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Engaged STEM Learning using Catapults

Peter Willmot¹ and Anthony Sutton²

¹Loughborough University, UK, P.Willmot@lboro.ac.uk

²Loughborough University, UK, A.Sutton@lboro.ac.uk

Abstract

This paper describes one element of a year-long module for mechanical engineering students that is designed to enhance student engagement and improve professional skills. This mini-project embraces the concept of 'enquiry based learning' within a challenging student-centered team project. The intensive and competitive project was scheduled early in the first semester as a vehicle to assist students to adjust to their new surroundings at a time when there were no other lectures or classes. The 160 strong cohort was divided into tutorial teams of 6 and started with a review of the mathematical concepts related to simple kinematic systems and the laws of motion. Teams were then exposed to designing, manufacturing and testing a floor mounted catapult and competing to out-perform others through their efforts. Strong bonds became apparent among team members and the willingness on the part of many was shown to work beyond normal class hours were observed because of the exciting and motivational challenge. An online survey provided evidence that, in addition to substantial social benefits, the exercise proved a powerful vehicle for enhancing practical understanding of fundamental mechanics that had been revealed as generally lacking in freshers.

Keywords: *Teamwork, motivation, enquiry based learning, engagement.*

1. Introduction

The transition to higher education can be problematic and it is known that "Effective transition can help to improve rates of initial retention and ongoing success." [1] The Higher Education Academy surveyed a large number of students who had withdrawn early from UK universities [2] and cited poor quality of the learning experience as one of the major reasons and this is defined for us by the students own perceptions. Some pointed to their sense of isolation. For many, this was associated with large-scale lectures that allowed little, if any, interaction with academic staff or fellow students. Some commented on the impersonal nature, the difference between University and secondary school styles and the presumption that lecturers expected students to adapt instantly to their mode of delivery. Others commented on the lack of opportunities to make friends on their course or of intimidating or unapproachable staff. This paper proposes and investigates a possible strategy to address these concerns by introducing significant elements of Enquiry Based Learning (EBL) at the beginning of the degree programme to supplement, explain and inspire study of the more traditional scientific elements that continue alongside it. Enquiry-based Learning is a broad umbrella term to describe approaches to learning that are driven by a process of enquiry. The tutor establishes the task and supports or facilitates the process, but the students pursue their own lines of enquiry, draw on their existing knowledge and identify their learning needs.

The transition into higher education means that many students have to come to terms with an approach to teaching and learning that is markedly different from their previous experience. The first year is one of reorientation, and some students manage this more successfully than others. This paper describes one element of a compulsory Engineering Principles and Professional Skills (EPPS) module for mechanical engineering students, introduced 5-years ago, that embraces the concept of 'enquiry based learning' (EBL) throughout the first year. Student-centred projects and skills workshops sit alongside and provide motivators for a broadly traditional first-year curriculum. A break from normal didactic delivery takes place in the fifth week of the first semester to encourage and excite students who were evidently still adjusting to university lectures: it had been observed that some were starting to become unmotivated and inert. Providing motivators, in addition to those gained by the award of marks is a key challenge. Hertzberg's two-factor theory [3] suggests that, in the workplace, additional motivators are needed and that 'hygiene factors' or potential demotivators should also be addressed. There is no reason to suppose that people behave any differently in education. Interpreting Hertzberg's work suggests that to make study tasks motivating, participants must be given responsibility for it and that the deliverables should provide sense of achievement. To improve 'hygiene', we should remove excessive bureaucracy and paperwork, provide effective but non-invasive support, create a culture of dignity and respect for students and provide 'meaningful' work tasks. In other words, give students real ownership and involvement in their learning.

2. Defining Motivation

Effective engineering education requires the integration of knowledge, skills, comprehension and implementation, thus making engineering education, perhaps uniquely, challenging. Top students are observed to progressively mature through the course of their degree programmes: from the initial position where 'life begins when work ends' to life and work being indelibly associated where they become emotionally attached to and motivated by their work. The task, however, is to make this happen earlier and to a wider group with a 21st century skills set. In 'When Teaching becomes Learning' [4] wrote that motivation is already present in learners but it is a matter of creating situations that enable learners to become actively engaged and to use these experiences to reinforce the necessary fundamental knowledge and skills to support the science.

Extrinsic motivators such as coherent marking and grading schemes are generally well understood but students often have little accurate knowledge about the satisfaction and rewards their education may bring to them in later life. According to Herzberg, intrinsic motivators and extrinsic motivators have an inverse relationship: intrinsic motivators tend to create motivation when they are present, whereas extrinsic motivators tend to reduce motivation when they are absent. Intrinsic motivators represent less tangible, more emotional needs, such as challenging work, recognition, relationships, and growth potential. Extrinsic motivators tend to represent more tangible, basic needs. Motivators driven by enjoyment or curiosity in the task itself are observed to have little pull in lengthy and dull theoretical lecture courses whereas it is well known that pedagogies based on student-centered learning provide strong drivers towards learner autonomy and a mindset that promotes success.

The Higher Education Funding Council for England (HEFCE) provides evidence [5] for improved engagement through intra-modular interventions and modified teaching and learning styles within instructional units (modules). In recent years, researchers have formed a strong consensus on the importance of engaged learning in schools and universities. Recognition of the changing needs of the 21st century, stimulated the need for definitions of engaged learning. Jones, Valdez, Nowakowski, and Rasmussen [6] described such learners as self-regulated, able to define their own learning goals and evaluate their own achievement. They are energized by their learning; their joy of learning leads to a lifelong passion for solving problems, understanding, and taking the next step in their thinking. These learners are able to transfer knowledge to solve problems creatively. Engaged learning involves being collaborative: that is, valuing and having the skills to work with others. The researchers defined further indicators of environments where engaged learners will develop and thrive: where there are authentic, challenging multidisciplinary tasks and where there is performance-based assessment. Successful, well-motivated learners are responsible for their own learning.

In 2012, the first author undertook an international research project, visiting 14 Higher Education (HE) Institutions across three continents, interviewing staff and students. The results lend weight to the above arguments. Willmot [7] concluded that the biggest motivating factors were quality assignments; in particular, those where students were stretched and allowed to exercise creativity. Many students had talked about the 'value' of their assignments, at least, their perceptions of value. They commonly used phrases like 'real world', 'practical', 'useful', 'real life applications', and 'industry related' to describe those that engage and spoke of 'text book problems', 'theoretical work', 'step-by-step laboratories', and 'just to pass the exam' as negative drivers. This work, sponsored by the UK Higher Education Academy, was a powerful driver for introducing the activity outlined below.

2. Parallel Enquiry Based Learning

Attendance levels at lectures were steadily falling and coursework was mostly submitted but tutorial sheets remain largely incomplete. Typically text books appeared to be underused and lecture notes were seen to be filed away, unread by a sizeable proportion of freshers, only to appear a few days before the examination. Apart from the inevitable poor performance, the lack of participative learning had a negative effect on motivation and students who began to get behind, rapidly fell into a cycle of unhappy disengagement in the belief they might never catch up. A significant group of students were clearly unexcited by the courses and didn't know what was really expected of them.

It was a combination of a rising failure/withdrawal rate together with the realisation that young people arrive at university with very a different attitude and range of abilities to those of their forebears that drove the movement for change on the Mechanical Engineering degree programme at Loughborough University in 2009. The ideas that were adopted are founded in the widely known constructivist educational theory where learners are invited to construct knowledge for themselves, become actively involved in their community and learn how to learn while they learn. The several EBL tasks around which the module was built were designed to be authentic and challenging; generating a degree of creativity and competition and promoting real motivational value in an

unconstrained environment. An external evaluation of the whole module has previously been published in the Journal of Engineering Education [8]. Naturally, the various EBL tasks have been developed and refined over the last five years and the most recent catapult project assignment, described below, postdates this review.

3. Project Week

Students, initially excited by thoughts of technology and machinery had arrived at university to find they were sitting in lecture theatres for long hours and spending their evenings working through problem sheets that closely resembled their familiar, but not much loved, homework from high school, the previous year. With interesting major projects still apparently years away, it is no wonder that some were considering if this was right course for them. ‘Project Week’ was introduced half-way through the first term at the time when enthusiasm had apparently begun to wane. Lectures were removed from the timetable that week and students were to tackle intensive stimulating challenges.

3.1. The Catapult Competition

A trebuchet was a machine used in medieval siege warfare for hurling large missiles and the challenge would be a variation on this theme, in miniature. Unlike Roman siege engines that were generally powered by a falling weight, the model trebuchets, or catapults were powered by extension springs and the missiles were balls of Plastercine modelling clay, of varying mass, revealed on the day of the competition. While the design of mediaeval artillery was limited to trial and error, due to a lack of engineering knowledge and manufacturing technology, the challenge here was to demonstrate that Mechanical Engineering students can do better through the use of fundamental engineering knowledge and practice. Each team will be challenged to design and build a catapult, capable of firing fixed-mass projectiles accurately and repeatedly over a set distance.

There were two competitive challenges: (i) to fire a series of projectiles 3m across a room to land accurately onto a horizontal, circular 1.4m diameter target (see figure 1) and (ii) to simply propel a 50g projectile as far as possible. The projectiles for the target shoot would be of several different weights between 15g and 60g, announced on the day of the competition.

With 28 teams in play and limited facilities, managing and monitoring the teams was not easy but a deliberate policy of minimum intervention was adopted once the ground rules had been established. At all times, there was at least one member of staff available to offer support on request. And workspaces had been pre-booked. The competition took place on the final day of the week and all teams were given specific time slots to demonstrate the performance of their machines.

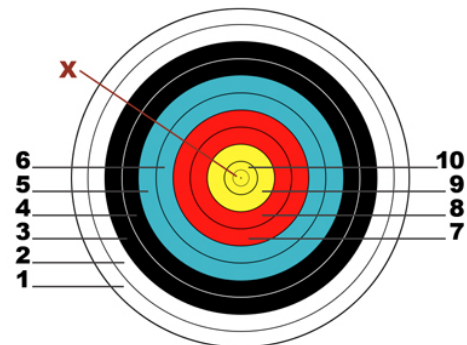


Figure 1: Target with scoring rings.

The first four days of the week would take the students through four distinct stages of the project leading up to the competition and, except for some essential limitations of laboratory and technician availability, teams worked at their own pace.

3.2 Phase 1; modelling the flight of the missile.

Students soon realised that achieving a desired range requires control of multiple parameters, not least the mass of the object – that would only be specified on the day of the competition so teams had to make their catapults adjustable to compensate for this if they were to hit the target and score points. Hence, students were required to build a mathematical model to assist with range finding using an Excel spreadsheet and allowing for input of variables such as the missile mass, launch angle the spring constant and the geometry of the catapult design. A single optional lecture provided general support for this activity.

A typical catapult, such as the one shown in figure 2, is a lever ($L_1 + L_2$) pivoting at height, P, and powered by the extension, δ , and force, F, in one or more springs. Although it is possible to analyse this device using Newtonian equations of rotational motion, an energy approach is far simpler and provided a reasonably accurate model of the system.

For this system, the input energy is entirely derived from the spring’s elastic potential energy found from $\frac{1}{2}k\delta^2$ where k is the spring constant (the students would need to determine this by experimentation). The stored energy is converted into kinetic energy of the projectile $\frac{1}{2}mv^2$. The gravitational potential energy is given by mgh where h is the height at any point. So the energy in the shot is at any point on the trajectory is $\frac{1}{2}k\delta^2 + mgh$ assuming that all the spring energy has been transferred to the mass on release. On the day of the competition,

teams should be able to use their model to quickly determine the release angle, θ necessary to hit the target. The process replicates, in simple terms, how naval artillery is actually targeted.

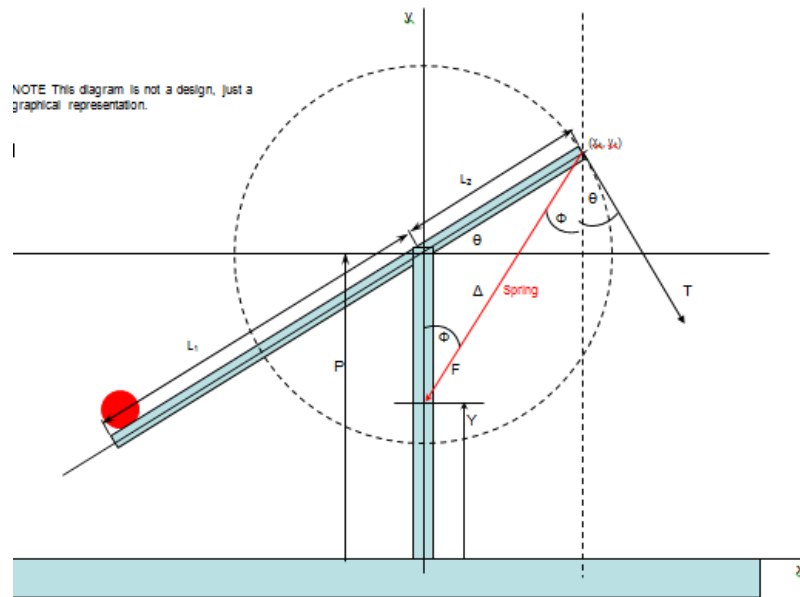


Figure 2: A typical spring powered catapult.

3.3 Phase 2: Catapult Design.

Some additional information was needed in parallel with optimizing the design geometry and used to extend the scope of the Excel model at this stage. In particular, students needed to determine the characteristics of the selection of springs supplied. To do this, they were encouraged to visit the strength of materials laboratory, where technicians had been primed to offer just enough assistance.

After only four weeks at university, students have only started to acquire basic 2D CAD skills. The catapult would be made from Medium Density Fibreboard (MDF) parts, cut by lasers to their design. Each team was issued with an extension spring, an A3 size sheet of 6mm thick MDF and a 150mm long plain steel pin for a pivot. There would be a fixed baseplate onto which the catapult must be bolted for the competition; this was specified. The actual design was for them to decide.

3.4 Phase 3; manufacture and assembly:

Teams needed to deliver their completed and checked CAD drawing showing how all the component parts would be cut from a single sheet of MDF to the laser laboratory.

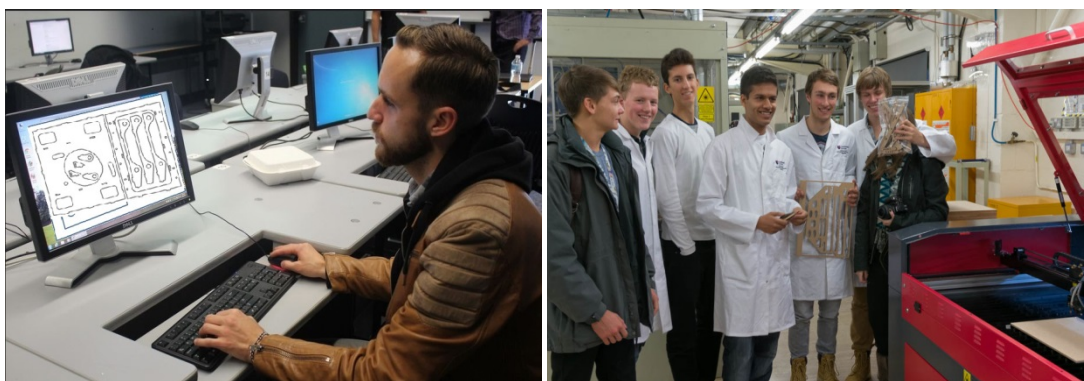


Figure 3. Computer Aided Design and Manufacture.

Teams took responsibility for booking a 'manufacturing slot' as soon as their design was ready. CAD drawings were quickly post-processed into machine control files and students could observe their parts being cut out. It

was then up to the teams to construct their catapult, fixing the parts with a suitable adhesive and at this point they would discover just how good their earlier design work had been.

3.5 Phase 4: testing and development

There was plenty of scope for creativity within the design, although in practice, it was clear that most teams followed the lead of the examples shown by the lecturers for the basic configuration. Once they had determined their preferred design, they were required initially to produce a tessellation of the various parts, drawn on a single A3 size sheet of 5mm square graph paper in preparation for converting this to a CAD file using their newly acquired CAD skills.



Figure 4: Students generally underestimated the time needed for testing and development.

Students quickly learned that translating conceptual and theoretical ideas takes longer than imagined. Typically their attention to detail was lacking, where precision makes all the difference. Two examples of the areas where iterative corrections were almost universally found to be necessary were:-

- (i) The 2 dimensional parts needed to be joined together to form the 3 dimensional machine and, unsurprisingly, this required the use of adhesives. However, impatient students would not allow sufficient time for the joints to cure. Worse, some chose to ignore that advice that had been given and simply butt the adjacent parts together. Those who incorporated joints that would be familiar to cabinet makers into their initial designs suffered far less catastrophic failures under the sudden impact of stopping the spring catapult. These details, when incorporated at the design stage actually added no complexity to the manufacture but added significantly to the design integrity and strength.
- (ii) First year engineering students are familiar with Hooke's law ($F = k\delta$) but apparently naïve about its practical application to the helical spring. The exercise provided a useful correction for some although many springs were quickly destroyed by being over-stressed. We learnt to keep a good supply of spares.

3.6 The Competition

On the last day of the week, all teams demonstrated their devices, for both accuracy and distance. They were told to fire two shots each of 15g, 20g, 25g, 30g and 35g, 10 in all at the target, and in a separate test, a single 50g shot was used for the distance metric. The students used their Excel model to set their catapult for each shot. The machines were also weighed as light-weight was another specified metric for the competition.

The score for each team was calculated according to the following formula, declared at the start:

$$\text{Team score} = \alpha A + \beta M + \chi D + \delta L$$

where A = accuracy (sum of scores for 10 shots), M is the relative mass (of the device) score calculated in proportion from the heaviest device to the lightest, (light = best), D is a tutor-judged design score (%) and L is the length of the distance shot in metres; with coefficients; $\alpha=0.5$, $\beta=0.2$, $\chi=0.2$ and $d = 0.1$. A bonus accuracy mark was added if a projectile landed in the tin can placed in the centre of the target. Final scores varied between 40% and 81% with a mean of 56.9% and standard deviation (30 teams) of 9.8. Small prizes were awarded to the top three teams.

Staff, who had not been otherwise involved, were invited to attend the test sessions. Some were bemused by the appearance of mayhem but most were immediately converted by the enthusiasm of the students to appreciating the value of the exercise.



Figure 5: Photographs from competition day.

4. Post-Project Student Survey

An online survey was constructed and made available to all participants immediately after the project week to understand to what extent the social and learning objectives had been achieved and also to determine how well the disruption to normal processes had been received.

The student population was 157 with approximately 91% male and 9%, female. The response rate was 57%. 75% of the 28 teams were randomly constructed of 6 members while the remainder had between 4 and 7 students. The response rate for teams (at least 1 member responding) was 96%.

The following is a thematic discussion of the survey results.

4.1 On Teamwork.

Although all teams attempted to plan as they had been encouraged to do so by the staff, there was evidence that this planning had not been universally effective, unsurprisingly suggesting that new students need further development here but also demonstrating that many had identified the need to do this: only 21% claimed to have made a plan and stuck to it, whereas 51% stated that “their plan developed over time; Others said their plan had been overruled by events (16%) or that they just did what they needed at the time (10%).

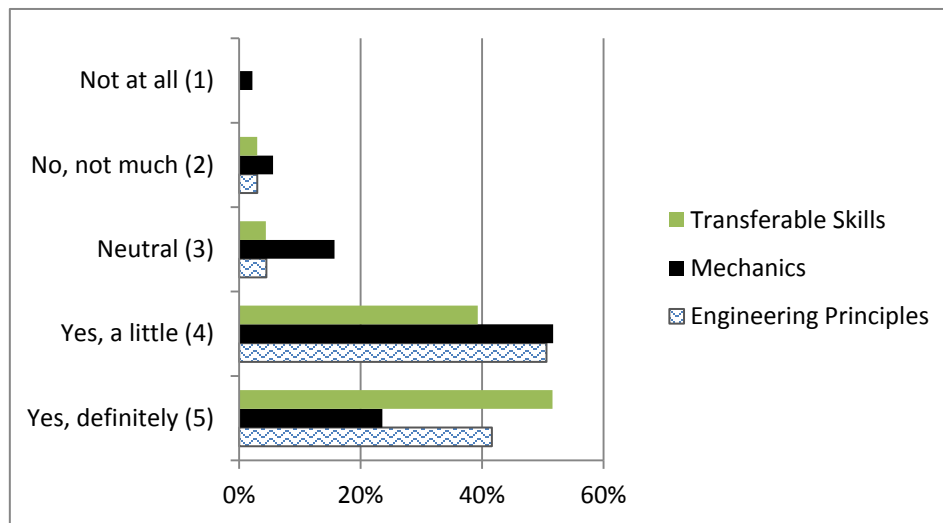
Given such freedom, it is not surprising that some within this relatively large cohort will not pull their weight. Asked how many individuals within their team did less than half the team-average man-hours, were regularly absent or failed to deliver tasks, the survey returned that 57% had experienced an even work distribution, 22%

had one weak member and the remaining 11% had two or three within their number. The majority claimed to have spent a useful amount of time participating in the project. 64% had been active at some point on all five days and over half had spent between 15 and 25 hours working, and 5% more than that.

4.2 On Learning

Students were asked if the project had enabled them to learn or consolidate knowledge of engineering principles, and mechanics and if it had been effective for improving transferable skills such as researching, communication or IT and rate their perceptions on a simple 5-point Likert scale. There was spectacular agreement in all three sections and the data are compiled in table 1.

Table 1. Perceptions of improved understanding or ability in three aspects.



4.3 On Commitment and Community

Helping students feel engaged with and committed to both the School and the profession was one of the central aims of the project. Education need not be dull or boring and it is well known that humans do their best work in a lively and enjoyable atmosphere. It is therefore, of some concern that engineering coursework can so rarely be described as enjoyable: consider writing the average laboratory report, for example. The results of this survey were different: asked “on the whole, did you enjoy the task?” 90% said yes and of the remainder, 8% were neutral, and this was backed up by the enthusiastic responses to a supplementary free text question asking “what was the best thing about the project”. Almost all respondents wrote something and the overwhelming majority talked about things like working together as a team, exercising creativity in an unconstrained environment, seeing a design through to fruition and being allowed to put theory into practice.

The questionnaire went on to compare this method of learning with other more conventional styles and to enquire whether they would have preferred more staff interventions and support but, there was overwhelming support for the status quo. Asked “would you have preferred more formal class sessions in the project?” 75% said no!

On the wider aspects of engineering, and, postulating that a good experience here might encourage better engagement in the more traditional engineering sciences, students were asked if the project had made them more or less interested in Mechanical Engineering: the results were 71% more interested; 27% neutral and 1% less interested.

5. Conclusions

The obvious enthusiasm derived from work like this is undeniable. External evaluation [8] had already shown that there is a strong consensus regarding the benefits of the module, not only between staff and students, but also with the information on the module feedback forms from previous years, information freely given in the student survey and copious anecdotal evidence. Taking a break from conventional teaching to incorporate team-based project work where staff and students work together in a competitive environment appears to improve relationships and sets students at their ease. The reported capacity for learning in three separate aspects is

encouraging. More important, students appear to thrive on exercising creativity, and for most, this, coupled with the competitive element is a strong motivator that tends to compensate for other course elements they find less exciting. The authors are confident in having met the intended outcomes.

The catapult project has improved on the original model. In particular, it has introduced a stronger element of engineering science and the application of newly learned CAD skills. An unexpected bonus was the additional learning that surrounded the use of the spring. Many variations on this basic theme Model – design – manufacture – build – test – compete, are undoubtedly possible and could be tailored to any engineering discipline and tuned to whatever level.

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Authors

Principal Author: Peter Willmot holds a PhD in Mechanical Engineering from the Loughborough University. He is a National Teaching Fellow and Fellow of the UK Higher Education Academy and a Chartered Design Engineer. For many years he headed the degree programmes in Mechanical Engineering at Loughborough.

Co-author: Tony Sutton is a University Teacher and former programme director of mechanical Engineering holds a first class BSc (Hons) degree in Mechatronics from De Montfort University in Leicester. He is also a Fellow of the Higher Education Academy and a member of the Institution of Electrical and Electronic Engineers.