Accelerating the Development of Engineering Judgment in Students through Inquiry-Based Learning Activities

Lt. Col. Jakob C. Bruhl, U.S. Military Academy

Lieutenant Colonel Jakob Bruhl is an Assistant Professor in the Department of Civil and Mechanical Engineering at the United States Military Academy, West Point, NY. He received his B.S. from Rose-Hulman Institute of Technology, M.S. Degrees from the University of Missouri at Rolla and the University of Illinois at Urbana/Champaign, and Ph.D. from Purdue University. He is a registered Professional Engineer in Missouri. His research interests include resilient infrastructure, protective structures, and engineering education.

Dr. James Ledlie Klosky, U.S. Military Academy

Led Klosky is a Professor of Civil Engineering at the United States Military Academy at West Point and a past winner of ASEE's National Teaching Medal. He is a licensed professional engineer and works primarily in the areas of infrastructure, subsurface engineering and engineering education.

Capt. Todd Mainwaring P.E., U. S. Military Academy
Prof. Joseph P. Hanus, U.S. Military Academy

Colonel Joseph Hanus is the Civil Engineering Program Director at the U.S. Military Academy, West Point, NY. He received his B.S. from the University of Wisconsin, Platteville; M.S. from the University of Minnesota, Twin Cities; and Ph.D. from the University of Wisconsin, Madison. He is an active member of ASEE and is a registered Professional Engineer in Wisconsin. His research interests include fiber reinforced polymer materials, accelerated bridge construction, and engineering education.

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ABSTRACT

It is well known that engineering judgment is critical to effective engineering practice, particularly when design thinking is required. As computer-aided design tools have made detailing far more automated, engineers are being asked to take on higher-level tasks earlier in their careers, necessitating the development of this judgment in undergraduates. This clearly has become a priority for many programs, as evidenced by the growth of project-based learning. Developing this type of judgment and creativity is challenging, but inquiry-based learning will play an important role and well-tested tools for inspiring new types of knowledge acquisition methods in our students are needed.

This paper describes hands-on, inquiry-based learning activities that were recently designed and implemented in the first mechanics course taken by students in the Department of Civil and Mechanical Engineering at the US Military Academy in part to help accelerate the development of students' engineering judgment. These activities enabled and encouraged knowledge acquisition through personal effort which inspires deeper inquiry. This introductory course combines statics and mechanics of materials: the activities described in this paper address both foundational topics. Inspired by inquiry-based learning techniques, these activities are student-focused rather than instructor-led activities and are somewhat open-ended.

The first activity required students to assemble an engine hoist and use four basic scales and basic concepts in statics to determine the weight of an engine block. Students then predicted what would happen to the distribution of the weight as the location of the engine block moved along the engine hoist arm, reinforcing the concepts of reactions and moments of a force. Another activity used an aluminum load cell with longitudinal strain gages to weigh the engine block. This activity reinforced the concepts of stress, strain, and Hooke's law while exposing students to the world of instrumentation and data acquisition for the first time. In another activity, students were asked to predict strains occurring within a beam in bending – before the concepts and theories of bending had been introduced. Challenging their previous knowledge about axial strain, the linear strain distribution through the depth of a beam was discovered by the students measuring strains at various points through the beam's depth. Expanding this knowledge in a following lesson, students were required to predict strains on beams of equal cross-sectional area but different shapes (rectangle, square tube, and I-shape). These beams were loaded and strains were measured allowing students to observe the influence of moment of inertia on strain and, therefore, stress. Each of these activities was rich in what might be called "second order" learning, exploring topics (things like Wheatstone Bridges and analog-to-digital data conversion) well beyond the basic concepts and theory being taught.

In addition to describing the activities in detail, this paper provides preliminary assessment data about the effect of the hands-on learning activities on specific learning objectives and more broadly within the context of developing judgment. Qualitative commentary on the use of these activities is also presented.

INTRODUCTION

It is well known that engineering judgment is critical to effective engineering practice, particularly when design thinking is required. As computer-aided design tools have made detailing and even complex analysis far more automated, engineers are being asked to take on higher-level tasks earlier in their careers, necessitating the development of this judgment in undergraduates. This clearly has become a priority for many programs, as evidenced by the growth of project-based learning. Developing this type of judgment and creativity is challenging, but inquiry-based learning activities (referred to in this paper as IBLAs) will play an important role and well-tested tools for inspiring new types of knowledge acquisition methods in our students are needed. This task of developing judgment is made more critical given the rapid advance of computer-based design, where failure to recognize bad outputs due to errors buried deep in the assumptions and inputs could have tragic consequences.

In an effort to address this need, and as part of a thorough revision of the mechanics curriculum[1], a series of hands-on learning activities were designed and implemented in the first mechanics course taken by students in the Department of Civil and Mechanical Engineering at the US Military Academy. These activities enabled and encouraged knowledge acquisition through personal effort which inspires deeper inquiry and were expected to help accelerate the development of students' engineering judgment. Inspired by inquiry-based learning techniques, these activities were student-focused rather than instructor-led activities and were designed to be require students to make predictions prior to taking measurements and were intended to be somewhat open-ended. Each of these activities was rich in what might be called "second order" learning, exploring topics well beyond the basic concepts and theory being taught. These activities opened exciting opportunities for instructors and students to reach further towards a holistic understanding of engineering, leading to broader inquiry and deeper conversations in the classroom.

BACKGROUND

Engineering judgment could be defined as the ability to recognize and/or predict, through a combination of intuition, insight and experience, the probable outcome of an analysis, design or process. As Schmidt (2014) explains, the problems that practicing engineers typically face are not well-structured problems with clear solutions[2]. The engineering theories, concepts, and design procedures learned in academic courses provides the necessary foundation upon which to solve these problems but experience is necessary for an engineer to "discern quickly what is important in a specific set of circumstances and then select a suitable way forward." While this might suggest that engineering judgment can only be developed outside the classroom through direct contact with design or other project work, that experience is often costly in terms of mistakes and diminishes the value of the new engineer to a given project as they are forced into the role of observer due to lack of experience. While the authors will definitely not argue that it is possible to replace field experience with classroom activities, we are obliged by the rapid development of design tools and quickening thought-to-product cycles to do as much as we can during a student's education to not just plant the seeds but actually grow design thinking and engineering judgment.

As Davis (2012)[3] explains, “one who otherwise knows what engineers know but lacks ‘engineering judgment’ may be an expert of sorts, a handy resource much like a reference book or database, but cannot be a competent engineer.” In other words, it is not enough for an engineer to know concepts and perform calculations; it is imperative that the engineer exercise sound judgment in the application of those concepts and the interpretation of those calculations. Davis goes on to explain that students of engineering need more than textbooks from which they can gather facts. They need capable teachers and hands-on learning experiences. To learn the discipline, Davis argues, students “must solve problems, participate in discussions, work in labs, write reports, and otherwise practice the discipline, under the supervision of those who are adept at it.” Finally, he states that as judgment is developed, learning engineering theories and concepts becomes easier, eventually enabling self-directed learning.

These drivers encourage educators to rely more and more on open-ended classroom activities that emphasize hands-on learning and IBL methods, both of which encourage student engagement and discovery while at the same time building design thinking and engineering judgment. It has been shown that discovery learning (or more broadly, active learning) improves student learning[4]. Using data from over 200 studies of active learning and lecturing, Freeman et al. (2014)[5] conducted a metastudy concluding that exam scores improved by 6% when active learning was used rather than only lecture. In fact, students in classes using only lecture were 1.5 times more likely to fail than if they were taught using active learning techniques. Active learning does more than boost student performance in class, however. These activities promote development of metacognitive skills (i.e. knowing about what you know) which are vital for self-regulated learners[6].

One common concern with learning activities such as IBLAs is the time required to complete these exercises. It is true that such activities provide the instructor with less time for formal instruction at the chalkboard or presenting a lecture. Recent advances in flipping the classroom point to ways of creating time to make these activities possible, exchanging the traditional presentation of theory in the classroom for applied exercises through the use of out-of-class materials that cover the theory[7, 8]. While this paper doesn’t cover the flipped classroom, it is important to note that these techniques are critical to creating the space necessary to implement the activities proposed.

In addition to getting the student meaningfully involved as early as possible, carefully planned IBLAs attempt to leverage divergent learning opportunities. Several foundational theories describe the various learning styles that students can possess, and how instructors can leverage the inertia behind those innate learning styles by shaping their teaching styles to "cut with the grain" instead of against it.. Felder and Silverman’s Dimensions of Learning and Teaching Styles[9] and Fleming and Mills’ VARK typology[10] were particularly significant in the development of embedded learning activities. Several studies[11, 12, 13] have shown that most students tend to be visual, sequential, and active in their learning orientation, and that many students also possess a kinesthetic learning style. Indeed, many design courses are designed with these theories in mind—at least in the build and test phases of the projects. Incorporating an active instructional method in the early stages of student development leverages its benefits when most needed – at the difficult phases when the students are learning new material[14].

Many educators have taken active learning, of which IBLAs are a specific type, beyond individual classes and into entire programs. Hesketh, Farrell, and Slater describe their work across several different classes (fluid dynamics, heat transfer, and a freshman cornerstone course) in introducing experiments to provide opportunities for inductive learning[15]. Inductive learning has been shown to aid long term retention and transfer of concepts. In a program which embraces project-based learning, both retention and transfer are needed so that the learned material can properly be applied to the design effort at hand. One of their techniques that was utilized in the current work was asking students to predict various outcomes beforehand and then confirming (or denying) their understanding of the material after the IBL activity had been completed. The biggest advantage in doing this was that the students' curiosity was elevated and they were more engaged with the material.

Lastly, it is worth mentioning the body of literature on hands-on-learning, including the Hands On Mechanics effort[16, 17, 18]. These demonstrations in mechanics are highly adaptable to the IBL approach, and in fact the early efforts towards the beams in bending IBLA are described in some detail by Griffin et al (2003)[19]. Vander Schaaf and Klosky maintained that once a student begins to lose connection to the topic, the likelihood of disengagement is high and, therefore, it is important to seek ways to engage student interest, build enthusiasm, while reinforcing basic knowledge in mechanics[16]. They believed that direct, interactive demonstrations of basic concepts where most effective when the following four principles were considered:

1. Push students towards an active mode of learning,
2. Excite interest in the topic,
3. Link theory to the student's natural knowledge, and
4. Engage global learners fully.

That said, IBLAs push considerably beyond these four principles for classroom demonstrations, as discussed in the next section.

DESIGN OF LEARNING ACTIVITIES

The authors have many years of collective experience with in-class demonstrations conforming to the four principles stated above. However, there was strong consensus that simply demonstrating something to a student, no matter how engaging, wasn't going far enough towards meeting the twin goals of growing design thinking and engineering judgment. Thus, instructor-led demonstrations still are an important part of the kit-bag, but when time and resources are available, those demonstrations should go a step further – putting the control of the exercise in the hands of the student. This casts the student in the role of explorer rather than audience member, doing not receiving. Where is the instructor in all of this? Facilitating, guiding, encouraging and at the same time making sure nothing catches fire or falls on a student! With that in mind, the authors proposed the following updated guiding principles for the design of IBLAs:

1. **Reality**. Every activity should, to the greatest extent possible, involve real engineering applications and problems, preferably familiar to the student and not overly complex. From engine hoists to helicopter blades at rest to engine components, there are many great examples available and many students choose to study engineering because they

wanted to know more about those sorts of things. Avoid “a potato in space is impinged on by an arrow” and turn to problems with a real value proposition for the learner.

2. **Let the problem lead**. Good engineering work begins with defining the problem thoroughly and determining what it is you are after. Let the students do that and discover a need for the background and theory. For example, have them discover the utility of a free-body-diagram when trying to predict what a scale will read in a particular loading configuration.
3. **Use lesson objectives to guide, in a specific way, what the activity should be**. These activities, while hopefully enjoyable to students, are not created simply to be fun. Each activity must be carefully designed to achieve specific learning objectives.
4. **Test, test, test!** The IBLA may look like a brand-new voyage of discovery, but it shouldn’t be that way for the instructor! Like a murder-mystery that has been running on Broadway for 10 years, it should be the audience not the actors who are surprised by the outcomes. This gets particularly important when things like electronic instruments or combined loads are present.
5. **Make sure the timing works**. This means making the design of the IBLA of appropriate ambition and taking action as the facilitator to keep things moving in the classroom.

This paper describes four activities from an introductory, sophomore-level, engineering course: MC300, Fundamentals of Engineering Mechanics and Design, that were designed using the five principles listed above. This course is taught to engineering and non-engineering students and combines statics and mechanics of materials. The course was recently redesigned to emphasize hands-on learning experiences for students[1]. Following IBLA techniques, each of the four learning activities that follow are student-focused rather than instructor-led activities and many are somewhat open-ended.

INFLUENCE OF LOAD LOCATION ON REACTIONS

Among the most fundamental concepts a young engineer must grasp is the idea of a normal force. Instructors can convey Newton’s Third Law – for every action there is an equal and opposite reaction – to show that the weight of an object must be counteracted to maintain equilibrium. Free body diagrams can display downward forces resisted by upward forces from the ground. Students can relate the concept to an everyday bathroom scale. An instructor inquires: what is it measuring when they step on it? Their weight or the force from the earth? In that case, it is simple, they are equal, but real-world objects distribute their weight and loads over areas or across multiple points. To develop a student's intuition regarding normal forces, they must see how a complex object conveys it’s self-weight and applied loads to the ground.

To demonstrate the distribution of reaction forces for a real object, an engine hoist, bathroom scales and an engine block are used to develop an engineer's judgment of normal force magnitude and distribution. This exercise is scheduled to occur in a lesson immediately following lessons on static equilibrium and free body diagrams. Students enter the classroom and in the center of the floor is an engine hoist and an engine block (see Figure 1).

Figure 1 The parts for the influence of load location experiment

The hoist's legs rest on four casters which serve as the frame's contact with the ground. Armed only with knowledge of free body diagrams and static equilibrium, students must answer the following questions:

- What is the weight of the engine hoist?
- Where is the center of gravity of the engine hoist?
- What is the weight of the engine block?
- What happens to the reactions if the engine hoist arm increases?

Tools are provided to help answer these questions – weight scales, measuring tape, plumb bobs, carpenters levels, chalkboards and calculators – but information that is typically given in a problem statement is now a part of the problem. How would you measure these things? This is the start of intuition. Students quickly arrive at the simplest conclusion: lift the hoist onto four bathroom scales, one placed under each caster.

An important discovery is that the weight measured by each scale is not equal, front to back or left to right. A relevant discussion of the precision of measuring devices and environmental conditions (unlevel floors, for instance) follows, further developing their understanding of the real world. What's more, students now see that this three-dimensional object's weight is the sum of each scale, but that weight is not evenly distributed. This leads many curious students to wonder: why? Calculating the location of the center of gravity (COG) using equations of equilibrium and a free body diagram answers this question. The hoist boom, piston and support are all shifted toward the rear of the frame.

Calculations confirm that, indeed, the COG is approximately 18 inches from the rear wheel (the front and back wheels are 60 inches apart.) Most students have been introduced to the concept of COG in physics course and correctly assume that the COG is nearer the back of the hoist. This quick activity reinforces the students' intuition.

This intuition is further developed when the engine block is introduced. Before lifting the engine, students are asked to consider: how will the location of the suspended engine block affect the readings of the individual scales beneath each wheel? This creates another judgment-developing situation. Students make predictions and then observe how the location of the load, relative the hoist's COG, affects the scale readings. The hoist boom is in its shortest setting as students lift it off the ground. They can see the scales change as it rises into the air (Figure 2). Its weight is the difference from the recorded hoist weight, but now in this particular configuration, each scale is almost equal. The students may have correctly predicted that the front scales would change more than the rear because of the location of the engine and this activity reinforces that knowledge. However, some students may have predicted the opposite and the activity now corrects a misconception. Subsequent discussion includes why the designer would want the load to be evenly distributed in a setting which mechanics would lift the heaviest load (up to 2000 lbs).

Figure 2 The Engine is hoisted and reactions at scales are read

With this new sense of engineering intuition, students must predict the reading of the front and back scales if the boom arm were extended to its furthest length. They have just physically observed that adding weight to the arm shifts the normal forces towards the front wheels, so they know this should continue, but by what magnitude? By drawing a free body diagram and solving equations of equilibrium predicted values are obtained. The lesson concludes by changing to the longest setting, lifting the engine and verifying their calculations with the scale readings. The numbers will most likely be slightly different than the predicted values (within 5-10%) which provides an opportunity for an important discussion about the precision of measurements and how many significant digits to report.

This entire exercise takes about 55-minutes, has students actively involved in the experiments and discovery the entire time, and provides practical reinforcement of fundamental concepts in a way that cannot be achieved simply by working example problems. In addition to reinforcing concepts, this exercise facilitates important discussions about predictions, precision of measurement, and the physical environment.

MEASURING STRAIN TO CALCULATE AN OBJECT'S WEIGHT

Using the same hoist and engine block from the reactions exercise, a simple IBLA was designed to reinforce the concepts of stress and strain and introduce students to instrumentation - namely the strain gage. The objectives of the lesson were:

- Apply Hooke's Law to a real-world situation
- Calibrate a simple instrument and determine Young's Modulus
- Measure the weight of an unknown object

To accomplish this, a simple 6061-T6 aluminum "dog bone", as shown in Figure 3, was machined from 0.25 x 2 in flat stock, having a 0.25 x 0.25 in throat on which strain gages were mounted. The dog bone was hung from the same engine hoist used in the reactions lesson (Figure 4), being very careful to use connections that did not transfer moments to the instrument (hence the shape of the instrument). In our case, clevises hanging from chains worked well for this no-moment connection. Further, a dummy set of two gages were mounted on a separate piece of the same material (the top piece in Figure 3, which happened to be a preliminary version of this instrument which did not function as expected). This dummy piece provided a full bridge with temperature correction. It is worth noting that numerous initial attempts to make this "simple" demonstration work were unsuccessful due to a variety of errors, from uncorrected resistors to insufficient strains in the original instrument; testing of hands-on activities is absolutely essential prior to taking it live in the classroom[17]. Further, depending on the configuration of the readout device, half bridges may report double the actual strain.

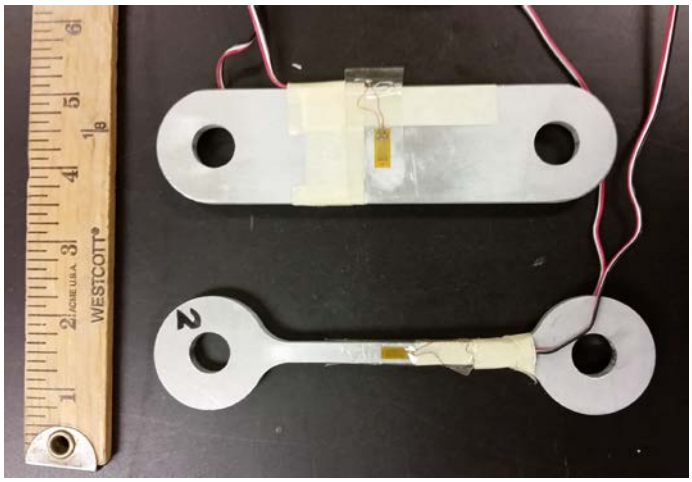


Figure 3 Dog Bone gage (at bottom) and temperature-correcting dummy gage (at top)

Figure 4 The engine hanging from the Dog Bone.
(Note connections designed to prevent transfer of moment)

Once the gage was mounted properly and hooked up to the readout, students were given an introduction to strain gages and then asked to take a look at the device and predict what the strain would be when a 100 pound calibration weight was hung from the instrument. If desired, the instructor could spray paint poorly "NIST Certified!" on the gym weight and use that for a jump-off point for a conversation about standards of weights and measures and the reliability of weights of unknown provenance obtained online marked "100 Pounds". While that is a perhaps planted and somewhat humorous approach, it is true that, if the instructor properly manages the time, IBLAs offer exceptionally rich opportunities for exploring the world of engineering beyond the bounds of specific objectives of the activity.

Generally, the student determination of the likely strain, even when properly computed, will vary slightly from the measured strain, especially for aluminum since the modulus can vary quite a bit depending on the alloys and other factors. To resolve this, the 100 lbs is taken as a standard and used to determine a calibration factor for the instrument. The unknown weight, in our case an engine block (used because it adds realism to the engine hoist scenario) is hung from the same instrument using a safe, appropriate harness and lifting the engine off the floor only a very short distance (perhaps an inch), for safety. Students are asked to predict the reading on the strain gage readout based on the weight determined in the reactions lesson and then use the calibration factor to find the actual weight of the engine block, usually a couple of pounds different from the reactions lesson determination. A discussion follows about stress, strain, strain gage uses and which method – the reactions lesson method using spring scales or the current lesson with the dogbone – likely yielded the more precise measurement. Students generally arrive at the fact that the strain gage, which has been calibrated and is more precise, yields a more precise measurement than the four uncalibrated bathroom scales.

DISCOVERING STRAIN DISTRIBUTION IN BENDING

On the day that flexural theory is scheduled to be described in class, students enter the classroom to discover an experiment set-up for groups of 3 or 4 students to complete. They find an aluminum beam with a rectangular cross section spanning two desks (see Figure 5). The beam is supported at both ends in a way that prevents vertical displacement but permits rotation - a simply supported beam they later learn. The beam looks like a patient in the intensive care unit of a hospital with wires coming from mid-span connected to readout boxes. Having been introduced to strain gages in the lesson described above, students quickly discover that the beam has a strain gage on the top surface, one half-way down the side, and a third on the bottom surface. The students are familiar with the strain readout box from the previous exercise, but the switch-and-balance box is an unfamiliar piece of equipment. The instructor provides a brief explanation and instructions for use.

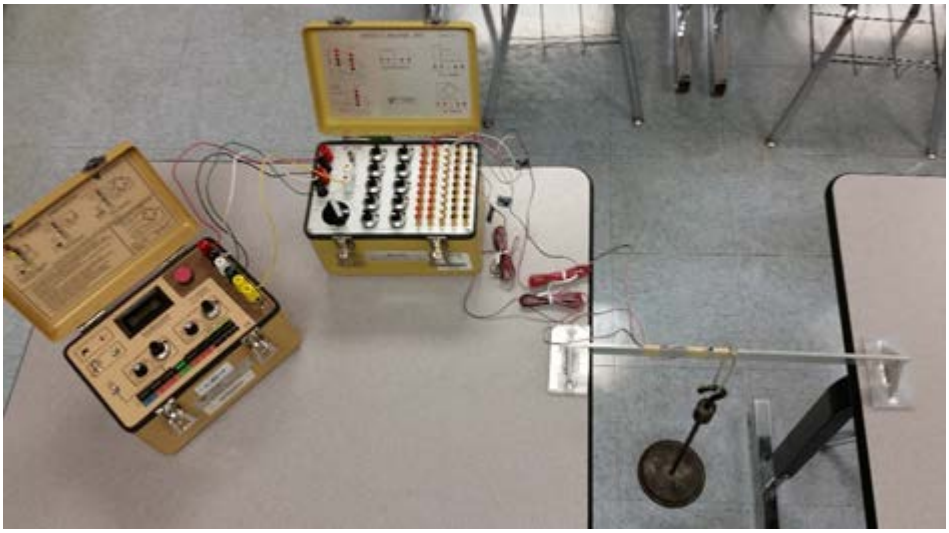
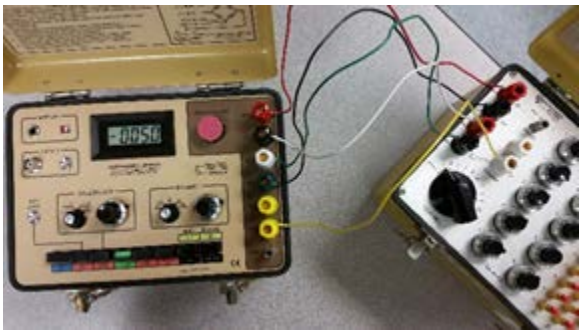


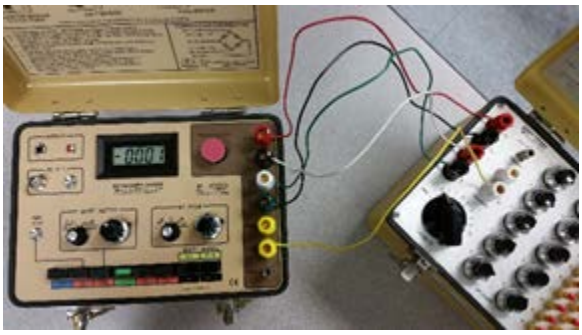
Figure 5 Setup for strain distribution in bending IBLA

Before conducting the experiment, students are asked to predict what the relative strain at each of the three locations will be when a mass is hung from the beam at mid-span. Because the only types of strain that they have learned about to this point is axial normal strain and the associated transvers strain due to Poisson's effect, many students predict that the three measured strains will be equal. Students are required to discuss their prediction with the others in a group and come to a consensus prediction. For some groups, students understood from the lesson's reading that normal strains vary through the depth of a flexural member and will explain this to other members of their group, using sketches or hand gestures in some cases. Some of these groups may be unsure of which strain will be largest while other groups will conclude correctly that the bottom strain will be largest, the middle strain will be next largest, and the strain on top of the beam will be smallest.

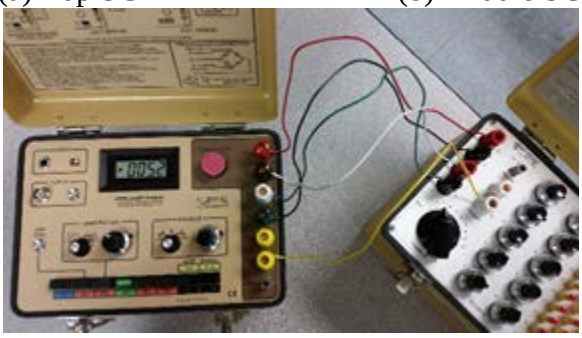
After coming to a group consensus, a student carefully hangs the 2-kg mass at mid-span and measured strains are recorded. Students observe that the top and bottom strains are approximately the same magnitude but opposite signs and the middle strain is approximately zero (an example is shown in Figure 6).



(a) Top SG



(b) Middle SG



(c) Bottom SG

Figure 6 Strain readings for 2-kg load

With this discovery, the instructor graphically summarizes the strain distribution through the depth of the section. Applying Hooke's law, the stress distribution is calculated from the strains. The location of zero strain and, therefore, zero stress introduces students to the concept of the neutral axis and demonstrates that it passes through the centroid of the cross-section. Using the stress profile and reinforcing that the basic definition of stress is a force distributed over an area, equivalent compressive and tension forces are calculated and the students observe that these are equal in magnitude, opposite in direction, and parallel. Recognizing this as a force couple, the concept of an internal bending moment is discovered. Building on this understanding, the instructor defines the elastic flexure formula and the students return to the experiment but now to predict strains when 4-kg and 6-kg loads are added.

The groups perform calculations using the elastic flexure formula and Hooke's law and then read strains at each load increment, record them, and compare them to the calculated values. In doing so, the validity of these calculations are reinforced and the linear relationship between load and measured strain is observed. This leads to a short discussion about the validity of these equations in the elastic region of behavior. Rather than simply being an assumption listed on the chalkboard, the students have now observed the linear elastic relationship. In this course, the elastic flexure formula is not derived in class but its associated assumptions and limitations are emphasized. In addition to discovering principles about bending mechanics, precision of measurements is reinforced as measured strains differ slightly between groups and measured strains are not precisely the same as predicted values.

DISCOVERING THE INFLUENCE OF MOMENT OF INERTIA ON BENDING STRAINS

Students enter the classroom for this lesson and are confronted with a nearly identical setup to what they saw in the bending strain distribution IBLA, described above, but the setup now includes three different beams: the rectangular beam (from the previous activity), a square tube and an I-shaped beam. Figure 7 shows the activity set up. Each beam is composed of aluminum and all have approximately the same cross-sectional area (0.25-in^2). Building on the intuition developed in the strain distribution in bending IBLA, this activity develops the students' judgment about the influence of a flexural member cross-section shape and expands their understanding of the second moment of area (the area moment of inertia). Previous lessons covered shear and moment diagrams which illuminate the effect of load type/location on the internal forces of beam, but exactly what influence the member's cross-sectional shape has not been explored.

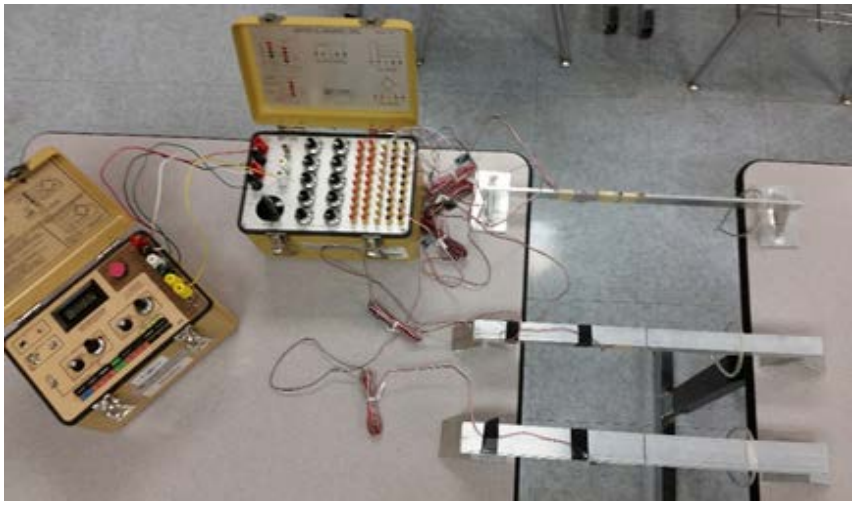


Figure 7 Setup for influence of moment of inertia IBLA

With little or no prior knowledge of area moment of inertia, students must decide which beam will experience the greatest strain on the bottom fiber if they are all under the same load conditions (Figure 8). Students often draw free body diagrams or use their hands to simulate loading the beams – examples of judgment being developed. They are using what they know to inform something they do not. Conferring with their peers before experimenting, students have an opportunity to share their knowledge and assumptions with others, and the group must come to a consensus prediction.

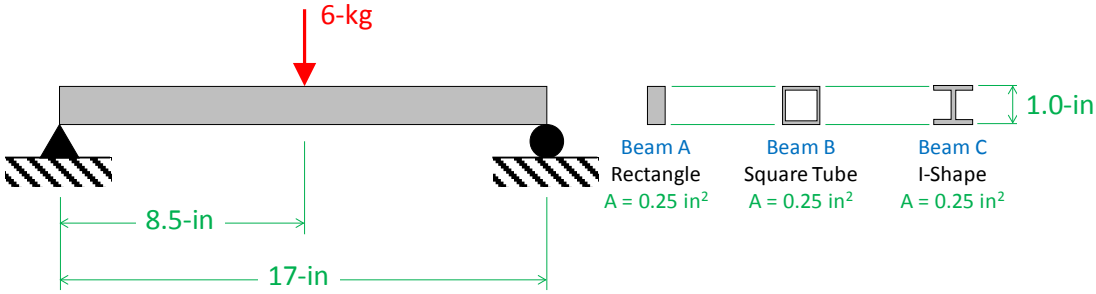


Figure 8 Given information for moment of inertia IBLA

The investigation of their prediction follows. Each beam is loaded at mid-span with a 6-kg load the measured strains are recorded. The data either confirms or denies their intuition. This is critical. With all other factors constant--loading, area, end conditions--students are faced with an undeniable fact: the *shape* matters. After all groups are finished with the experiment, the instructor leads a discussion about how to quantify the shapes resistance to bending - the area moment of inertia. Students use calipers to measure the beams, calculate the moment of inertia for each shape, and apply the flexural stress equation and Hooke's law to determine what the strain should theoretically be for each beam. By comparing these calculated values to the measured strains, the validity of the equations is confirmed and precision of measurement is reinforced.

This IBLA provides a powerful and memorably learning point. The concepts of flexural strain and stress now have tangible points to latch on to in the students' minds. When area moment of inertia appears in future equations, students now have a sense for what this term physically means. To improve this understanding in future semesters, a fourth beam has been added: a T-shape which requires students to apply the parallel axis theorem to calculate the area moment of inertia.

INITIAL ASSESSMENT

These learning activities were implemented for the first time in the Fall 2016 semester. The course had an enrollment of 251 students and was taught by 9 different faculty with various backgrounds (one was in his first semester teaching, another was beginning his 21st year; eight were civil engineers, one was a mechanical engineer). Anecdotally, throughout the semester, the senior faculty were convinced that the excitement in the classroom and the discussions with and among students were more plentiful, richer and more engaging than in previous semesters. IBLAs seemed to inspire additional inquiry by students who were seeing engineering concepts not just as a theory with accompanying equations, but as tangible concepts that they could visualize because of these activities. To get a better indication of student opinion about the effectiveness of these activities, a survey was administered at about the mid-point of the course. Students agreed (4.2 / 5.0, n = 95) that the hands-on learning activities completed to that point were contributing to their learning. As shown in Figure 9, student opinion increased slightly (4.3 / 5.0, n = 227) by the end of the term when the same question was asked again on the course-end-feedback survey.

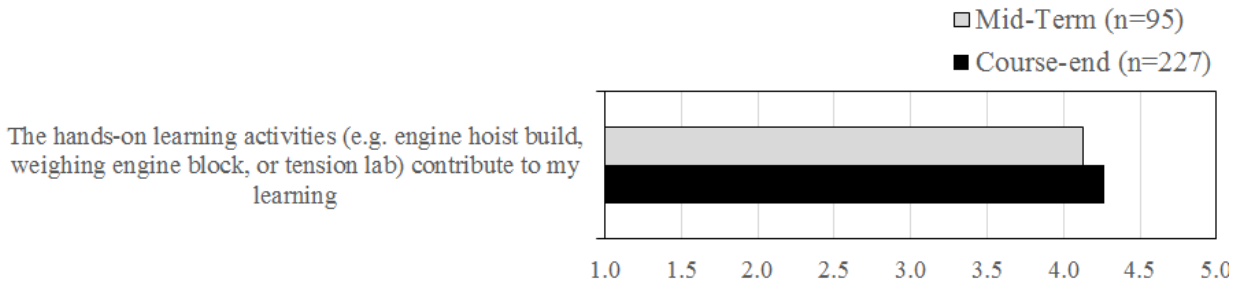


Figure 9 Student feedback on value of hands-on learning activities (1-strongly disagree, 2-agree, 3-neither agree nor disagree, 4-agree, 5-strongly agree)

Many of the student comments on the mid-term feedback survey reflected a positive opinion of the hands-on activities. A few representative examples are:

- The hands on demonstrations and classroom activities has helped me learn in this course.
- I believe the hands on demonstrations along with calculations that follow have helped me the most when trying to learn the topics.
- So far, I enjoyed the practical application of the problems.
- The hands on portion. As a very visual learner, building things helps a lot.
- Everything we do that is hands on. The labs are great.
- I like the practical exercises and study guide problems are the most beneficial to my learning. I like the practical exercises because they help me to better understand the equations and problems.

As part of the course-end-feedback, we sought to obtain better insights into why and how the IBLAs helped students learn the concepts most effectively. A word cloud from the comments (n = 227) is shown in Figure 10. The perceived benefits came from the opportunity to see real objects demonstrating the concept discussed in class. Many students appreciated seeing how theoretical calculations compared to measured properties - most of these reinforced the accuracy of calculations but highlighted the importance of measurement precision. These comments are important aspects of developing engineering judgment - seeing beyond calculations, developing a sense for physical reality, and understanding precision of calculated values.

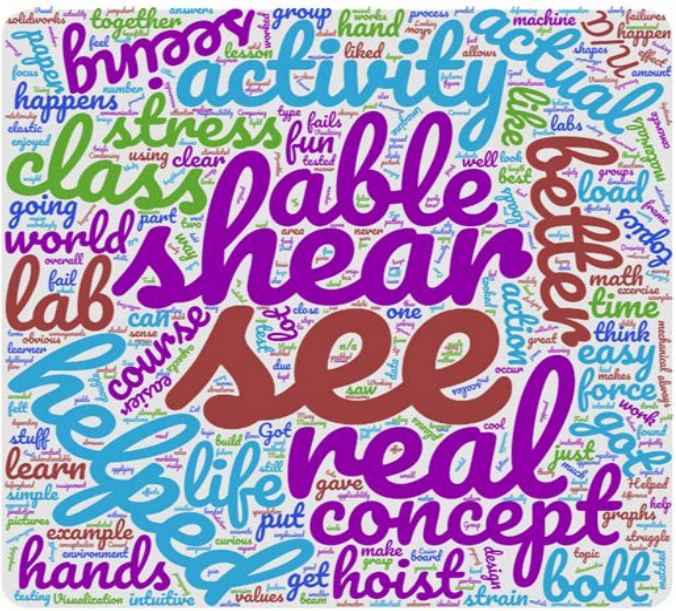


Figure 10 Word cloud from open-ended responses to the question: "What was it about the hands-on learning activity that made it the most helpful?"

FUTURE ASSESSMENT PLANS

While the assessment of this initial implementation is generally positive, the real test lies in our students' ability to apply these concepts in future courses, particularly in their capstone design project. It will be then that a sense for the engineering judgment developed throughout their education can be best observed. Of course, development of judgment and a sense for the connection between theory and practical application must continue to occur throughout their remaining engineering courses.

The course will continue to assess the effectiveness of these learning activities (and the others that were introduced but not discussed in this paper.) In addition, assessment of student conceptual understanding and application of mechanics principles in follow-on courses will be gathered to determine if there are any gains in academic performance that may be attributed to the increase in hands-on learning activities. Design courses and student products from their capstone course will be used to assess development of engineering judgement. This is admittedly very difficult to do and likely to be somewhat subjective. Nonetheless, student performance in future courses will be important data to assess the effectiveness of the learning activities described in this paper.

SUMMARY

The faculty and students involved in this first semester of incorporating extensive new Inquiry Based Learning Activities (IBLAs) perceived a highly positive outcome from this change. The integration of IBLAs, with their strong hands-on focus, generated excitement in the classroom and provided students in their first engineering course an opportunity to begin connecting engineering concepts to physical reality. The exercises described in this paper have been tested in real classrooms with real students from a variety of backgrounds (engineering and non-engineering majors). They were facilitated by faculty with a variety of experiences. This indicates that with appropriate resources, especially time for instructor preparation, and by following the design guidance provided, these or similar activities can be implemented successfully.

Additional resources, including student course notes, supply inventories, detailed set-up instructions, and lecture notes for each activity can be obtained the authors. Please contact them if you would like to try any of these exercises in your own classroom.

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