with more engineering design experiences. Most engineering curricula have at least one design experience each term during the junior and senior years. These experiences are typically project-based [Blumenfeld, et al. 1991] with students completing representative design tasks in small groups, over the course of a term, with intermittent submission of pre-specified deliverables. Such a pedagogical approach has many strengths including implicit learning of concepts and skills from experience, memory of an episode and thus a case from which to reason, the strength of the situated and contextualized learning that can result, and the motivational nature of working on a authentic activity. More experiences may help students but will be costly in terms of student and faculty time as well as resources. In addition, there is evidence to suggest that project-based design classes create opportunities which go uncapitalized [Newstetter & Kolodner 1995]. At least one engineering educator has recognized this situation and warned that we need to be careful not to confuse experience with learning [Dixon 1991].

A complementary approach is thus to help students process existing design experiences more effectively. From an economic perspective, learning to make the most of a costly experience is always valuable. From a cognitive perspective, many theories of learning suggest that there is more to learning than simply experience (e.g. [Kolb 1984; Kolonder 1995]). In general, the experience can be (needs to be) processed in many ways include abstraction, generalization, and the determination of applicability/transfer conditions. The general thought process which can be said to underlie these higher-order cognitive activities is reflection. Reflection, as used in this paper, can be defined as any cognitive activity directed toward organizing and refining one's personal knowledge. Although orchestrating reflection is not without its difficulties, documented evidence of the benefits of reflection exist in several domains (e.g. [Chi, Leeuw, Chiu, & Lavancher 1994; Recker & Pirolli 1992], etc.). The challenge is to determine the role that reflection needs to play in learning from experience in engineering design courses.

This paper explores the role that reflection can play in enhancing engineering design students learning from experience. The next section describes some lessons about reflection taken from our work in a specific engineering design course. This analysis suggests three questions which need to be answered in order to have an effective reflection activity. These questions along with other research on reflection in different contexts are used to guide the specification of a reflective activity to complement project-based engineering design courses. The last sections of the paper describe how the activity specification is being instantiated in two different project-based engineering design courses and the evaluation that is proposed.

2. Reflection in a Mechanical Engineering Design Class

During the past year, my colleagues have been both observing existing reflective activities as well as trying to induce reflection in a mechanical engineering design course, ME3110 [Guzdial et al. in press-a; Guzdial et al. in press-b; Guzdial, Turns, Rappin, & Carlson in-press; Newstetter & Kolodner 1995; Turns 1995]. ME3110 (Creative Decisions and Design) is a junior level mechanical engineering course in which students learn about mechanical engineering design through participation in a term-long, group project. The students work in groups of three to six students where they strive to understand design requirements, plan the design tasks for the quarter, complete the design tasks culminating in a demonstration of the mechicanal devices that they have created. We have studied reflection in the class using three strategies - observations of an intervention designed to support collaboration and engender reflective discussions, observations of a current reflection activity - the individual learning essay, and an ethnographic study of the activities of one design group.

CaMILE, Collaborative and Multimedia Interactive Learning Environment [Guzdial 1995], is an educationally motivated collaboration tool which we introduced into the course and studied for three quarters [Guzdial et al. in press-a; Turns 1995]. In addition to supporting and facilitating student collaborations with the tool, we hoped to promote and subsequently see evidence of students reflecting on their emerging designs through electronic discussions with their peers. Although CaMILE use was high, it was not exactly consistent with our expectations. We learned that students were capable of and even preferred to manage the day to day collaboration without CaMILE. With respect to more reflective collaboration, such as discussing their designs within CaMILE, we discovered that the students did not perceive the benefit as high enough to make the effort worthwhile. The students seemed to need scaffolding as well as motivation for such reflective discussion activities. The students had no examples of how to have such a critical discussion, they did not have access to modeling of such discussions as cognitive apprenticeship would suggest as important [Collins, Brown, & Newman 1989], and finally they did not see enough benefit in such activity for them to feel very motivated to exert the effort.

Our attempt to orchestrate reflection in this course was not the first attempt. Students in this course have regular written learning essays, essays submitted along with each deliverable where students articulate what they believe they have learned. In talking with students and instructors and through reading these essays ourselves, we have noticed the activity to be fraught with similar issues as those uncovered when trying to engender reflective CaMILE discussions. More specifically, the students do know what to write or how to write about their learning. They frequently resist believing that they could be evaluated on such an open ended activity since they do not understand how they are evaluated. As a result, they are not always motivated to invest effort. Additionally, the content of the essays is often superficial. Because the activity is performed weekly, though, many of these problems are mitigated over time with students getting at least acclimated to the task, and subsequently their performance improving and objections subsiding.

The ethnographic study provided observations that round out, for now, what we have learned about reflection in this course [Newstetter & Kolodner 1995]. The findings of this study help explain some of the observations in the previous two studies. This study found that students frequently 1) lose sight of the big picture and 2) complete tasks in a rote manner with little functional understanding of the tools or methods they are using. In other words, the pace of the class, the volume of required work, and the novelty of formal collaboration for design problem solving often induces students to simply complete the required activities without giving much thought to the purpose of the activity or the potential usefulness of the activity in the future. The observed students completed the course knowing what they had done but not necessarily why they had done it and how their experience could guide them in the future.

3. Specifying Reflection-Inducing Activity

The results of the ethnographic study coupled with the contents of the learning essays suggest that there is a need to induce more reflection in order to get the students to process the experience better. The results of the first two studies suggest, though, that there is more to inducing reflection than simply providing opportunity. In particular, the experiences described above suggests that attempts to induce reflection need to be specific with respect to the following three questions:

1. WHY: What is the goal of reflection?
2. WHAT/HOW: What is the method or activity which will be used to induce reflection?
3. WHEN: At what times during the course of an experience will the reflective activity become the focus of cognitive effort?

These questions are answered implicitly in the medical school work on problem-based learning [Barrows 1986], where reflection plays a major role in the overall activities students complete. In problem-based learning, small collaborative groups work together to solve diagnosis problems and in the process learn about the scientific knowledge on which the field of medicine is based. Reflective activities are used with the *goals* of helping students to clarify their emerging knowledge about how to use resources, to clarify their emerging knowledge base, and to learn to assess their own performance. Group *discussions*, orchestrated by a facilitator, are used to induce this reflection. Discussions centered around the first topic occurs *during each problem solving session*, while discussion centered around the latter two occurs when each *diagnosis problem is finished.* These discussions form a cornerstone of the problem-based learning method. Those involved in problem-based learning curricula believe that these reflective phases are crucial to the success of the problem-based learning method.

In the context of engineering design education and specifically the class just described, these questions have been addressed in a haphazard manner thus far. The ethnographic study and the course objectives can be used to suggest reflection goals. In particular, the goals for reflection in engineering design need to be focused on helping students get the big picture as well as helping them understand and learn the applicability conditions associated with the methods, tools,. and concepts they are learning in the project-based design experiences. A framework for thinking the choice of method and timing for the reflective activity are explored in the next section.

4. A Reflective Activity in Project-Based Engineering Design

It is easy to conceive of many activities (specifications of method and timing) which can induce reflection relative to a set of learning or reflection goals. Such reflective activities might include collaborative discussions, debates, resolution of large philosophical questions, and explanations of externally represented problem solving performance. This section proposes six features of a specific reflective activity that is amenable to the reflection goals described in the previous section and takes into account the weaknesses observed in previous attempts to orchestrate reflection in ME3110, the strengths of the problem-based learning approaches to reflection, and other literature on reflection. In particular, a reflective activity appropriate for project-based, term-long, engineering design classes can be characterized along the following six dimenstions:

1. Students create and maintain *specifically designed external representations* which capture goal oriented and meaningful units of knowledge. The choice of representation enables the activity to be adapted to particular learning goals. For example, a planning representation that contains information about the sequencing of tasks during the design process would help students focus on the overall process and thus the big picture. Having the representation be external means that students must understand their thoughts and processes well enough to articulate them and that these articulations can then be reviewed and critiqued by others. Externalization of personal understanding is a critical feature of Cognitive Apprenticeship, a form of apprenticeship adapted to cognitive activities such as reading, writing, and reflection [Collins, Brown, & Newman 1989]. This focus on externalization through representation should be readily adaptable to the culture of engineering education. In this context, students have long been advised to create diagrams and representations since good representations can both permit inspection and make it easy for one to discover the important issues and even become attention directing devices, actually drawing one's attention to the critical issues.

2. These representations are maintained on an *continual and formalized manner.* Performing reflection in an on-going manner seems to be important to its success. Chi et al. found continuity to be an important aspect of successful reflection. In their experiment, they had students reflect on biology texts by suggesting to them that they self-explain each sentence after it was read. They found that self explaining significantly improved scores on reading comprehension relative to control subjects who simply read the text twice [Chi, Leeuw, Chiu, & Lavancher 1994]. They attribute the success of the self explanation activity to its continuous as well as integrative and constructive nature. Ensuring that the reflection occurs in an on-going manner is easier when the role of the reflective activity is formalized. Reflection has a formalized role in the problem-based learning pedagogy [Norman & Schmidt 1992]. In the ME3110 research described earlier, the role of CaMILE was not formalized and students simply ignored it in favor of their task goals. The learning essays, because their role was more formalized, showed improvement over time as students learn the nature of the task and thus can focus on the goal of the task.

3. The reflective activity needs to have *consistent structure that has been proven effective and permits minor adaptivity*. Coupling the continual nature of the activity with a consistent structure will allow students to become expert at doing the activity. Over time, this will permit learners to focus on the learning issues, not the structure of the task. Our observations from the ME3110 studies are that reflection is not easy. Students need help in learning how to do it. With a consistent structure to the activity, they will be able to learn through practice. In addition, the task can be modeled for the students, permitting the students to gain a general understanding the task through observation. Modeling is another important feature of cognitive apprenticeship [Collins, Brown, & Newman 1989]. The consistent structure should involve both summarization and abstraction. In the Chi et al study, the better students not only reflected more but a greater portion of their self explanations were abstraction statements [Chi, Leeuw, Chiu, & Lavancher 1994]. The summarization could take the form of updating the external representations, while the abstraction could be induced by posing specially designed questions.

4. The reflective activity needs to be *contextualized* with respect to the project-based engineering design task. Part of the student difficulties in using CaMILE can be attributed to the decontextualized nature of the tool. The students were responsible for adapting the tool to the reflective task, something which they were not able to do very well. Students need cues that help them tie the reflection to the design tasks. Such contextualization can be in the form of prompts that ask students for details of their design experiences, questions and subtasks that help students to focus on integrating their new experiences with their existing knowledge, design specific terminology that makes it easy for them perform the mapping, and even links to engineering design materials that provide examples. The contextualization can make it easy for students to see the value of the activity as well as focus their efforts on integrating new knowledge with existing

knowledge. This latter issue of integration was the third characteristic of the Chi self explanation activity that was used to explain its success [Chi, Leeuw, Chiu, & Lavancher 1994].

5. *Motivation* should be considered. Motivation is a complex phenomena tha cannot be ignored when thinking about how to achieve instructional goals. Students who are more motivated will, in general, learn more. Motivation can be manipulated via many means including 1) providing students with explicitly stated evaluation criteria [Barrows 1986], 2) ensuring that students know how they will use their new knowledge in the future [Recker & Pirolli 1992], and 3) capturing students personal interest [Blumenfeld, et al. 1991]. In the context of engineering design education and the proposed activity, motivation could be managed through several different strategies including grading of the activity, making the activity represent authentic and anticipated uses of the knowledge, and providing clear demonstrations of the benefits of the activity in the design or learning context.

6. The *implementation, resource, and time demands* of the task need to be *balanced* with the potential benefits. If the time requirements demanded of a student for the new activity are excessively high, the resources are unavailable, or the technology in which the activity is implemented is unreliable, students may avoid the activity despite any perceived benefits, potential benefits, or existing motivation.

5. Two Instantiations

We are in the process of using this reflective activity framework to design specific reflective activities and associated technology environments for two distinct project-based engineering design classes. In this section, the two targeted classes are described along with details of the instantiation of the framework. In both cases, the activity can be characterized as a form of *planning, tracking, and progress reporting*, where students anticipate, track, and report progress relative to both design goals and learning goals. The details are summarized in [Tab. 1].

Table 1. Profiles of the Reflective Activity, adapted to two Specific Project-based Engineering Contexts.

ME3110	General Feature of Activity	ISyE3010
Design process and issues are foci of the class. Process representation (e.g. PEI) and activity and issue logs are foci of the activity (e.g. org. stmt, mtg. log, activity log).	Activity is based goal relevant external representations	Design process and domain specific methods are foci of the class. Process representation. (e.g. PEI) and method characterizations are foci of activity.
Weekly progress peports are the context for the activity.	Activity has continual, formalized role in class	Weekly, post-deliverable individual reflection is context for the activity.
Project reports require updated representations, responses to questions, and a submission of a generated report.	Activity has consistent structure with that permits adaptivity	Individual activity requires appending of new info. to report, performing practice activities, and submission of report.
Progress report is based on project. Questions are based on anticipated uses of knowledge.	Activity is contextualized with respect to engineering design	Individual report is based on methods and design project from class. Practice is based on anticipated use of know.
The activity will be graded, will form basis for exam preparation, and may help students judge design process progress.	Motivation for activity is explicit	The activity will be graded, will form basis for exam preparation, and may help students judge design process progress.
The environment is web-based for easy access, the environment will manage task, time required for activity will be managed.	Activity implementation manages both costs and benefits	The environment is web-based for easy access, the environment will manage task, time required for activity will be managed.

ME3110: Creative Decisions and Design.

ME3110 is the junior level mechanical engineering design class described earlier. The focus of the course is on learning about design process issues as well as domain-general methods that make use of their prior mechanical engineering knoweldge. Many of the issues and challenges in this context have already been discussed. Currently, planning and progress reporting are required tasks, although the focus is specifically on reporting progress with respect to design goals not necessarily progress with respect to learning goals. In the beginning of the quarter, the project groups each create a multi-component plan specifying how they will collaborate to complete the design tasks by the end of the quarter. The components of this plan include a team contract and a time-based representation of the design activities, the PEI diagram. The PEI diagram shows the anticipated phases, events, and emerging information for the design process as bars drawn horizontally relative to an x-axis time line. The PEI diagram is particularly important since it is an external representation of the design process. These two representations along with meeting logs, group activity logs, and individual activity logs are updated weekly and submitted as progress reports. The planning and progress reporting activities are authentic to engineering design and have the potential to induce reflection since they involved looking back at what was accomplished. Several obstacles seem to exist that preclude students from treating the activity as truly reflective. The tasks are extremely paper-based and time consuming. They are not graded and thus students do not spend much time on these activities. During the ethnographic study, Newstetter observation that in the completion of these activities, students seem to reflect little (Newstetter, 1995).

The existing planning and progress reporting activities form the foundation for the proposed reflective activity in ME3110. Students will be able to build the plan, including the PEI diagram and other text-based representations, within a specially designed computational environment. Students will then continue to update these representations each week, following the completion of design deliverables. They will also respond to questions and prompts that induce them to explore the meaning and potential uses of the new knowledge. These prompts and questions will be easy to manipulate throughout the quarter since the entire activity is currently being implemented to run within Netscape and to store data in an Oracle database. From a technical standpoint, this will improve accessibility, reliability, accuracy, and flexibility for the students. The environment will support students by managing their data and by automatically generating the progress report submissions, based on their entries during the previous week. We anticipate that grades will provide one form of evaluation, but we will also try to motivate students by by having questions or prompts be thought-provoking potentially by making the progress reports become the cheat sheets that students bring to the exam.

ISyE3010: Human Machine Systems.

ISyE3010 is a junior level industrial engineering course which focuses on the design of complex systems in which the human operator has a critical role. In general, that role is designed into the system by taking into account human capabilities and limitations, both cognitive and physical as well as other factors. The course deals with human factors, interface development, cognitive science, and complex system issues, all in the context of a design curriculum. Students work in small teams of three or four students to gather data on an interface design problem, model the problem components (i.e. user, task, and environment), design and prototype the interface, formatively evaluate the interface, and finally redesign the interface based on the evaluation data. The nature of this class is a slightly different from the previous course in that both design understanding and domain specific design methods (e.g. data collection methods, prototyping methods) are jointly foci of the course. Otherwise it shares many of the same features.

Currently, there is no preexisting activity in the course which can be adapted to be consistent with the framework - the existing course has only design deliverables but neither planning reports or progress reports. This is not an obstacle since the redesign of the course is under development and the reflective activity is being designed specifically into the new course. It is envisioned that the basic reflective activity will be the annotation of a design process representation (e.g. the PEI diagram) with information about the design methods used in class during a particular stage of the design process. For example, during the data collection phases, students will update the portion of the design process representation with information about data collection methods including strengths, weaknesses, alternatives, costs, and benefits. In addition, students will be prompted with questions that induce them to use the knowledge to solve some conceivably authentic problem. Students may be given a design scenario in which a particular data collection method has been proposed, be told that the method is too costly, and be required to suggest alternative methods. Students will perform these reflective activities during each week of the course. This activity will be implemented using the same basic Web-based structure as in the mechanical engineering context. Again, both grading as well as having the product of all reflectivity be the cheat sheet for the exam will be at least two forms of motivation provided.

While the instantiations in the two context are guided by the same framework, they do have slight differences. ME3110 has collaborative element in that the progress report with the exception of the individual activity log is a group endeavor. The activity, as envisioned for ISyE3010, is primarily individual. In ISyE3010, the role of the activity is explicitly being designed into the course while ME3110 is leveraging existing role. Through implementation in these two contexts, we seek to illustrate the generality of the framework described.

6. Evaluation

The evaluation of this framework will consist of three parts. We will be performing 1) ongoing expert evaluation of the concepts, particularly in light of new data, 2) formative evaluation of components of the environment and activity with individual groups in the courses, and 3) summative evaluations in each of the two courses. A currently ongoing ethnographic study of ISyE3010 and the use, by ME3110 students, of a Web-based environment for writing, submitting, and receiving feedback on the learning essays are parts of the first two evaluation strategies. The summative evaluation will be performed across two phases. During the Fall of 1995, we will evaluate the entire framework and proposed activity, embedded in planning and progress reporting, in ME3110. We will compare the designed artifact, the course grades, grades on a specially designed exam for students in a class using the tool to students in class not using the tool. In addition, use of the tool will be monitored to help understand and explain outcomes. During the Winter of 1995, we will evaluate the framework in a redesigned ISyE3010 where the role of the framework is designed into course. Again we will look at the designed artifact, the course grades, grades on a specially designed exam but this time students in a class using the tool and having a new structure will be compared to status quo class.

7. Summary

In engineering design education, we need to be focusing jointly on providing students with rich experiences and helping them reflect on and learn from these experiences. Our previous work has demonstrated the need to be specific with respect to the goals, methods, and timing of the reflective activity. Research from diverse sources suggests that the methods and timing issues can be addressed via an activity that involves students 1) making on-going updates 2) performed via a consistent structure to 3) external knowledge and design representations 4) contextualized with respect to the design tasks and class discussions where issues of 5) motivation and 6) attention to implementation details are also high priority. Project planning, tracking, and progress reporting represent a general type of authentic activity which fulfills these guidelines and can be adapted to the unique goals of design courses in different domains. In a research environment where many are talking about the benefits of reflection for learning but few formalisms and little empirical evidence is being supplied, we are attempting to provide a single step.

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