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A Guideline for Teaching Engineering through Project-Based Learning

Tomorrow's Teaching and Learning

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This article aims to help the faculty and institutes who are new entrants to this exciting and highly promising pedagogy, project-based-learning. It will also help those faculty members who want to evaluate this pedagogy before deciding to go ahead with it.

Folks:

The posting below, while longer than most, gives a good look at the state of project-based-learning in engineering education and the key areas to pay attention to if you want to expand its use in your courses. It is by **Sanjay Goel**, JK Lakshmipat University, Jaipur, India, and was posted on his blog on March 31, 2019 and updated on February 22, 2020. The blog seeks to stimulate and promote the discourse for transformation of our understanding of objectives, required content, and desirable processes of higher education, especially engineering and computing education in India.

Regards,

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A Guideline for Teaching Engineering through Project-Based Learning

Many new engineering education regulating bodies and universities world over are now enthusiastic about using project based learning (PBL). However, currently the phrase seems to be in use to convey different meanings. While for some, mere inclusion of project work in a course qualifies it to have been delivered using PBL, education literature uses the phrase for a more transformed way of teaching where project work is the main learning engagement even for developing conceptual foundations. My personal fascination with this and other inductive approaches of teaching goes back to late 1980s when I started teaching Computer Engineering at Delhi University. For more than a decade, my initial experiments in inductive teaching and active learning were not informed by education research and the theoretical foundations of pedagogy. Later, when I got exposed to this body of literature, I realized that an earlier exposure would have helped a lot in making those experiments more systematic and effective. Gradually, my fascination with such approaches led me to get actively involved in computing education research at Jaypee Institute of Information Technology, Noida. In collaboration with several enthusiastic faculty members, we experimented with various ways of integrating project work in most computer science courses. Some experiment and course models for using project centric or project-oriented approaches in Computer Science courses were reported (Arora and Goel, 2009, Goel 2010). However, a satisfaction with a certain level of success of an ongoing model, lesser flexible curriculum structure and evaluation scheme as well as a large student and faculty population limited the innovation possibilities and scale in these experiments.

In the last decade, many institutes have been trying to adopt PBL pedagogy, especially in engineering courses. Fortunately, in the past few years, many training programs on pedagogy are being organized to expose engineering and other faculty members to this exciting body of knowledge. However, research is required to understand the impact of these training programs. This article aims to help the faculty and institutes who are new entrants to this exciting and highly promising pedagogy. It will also help those faculty members who want to evaluate this pedagogy before deciding to go ahead with it. The following text is a work in progress and is a result of collation of key ideas from several published research papers on PBL as well as research and experience-based insights of the author. I intend to update this article based on further deliberations and insights. I invite the enthusiastic readers to give their feedback on this text and/or share their experiences and insights on using PBL in their courses.

So far only a few institutes like Olin College of Engineering, USA have successfully implemented PBL across the curriculum. This success has helped Olin to earn worldwide recognition for its efforts. Inspired by Olin College's model, JK Lakshmipat University, Jaipur, India has been using PBL approach in some courses since 2018. Several interactions with Olin college faculty have helped JKLU faculty and leadership to adopt the model in Indian context. Since 2018 fall semester, a few JKLU courses running in PBL mode has been jointly reviewed periodically by the JKLU and Olin faculty. I joined JKLU as the Director of the Institute of Engineering and Technology in October 2018. As a result of this new approach at JKLU, in the first year itself, each BTech first year student admitted in 2018 worked on more than 10 projects. They all conceptualized, built, tested, and demonstrated a few working prototypes of some artefacts, in the form of hardware/software. The approach has been further refined with the next batch of students admitted in 2019.

A. Essence of Engineering as a discipline

US Accreditation Board for Engineering and Technology (ABET) defines engineering as "Engineering is the profession in which knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind." Engineering is not just applied science; it is as much about process as it is about technical knowledge. An engineer's task involves conceiving, designing, developing, and maintaining products, processes, and systems, and to predict their behavior using science. Essence of engineering is the process of integrating different forms of knowledge to some purpose. Engineering Professors Council (EPC), United Kingdom identified the following primary competencies for engineers:

1. Transform existing systems into conceptual models
2. Transform conceptual models into determinable models.
3. Use determinable models to obtain system specifications.
4. Select optimum specifications and create physical models.

5. Apply the results from physical models to create real target systems.
6. Critically review real target systems and personal performance.

B. The Phenomenon of Learning

Learning is a natural multi-faceted process that helically progresses through making and rendition of meaning at progressively deepening levels. It is driven by voluntary and/or involuntary efforts made in response to stimulating experiences. Such stimulating experiences create ‘cognitive dissonance’ and ‘learning contexts’ by inducing recognition of inadequacy of existing meanings. These contexts catalyze the activation of operating learning processes. Meaning making and rendition processes unfold in a multi-dimensional and evolving space of physical world, psycho-motor, cognition, emotion, attitude, values, community, and culture. We render our meanings in abstract forms like models and theories, and concrete forms like artifacts and body actions. From the perspective of Situated Learning Theory, learning is not seen as the acquisition of knowledge by individuals, but as a process of social participation in a ‘community of practice.’

A disjoint ensemble of inflexible and incoherent superficial meanings results in surface learning. Deep learning requires the learners to create integrated, coherent, and transferable meaning at deeper levels. In order to stimulate deep learning, education programs need to create and offer such learning contexts that induce forwarding levels of meaning-deficits, enabling flow of emotions, rich set of mental objects and representations, enhanced self-awareness, multifarious perspectives, and persistent practice of meaning integration.

Non-threatening levels of perceived meaning-deficits generate manageable meaning deficit, cognitive dissonance and load enabling flow of emotions and positive incongruence. When the positive incongruence is within an individual’s ‘threshold’, it supports learners to sustain their motivation, enjoyment, and efforts. However, perceived inadequacy or overloads of meaning-deficit can create long-term negative emotions such as anxiety, fear, boredom, frustration, humiliation, dejection, and so on. Continued long term continuation of such sustained negative emotions slow down learners’ efforts and may also lead to complete withdrawal. The traditional teacher-centric lectures do not create much or any dissonance among learners. Hence, they are often ineffective for deeper learning. On the other hand, some instances of students’ centric learning may result in over-load of meaning-deficit and cognitive dissonance and result in students’ frustration and withdrawal. These ‘thresholds’ depends upon the learner, learning context, culture, and community. Hence, in order to help the learners to develop their ability to learn, and also the ability to solve ill-defined unfamiliar problems, the prime aim of higher education has to be to gradually increase this threshold. Many modern pedagogies of engagement are appreciated for deeper learning because they also facilitate gradually increasing this threshold through repeated educational experiences.

C. Changing Pedagogies in Engineering Education

In the traditional form of engineering education, based on teacher-centric broadcast approach, the teacher is seen as the source of knowledge. Success in learning is often seen as the reproduction or direct application of what the teacher has taught. Such instruction, in which abstraction precedes the instantiation and concretization, helps students in developing skills in deductive reasoning and succeeds in creating a knowledge-base as an inventory of concepts. It also trains students in linear thinking. However, this traditional approach is not effective for producing creative engineers who are prepared for fast changing world that needs a new breed of students who are willing to take risks and try new things, who are eager to define their own problems rather than simply solve the ones in the textbook and who come up with the most innovative ideas and creative new directions. The traditional approach places a higher priority on teaching students to follow instructions and rules rather than on helping students develop their own ideas, goals, and strategies. Unfortunately, this problem is not even visible by looking at students’ grades and exam scores as students are performing well according to traditional measures.

Various studies have shown that learner centric methods like project work, laboratory work, discussions with other students, thinking and work oriented lectures, and teaching peers/juniors were rated as the most effective educational experiences. The National Academy of Engineers (NAE) suggested that the essence of engineering—the iterative process of designing, predicting performance, building, and testing—should be taught from the earliest stages of the curriculum, including the first year. Project Based Learning and other methods of inquiry-based learning are increasingly being recognized as the way forward to transform the education system.

D. Project Based Learning

Discipline specific professional engineering bodies have also been making recommendations for significant transformation of engineering education. ACM-IEEE Computing curriculum for Software Engineering 2004 recommended usage of project-based classes that would mimic typical industrial projects so as to give the students experience of working on such projects. ASME’s Vision 2030 task force has recommended that engineering education be re-thought significantly such that students get high levels of multicultural acumen, ethical development, a team orientation, and project based learning experiences.

Adapting from the kindergarten model, MIT Media lab has developed an educational approach of lifelong kindergarten based on a set of four guiding principles for helping young people develop as creative thinkers: *projects, passion, peers, and play*. They believe that the best way to cultivate creativity is to support people working on projects based on their passions, in collaboration with peers and in a playful spirit. A central goal of PBL is to facilitate the deeper learning process and support students’ acquisition of complex cognitive competencies, e.g., rigorous content knowledge and critical thinking skills. The projects engage students in the problem definition, design process, contextual understanding and systems thinking approaches. Students learn to work in teams, and to plan and carry out different tasks that are required during a project. They come to understand their own and their team-mates strengths and skills. Students are expected to draw information from a variety of sources and be able to filter and summarize the relevant points. They are also expected to communicate to different audiences in oral, visual and written forms. In the PBL approach, rote learning is de-emphasized and more emphasis is placed on understanding and application of engineering design principles. Because of frequent assessments throughout the course plagiarism can be more easily controlled. If the project themes and briefs also change every semester, one cannot even copy from previous or senior students.

PBL has often been reported to be associated with enhanced rigor. However, it does not automatically ensure rigor as without careful planning, it can also result in low levels of rigor and encourage “doing for the sake of doing” without students experiencing deeper conceptual understanding. PBL implementation is particularly challenging because it changes student-teacher interactions, demands a shift from teacher-directed to student-directed inquiry, and requires nontraditional modes of assessment. Hence, it is very important to follow appropriate instructional strategies and design principles for effectively implementing PBL course.

Several interactions with Olin faculty in connection with implementing PBL at JK Lakshmipat University have also helped in understanding the Olin approach and experiences. At Olin, one of the main curricular innovation is several large interdisciplinary courses starting from the 1st semester. Often mathematics and engineering faculty team-teach courses using PBL approach. Many conventional courses have been replaced by such integrated courses. The concepts are carefully chosen by the faculty for inclusion in the syllabus and many concepts, conventionally included in syllabus, not considered important by the faculty from the long term perspective, are not included in the syllabus. Institutes aspiring to adopt PBL approach should be ready to undertake comprehensive curriculum restructuring too. At JK Lakshmipat University, we have developed several such integrated courses.

Olin model is also characterized by a relatively smaller group of highly committed faculty and students. Olin admits only highly motivated students who demonstrate their ability to work well on projects during a pre-admission immersive induction program called “candidates’ weekend.” On the other hand, many institutes aiming to adopt PBL approach already have or are soon planning to have a much larger number and variety of students and faculty. Institutes with a smaller number of students will find it easier to adopt the PBL approach. At Olin, currently about 75% courses use PBL model for teaching. It has gradually increased over the last 3 decades. Typically, PBL courses at Olin also include about 25% concepts, that may not be delivered using PBL approach. This can sometimes go upto 50%.

The following text outlines fundamental assumptions and the key pedagogical elements for effective delivery of PBL courses to engineering students.

D.1. Fundamental Pedagogical Assumptions:

Engineering institutes and faculty aiming to use PBL in their courses first need to transform their fundamental assumptions related to their and students’ role and responsibilities in teaching – learning process. They also need ‘to change their beliefs about the role of project in the education process.

1. Projects are seen as the central vehicle of instruction. Projects are not seen as the culmination of learning (as they often are in standard classrooms), but instead are the process through which learning takes place.

2. As learning facilitators, teachers are essentially students' experience and engagement designers. Their role is to facilitate the progress through the cycles of work. They need to ask planned questions and give cues to make thinking visible, giving students authority to define and address problems and encouraging them to be authors and producers of knowledge. Readiness for learning; new content has to be developed before students are exposed to that content. Students first take on the role they will play in the project before they are exposed to new content during the "telling" that refers to the delivery of the background knowledge necessary for students to engage in the work and fulfill their project roles. This sequencing intends to enhance student engagement during the "telling."
3. The learning outcomes for cognitive as well as psychomotor domains are well defined.
4. Students are seen as active participants in the construction of knowledge. Faculty is sure that their students are intellectually ready for learning through this approach:
 - i. Students enjoy building tangible artefacts.
 - ii. Students have the required prerequisite knowledge and skills or the ability to quickly acquire the same through self-learning
 - iii. Students can put together different values, information, and ideas, and can accommodate them within their own schema through comparison, relation and elaboration.
 - iv. Students have developed the interest and ability to try to build generic abstract knowledge from specific concrete experiences.

D.2. Elements of PBL Courses:

After transforming their fundamental pedagogical assumptions and beliefs as mentioned above, the faculty should carefully plan for the following elements in order to effectively implement PBL in their courses. A slip on any of these elements may be counter-productive for learning and result in students' disengagement or disinterest in learning.

1. **Problem design:** Projects should be complex, open-ended, and realistic; have multiple solutions and methods for reaching solutions; and resonate with students' experience. The projects should involve an active, in-depth process over time, in which students generate questions, find and use resources, ask further questions, and develop their own answers. The projects should have real-world context, use real-world processes, tools, and quality standards, make a real impact, and/or is connected to students' own concerns, interests, and identities. They should require student to apply relevant theory and encourage students to integrate the knowledge gained from multiple courses. They should be designed to maximize the probability that students will encounter the big ideas specified in the learning outcomes and syllabus and should lead students to confront and resolve conflicting ideas to prevent "doing for the sake of doing." Some projects should allow for the consideration of not only technical aspects, but also economic, socio-cultural and ethical factors. The project should require students to demonstrate what they learn by creating tangible prototypes that are presented or offered to people beyond the classroom. Project brief or aim should not narrowly specify the solution or what should be built. The projects should give students the freedom to explore the context, define boundaries, research various sources and come up with a range of alternative solutions. Projects should allow for some freedom of expression and some experimentation allowing students to make some choices about the prototypes they create, how they work, and how they use their time, guided by the teacher and depending on their PBL experience.
2. **Task:** Projects must be planned in terms of various tasks where each task explicates what will be accomplished and carefully embeds the content to be studied. These tasks should be engaging, challenging, and doable.
3. **Process:** The steps necessary to complete the task should include activities that require analysis, synthesis, and evaluation of information. In order to avoid the risk of "doing without conceptual understanding," rigorous reading of good quality text/literature and good practice with diverse problems must be integral to each project task.
4. **Cooperative/Collaborative learning:** The project tasks must employ rounds of peer reviews or group brainstorming sessions.
5. **Resources:** Various learning resources like data, study material, and models of good work must be well identified and shared with students in advance. Students must be given enough time to use the resources, reason well and pursue a problem in depth.
6. **Increment Oriented Development Approach:** The artefact to be built should be viewed as an evolving network of components and in each increment/iteration, components and links are created, modified, replaced, enhanced, and integrated in order to provide added/more sophisticated functionality. Architecture of the tangible artefact to be completed through project activities should gradually grow incrementally, even involving iterations. In early years of engineering education, it is advisable to have well-planned and well-structured ladder of increments and iterations. In later years, when the students are more conversant with the engineering concepts and project-based learning, the structure can be more flexible. Conceptual schemas for student projects of increasing complexity for teaching a few computer science courses, e.g., Object oriented Programming, Database Management, Software engineering, etc., were reported earlier (Goel, 2010, Goel, 2011). One such conceptual schema, having 5 levels of growing complexity, for evolving project complexity through "Software engineering" course wrt increasing complexity of software requirements is as follows:
 1. Fixed, direct, independent and well-defined requirements
 2. Fixed, direct, independent and ill-defined requirements
 3. Fixed, direct, inter-dependent and ill-defined requirements
 4. Fixed, derived, inter-dependent and ill-defined requirements
 5. Evolutionary, derived, inter-dependent and ill-defined requirements
7. **Repeated use of diagrammatic representations for generic problem solving:** a few visual techniques for generic problem solving must be repeatedly used for problem analysis and/or solution development. These include concept maps, flow charts, affinity diagrams, systems diagrams (e.g., UML diagrams), cause and effect diagrams, etc.
8. **Briefing and Debriefing:** proper briefing must be planned "to set the stage" for each project, task, and session. The project brief can be ambiguous in order to allow students to research further information, think through the situation and decide as a team the tasks, the direction and the outcomes they want to achieve. The task briefs must link each task with some desired learning outcomes and sections of the planned syllabus. In early years of engineering education, the session briefs should be more focused and aim to link the tasks with specific theoretical concepts and also their other applications. Session briefs should also link to the specific learning material. Each session, task, or project must also have conclusive debriefing that should aim to consolidate the key learning in the dimensions of knowledge, skills, and attitude.
9. **Cycles of work and Continuous Critique & Reflection:** Time should be built into projects for students to reflect deeply on the work they are doing and how it relates to larger concepts specified in the learning outcomes and syllabus. Project work is designed so that there are cycles of work and revision and adequate time to complete them offering frequent opportunities for debriefing and reflection. These may include relevant in-class discussions, journal entries, or even follow-up questions about what students have learned. Processes should be set in place such that students frequently encounter feedback on their work and explicit suggestions for revision.
10. **Rigor:** Rigor is enhanced when students have the opportunity to struggle with a problem before teachers provide them with directive hints or solutions. Other indicators of rigor include: requiring students to explain or justify their thinking; giving them opportunities to summarize, synthesize, and generalize; having them compare and contrast different answers, solutions and interpretations; and asking them to apply knowledge to new situations.
11. **Logbook:** Students should be encouraged to record their rough notes, ideas and design decisions in their logbook for each project. They should record their own reflections on learning, project meetings and evaluations of self and team members. The logbooks should be checked by their faculty and feedback must be given to students at several points during the project.
12. **Guidance and Scaffolding:** The teaching approach uses a well-planned scaffolding of activities, and progressive learning in order to support deep learning. A learning scaffold can be thought of as any method or resource that helps a learner to "accomplish more difficult tasks than they otherwise are capable of completing on their own." Learning environments should scaffold students by reducing the complexity of the practices, while retaining their key elements. A key element of scaffolding is that the scaffold needs to be tailored to a student's current level of understanding (not

too much assistance and not too little). These typically include student- teacher interactions, practice worksheets, peer counseling, guiding questions, job aides, project templates, etc. To tailor a scaffold to a student's skill level or content knowledge, a teacher needs to engage in ongoing assessment of the student. Scaffolding should be faded over time as students learn to apply their new knowledge or skills on their own. *More support and structure need to be provided in the first year, compared to later years.*

Project Based assessment: Formative and summative assessments must be provided in each course. All the assessments should be related to the project, and follow the main stages of a design process. Formative and summative assessments should be provided in each project. Assessment rubrics should provide clear criteria of how marks are allotted in the design projects. However, these should be used more as guidelines and not too prescriptive. The rubrics should provide students a good idea of what is expected. Assessments need to take into account the range of acceptable solutions, and judge them according to the most important criteria of appropriateness to the context of the problem, how well the problem has been investigated, understood and resolved, the clarity of the problem definition, whether the solution space has been sufficiently explored, and how creative and innovative the solution is. It must also judge individual student's conceptual understanding of the embedded theoretical concepts. In doing so, it is imperative to assess individual student's theoretical understanding of the embedded concepts.

While Project Based Learning approach offers a great way forward to educate engineers, a superficial implementation without its proper understanding, expert faculty, curriculum restructuring, appropriate assessment, etc., can turn out to be counter-productive.

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