



## Discovery Learning Experiments in a New Machine Design Laboratory

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## Abstract

A new Machine Design Laboratory at Marquette University has been created to foster student exploration with hardware and real-world systems. The Laboratory incorporates areas for teaching and training, and has been designed to promote “hands-on” and “minds-on” learning. It reflects the spirit of transformational learning that is a theme in the College of Engineering.

The goal was to create discovery learning oriented experiments for a required junior-level “Design of Machine Elements” course in mechanical engineering that would give students practical experiences and expose them to physical hardware, actual tools, and real-world design challenges. In the experiments students face a range of real-world tasks: identify and select components, measure parameters (dimensions, speed, force), distinguish between normal and used (worn) components and between proper and abnormal behavior, reverse engineer systems, and justify design choices. The experiments serve to motivate the theory and spark interest in the subject of machine design.

This paper presents details of the experiments and summarizes student reactions and our experiences in the Machine Design Laboratory. In addition, the paper provides some insights for others who may wish to develop similar types of experiments.

## Introduction to Student-Centered Learning

In traditional college teaching most class time is spent with a professor lecturing and students watching, listening, and writing. Students work individually and cooperation is generally discouraged. In contrast, in student-centered pedagogical methods the focus of activity is shifted from the teacher to the learners.

Student-centered learning methods have been shown to have advantages relative to the classical teacher-centered approach in terms of a range of outcome metrics: short-term mastery, long-term retention, depth of understanding, critical thinking, creative problem-solving skills, positive attitudes toward the subject, and level of confidence in knowledge or skills.<sup>1</sup> Student-centered learning methods include *active*, *cooperative*, *collaborative*, and *inductive* learning.<sup>2</sup>

- Active learning is an instructional method that engages students in the learning process, in contrast with the usual lecture format where students passively receive information from an instructor.<sup>3</sup> In active learning methods students conduct meaningful learning activities; they think about and are connected to what they are doing. While this definition could include standard assignments such as homework, active learning most commonly refers to activities that are introduced in the classroom. The core elements of active learning are experiences that engage students. The more active the students are in the classroom, the more engaged they are in the learning process and the more they remember. Simulations of real experiences or “doing the real thing” involve students the most in the learning process and result in them remembering more of the underlying concepts to be learned.<sup>4</sup>
- Cooperative learning is a structured form of group work where students pursue common goals while being assessed individually. The most common model of cooperative learning includes five tenets: individual accountability, mutual interdependence, face-to-face interac-

tion, appropriate practice of interpersonal skills, and regular self-assessment of team functioning. The focus is on cooperative incentives, rather than competition, to promote learning.

- Collaborative learning refers to an instructional method in which students work together in small groups toward a common goal. As such, collaborative learning encompasses all group-based instructional methods, including cooperative learning. The core element of collaborative learning is the emphasis on student interactions, rather than on learning as a solitary activity.
- In inductive learning students are presented with challenges (questions or problems) and then allowed to learn the course material in the context of addressing the challenges. Inductive methods include inquiry-based learning, case-based instruction, problem-based learning, project-based learning, discovery learning, and just-in-time teaching. In problem-based learning students are introduced to relevant problems at the beginning of the instruction cycle to provide the context and motivation for the learning that follows. It is always active and usually cooperative or collaborative, and typically involves significant amounts of self-directed learning on the part of the students.<sup>5,6</sup>

Although some students may thrive more on one style than another, collectively these student-centered methods capture the essence of transformational learning. These methods serve as the background and basis on which the experiments reported in this paper are predicated.

### **Student-Centered Learning in the Machine Design Laboratory**

A new Machine Design Laboratory has been created in the College of Engineering at Marquette University. The 100m<sup>2</sup> Laboratory incorporates areas for teaching and training, and student-centered learning activities were specifically designed to foster student exploration with real-world hardware, machines, and physical systems. These activities promote “hands-on” and “minds-on” learning, and reflect the spirit of transformational learning that is a theme in the College of Engineering.

The Laboratory is equipped with workbenches, tools, instruments, computers, data acquisition systems, and an assortment of machines and mechanical systems to enhance creative exploration and investigation. The machines and systems include motorcycle engine assemblies (engines and transmissions), bicycles (including a chainless bicycle and a custom front-wheel-drive, rear-wheel-steer bicycle), a go-kart chassis, a Machine Fault Simulator training station, and various other systems (industrial gearboxes and gear-motors, automotive transmission and differential, drill presses, etc.)

The Machine Fault Simulator (SpectraQuest, Inc.), shown in Figure 1, is designed to create a range of common machinery conditions and faults, such as unbalance, misalignment, resonance, normal and worn bearing operation, normal and damaged gearbox operation, belt drive slippage and resonance, reciprocating mechanism operation, etc. The simulator can be preconfigured with components to present undesirable operating conditions, and then students are asked to identify the fault in a reverse-engineering approach.

The Laboratory is located next to a modern machine shop where students have access to fabrication equipment, ranging from traditional (lathes, CNC milling machines, etc.) to rapid prototyping (3D printing) machines. The Laboratory is close to a Materials Testing Laboratory, where students can use Instron tensile testing machines and other equipment.

## Discovery Learning Experiments

A first priority was to develop discovery learning oriented experiments for a required junior-level “Design of Machine Elements” course in mechanical engineering. In the past, students in the course were taught primarily by traditional class lectures. They saw a few examples of actual machine components and demonstrations, and were not engaged in laboratory activities; the primary focus was on lecture concepts and virtual designs. A survey conducted by the authors revealed that this approach is widely adopted at most universities. Very few schools have a dedicated laboratory associated with their machine design course.

Based on feedback from alumni, faculty, and industrial constituents, it was deemed essential to provide students in the course with more opportunities for practical experiences. In particular, there was a clear desire to have students in the course interact with physical hardware, use actual tools, and face real-world machine design challenges. Furthermore, it was important to embrace many of the student-centered learning methods described above in laboratory activities.

A list of desired core competencies relevant to machine design was compiled with the guidance of an Industrial Advisory Board (IAB) as well as input from several faculty members and mechanical engineering undergraduate and graduate students. New experiments were then created to intentionally immerse students in an environment where they would be forced to hone these core competency skills. These skills included the ability to identify machine components, know proper nomenclature, measure parameters (dimensions, speed, force), select components from catalogs for design challenges (understanding tradeoffs for performance, life, cost, etc.), distinguish between normal and used (worn) components, differentiate and predict proper and abnormal behavior, reverse engineer systems, develop engineering intuition, and communicate effectively in justifying design choices. These skills and others were identified by practicing engineers on the IAB as typically very weak and/or absent attributes of graduating engineers. Based on further input from IAB members, teaching assistants, former students, and faculty members, the initial experiments were refined and improved.

By design, the experiments incorporate several student-centered learning methods including active, collaborative, and project-based learning. They provide students with experiential learning opportunities that are similar to, but a subset of, those associated with industrial co-op, internship, design and research experiences. Working in teams, students face directed and open-ended challenges, many of which initially can be daunting. These challenges offer significant potential for learning, resulting in student confidence in solving machine design problems.

It was decided to replace the traditional laboratory report format for each experiment with two lab deliverables: (1) an end-of-lab session deliverable, which primarily poses qualitative challenges (for example, explain behavior) based on learning from lab experiences and activities, and (2) a post-lab deliverable, due one-week later, designed to connect the lab activities with lecture material, ask for more quantitative analysis, and prompt deeper thinking.

## **Experiments in the Machine Design Laboratory**

The experiments developed for the “Design of Machine Elements” course are described below. Teams of 2 or 3 students conduct the experiments in a 2 hour session each week. Each experiment lasts one to two weeks. The experiments are (1) Introduction to Machine Systems,

(2) Stress Measurements and Concentrations, (3) Fits and Tolerances, (4) Gears, (5) Flexible Components, (6) Bearings, (7) Bolts, and (8) Go-Kart Design.

## 1. Introduction to Machine Systems

This introductory experiment explores a range of topics related to machine components and systems. Students examine and interact with components and systems arranged at multiple stations. The systems include the Machine Fault Simulator (Figure 1), a drill press (Figure 2), a motorcycle engine (Figure 3), a chainless bicycle (Figure 4) that uses a driveshaft, and a go-kart chassis (Figure 5). The laboratory activities stimulate thought about machine design components and machines, emphasize the importance of proper nomenclature, and help gauge students' prior knowledge and experience with topics of machine design.

The purpose of the experiment is for students:

- to gain practical experience with various machine design components,
- to become familiar with how machine design components are incorporated into systems,
- to interact with tangible components and mechanical hardware, and
- to reinforce basic concepts of statics, dynamics, and mechanics of materials.

Students are prompted by questions leading them to investigate different characteristics related to the operation of the machines. For example, students are asked about the shifting process in the motorcycle engine transmission (what gear it is in, how to shift gears), about the different speeds available for the drill press (requiring students to measure the motor shaft speed, measure pulley diameters), about machine elements in the go-kart (nomenclature for different components) and possible reasons for design decisions, and about the operation as well as the advantages and disadvantages of a chainless bicycle.

## 2. Stress Measurements and Concentrations

The experiment reinforces prior material from a prerequisite course in “Mechanics of Materials” and supports review lectures on stress and strain. Key aspects of the experiment are (1) measurement of strain using strain gages (single axis and rectangular rosette gages) and photoelastic methods of loaded components, (2) effects of different kinds of loading (pure bending, pure torsion, combined loading) and (3) effects of strain concentrations on the measurement of strain and calculation of stress (holes, grooves, fillet changes.)

Students determine (1) the stress-strain relationship and critical section in a cast iron flat bar that has two geometry changes that incur stress concentrations (Figure 6), (2) the stress in a cantilevered aluminum tube under combined bending and torsional loading (Figure 7), (3) the stress distributions in small steel round bars with various geometry changes, such as holes, grooves, and fillets (Figure 8), and (4) the stress-strain behavior of loaded components via photoelastic methods (Figure 9).

An apparatus (Figure 7) was designed and built to allow the loading of a thin-walled aluminum tube under pure bending, pure torsion, and combined bending and torsion. Using a rosette gauge, students make measurements associated with different loading conditions and compare their results to their predictions. They are then prompted to understand differences between their predictions and measurements, raising issues of accuracy of material properties, strain gage measurements, data acquisition, etc.

Another apparatus (Figure 9) was designed and built to visualize the stress-strain loading using the photoelastic effect. Students explore the effects of torsional and bending loading on polycarbonate components viewed between two polarized sheets. They can visualize the distributed nature of loading and the magnification at stress concentrations.

The purpose of the experiment is for students:

- to experiment with methods used for measuring strain and determining stress,
- to investigate stress and strain relationships for loading bending, torsion, and combined loading, and
- to explore the effects of static stress concentrations in machine components.

### 3. Fits and Tolerances

This experiment investigates press fits of shafts and hubs. Students are presented with a precision ground rod and three coupler hubs, each with a slightly different hole diameter (Figure 10). By inserting the rod into the hole of each coupler hub, different press fits are achieved. The fits determine what, if any, torque can be transmitted. Students make measurements with calipers and use the Limits and Fits Tables in machine design handbooks and equations to find the maximum tangential and radial stresses that develop between the hub and shaft at the extremes of the allowances of the shaft and the torque capacity of the different fits.

Students also press fit an aluminum rod into a hole in a plate using an arbor press with a load cell attached to the ram (Figure 11). Students compare the measured force needed for the press-fit with a predicted force (from classical pressure vessel theory) based on measurements of the diameters and material properties.

The purpose of the experiment is for students:

- to gain practical experience with press and shrink fits,
- to become familiar with the use of different classifications for fits,
- to gain experience in designing and assembling a press fit, and
- to understand the relation between pressure vessel theory to stresses in interference fits.

The experiment helps students become familiar with the nomenclature and selection of different press fits; it also provides students an opportunity to “feel” the different kinds of fits.

Other questions that are posed include: (1) Do the assumptions underlying the table and equations apply to what was done? If not, how could the model be modified to improve the analysis? (2) Bearings commonly use very tight fits to ensure the inner race is properly located on a shaft. How are bearings installed and replaced on longer shafts? Is there a way to design the shaft to help with assembly? (3) Shaft designers often use chamfers to aid in assembly. How do chamfers help in assembling press fits? What are some advantages and disadvantages?

### 4. Gears

In this experiment students examine gears in different machine systems including a commercial gear box, a recreational vehicle leveler (Figure 12), a motorcycle engine transmission (Figure 3), and small geared motors (Figure 13). Students use the torque-speed tradeoff of gears to accomplish desired tasks, giving them experience with the fundamentals of gears and the design of gear assemblies.

The experiment has multiple goals, including the determination of transmission ratios, familiarization with different types of gears, and design of gear-train systems. Students are asked about different types of gears (spur, helical, worm, bevel, etc.) and tasked with identifying the type of gear as well as the situation in which the gear would be used. The students investigate gear trains in different real-world machines (commercial gearbox, RV leveler, motorcycle transmission, automobile HVAC baffle drive) to obtain transmission ratios and comment on design decisions (why was a spur gear chosen as opposed to a helical gear, why different materials were used for the gears, why the sizes chosen were selected, which gear or gears might fail first, etc.)

The purpose of the experiment is for students:

- to become familiar with different types of gears used in machine systems,
- to gain experience selecting appropriate gears from catalogs for specific applications,
- to understand the kinematics and kinetics of common (simple and compound) gears, and
- to design and analyze simple transmissions, appreciating space and assembly constraints.

The experiment has multiple stations. At a first station students are asked to identify different types of gears and to sketch a free-body diagrams that depict the forces acting gear teeth for different conditions. At a second station students select an appropriate set of spur gears (from catalogs) based on given design specifications, including speed and transmitted horsepower. At a third station students investigate the speed reduction in a geared motor assembly. Using a laser tachometer, they measure the speeds of the motor and output shafts, disassemble the assembly, count the teeth for each gear combination, and predict the train ratio. At a fourth station students assess the function of the meshed gears in a motorcycle engine transmission. The observations made in this portion of the experiment play a key role in the successful completion of a different transmission design problem. In a post-lab exercise, students are asked to design a 5-speed constant mesh transmission for the motorcycle engine using spur gears given several design criteria.

Students are also tasked with designing and building a gear-driven clock mechanism. Students have access to systems previously built to gather inspiration and insight. The students use CAD software to develop their designs, and then manufacture the gears using rapid prototyping 3D printers available in the department's machine shop. Students assemble the gear trains and test the accuracy of their clocks (Figure 14).

Students are challenged with a range of questions: (1) Why might an engineer choose to use a helical gear over a spur gear? (2) What are advantages and disadvantages of using lubricant? (3) Which gear is most likely to fail in a pinion and gear mesh? (4) Is backlash intentional in the design of the transmission? (What purpose might it serve?)

## 5. Flexible Components

This experiment investigates three flexible components – roller chains, mechanical belts, and wire rope – that are used to transmit power over longer distances than more rigid components such as gears. Additionally, due to some compliance they play a role in vibration isolation which often reduces design costs. Students investigate flexible components through activities at multiple stations.

At a first station students classify different types of wire rope, belts (V and timing), and roller chain (Figure 15). They are asked to identify a variety of samples of each type. At the second

station the interest is the design of the chain drive connecting the crankshaft and the transmission in the motorcycle engine assembly (Figure 16), which has been sectioned to expose its drive train. The focus of the third station is the double banded belt drive system (shown in the right side of Figure 1) in the Machine Fault Simulator when transmitting power.

At a fourth station students investigate the force carrying ability of a belt on a sheave (Figure 17). Students measure the tight and slack side tensions of the belt, and determine how the angle of wrap around a sheave affects tension. The mechanical belt apparatus is made of a drill press motor, a variable speed sheave with set screw, a V-belt connected to two force balances, and a weight wrapped around the sheave with a wire rope. It is designed to examine the relationships between power transmission, angle of belt wrap, and tension in the belt.

At a fifth station students design and assemble a chain drive system (Figure 18). They are provided with a set of sprockets and tasked with achieving a certain transmission ratio. Students select the appropriate sprockets and determine the necessary distance between the centers of the sprockets. They then bolt posts on to a steel plate with a matrix of holes, cut an appropriate chain length (requiring them to disassemble and reassemble chain link), assemble their designed system, and test it.

The purpose of the experiment is for students:

- to become familiar with flexible components used in machine systems,
- to gain experience identifying and selecting flexible machine elements from catalogs for specific application,
- to understand the design process for a flexible component system, and
- to give students an opportunity to interact with physical components: chains, belts, wire rope.

The activities of this experiment include component identification, selection, and design for power transmission, and integration of flexible components into machine systems. In a post-lab exercise students design a transmission system that uses chains and belts to obtain specified reductions. They select components from catalogs that achieve the desired speed reductions and are capable of withstanding the transmitted power.

## 6. Bearings

The goal of this experiment is to introduce students to various bearings used in mechanical systems and to provide experience in calculating the expected life of a bearing. The activities focus primarily on rolling contact bearings, or rolling bearings, and occur at four stations.

At a first station students identify different types of bearings and specific parts of bearings. At a second station (Figure 19) students spin (by hand) a flywheel that is mounted on a shaft supported by two bearings secured in housings. They listen for any particular sounds and place their hands on the bearing housings to sense any vibrations. They then swap out the bearing in the right-hand housing with a second bearing, and again listen and sense vibrations, noticing the dramatic difference between new and worn bearings. At a third station, students calculate bearing fatigue life using a web-based life calculator. (Bearing manufacturers, such as the Timken Company, offer web-based bearing life calculators that can be used to calculate the expected bearing life for a desired application.) At a fourth station students investigate bearings in different systems (Figure 20), including commercial gearboxes and a motorcycle transmission.



The purpose of the experiment is for students:

- to become familiar with the different types of bearings used in machine systems,
- to gain experience selecting an appropriate bearing for use in a specific application, and
- to gain experience selecting bearings from manufacturers' bearing catalogs for a given application.

In addition to identifying different types of bearings (using the correct nomenclature for types and parts), students must justify the situations in which different types of bearing are used. This is reinforced by having students discuss the reasons for bearing choices in several machines (the motorcycle transmission, gear-box, etc.). Students must select a specific bearing for a given task based on a desired life requirement and a given set of loads. Students are exposed to a faulty bearing to recognize the "warning signs" of a worn bearing.

## 7. Bolts

In this experiment, students explore the use of bolts as fasteners. In using a bolt to clamp two or more parts together, the clamping load elongates the bolt. By twisting the nut the bolt is elongated to near its elastic limit. As long as the nut does not loosen, the tension in the bolt remains as the preload or clamping force. The benefit of a bolted connection is that it can be disassembled without using destructive methods.

The experiment has multiple stations. At a first station students are presented with various bolts, a bolt grade chart, and thread pitch gauges. They are asked to identify and grade the bolts. This portion of the experiment involves classifying different fasteners in order to gain experience in properly measuring different parameters of bolts and cap screws to determine their nominal sizes. At a second station a test fixture is used to measure the clamping force using a torque wrench (Figure 21) and the turn-of-nut method. The fixture includes a plate with a hole in the center, a bushing with a mounted strain gauge, and a bolt and nut. In this part of the experiment students clamp bolts using different methods to determine if the proper preload (clamping force) has been achieved. Bolts and pieces are also over-clamped in order to show the importance of properly tightening bolts and fasteners. At a third station students investigate over-torquing a bolt. Torquing a bolt beyond its recommended limit can cause permanent deformation of the threads. If the bolt is stronger than the clamped pieces, over-torquing can cause plastic deformation of the parts, thus weakening and/or ruining them. In this part of the experiment bolts are purposely over-torqued to observe what happens to the bolt and the pieces being clamped.

The purpose of the experiment is for students:

- to gain practical experience with fasteners and torque wrenches,
- to become familiar with common thread sizes of fasteners,
- to investigate the strength properties of different grades of bolts,
- to measure clamping force and assess proper torquing, and
- to observe the effects of over-torquing.

Students obtain experience in torque, shear force, and clamping force measurements. They are exposed to different types of bolts and the correct nomenclature used to describe them. Students calculate the actual clamping force based on strain in the bushing using the torque wrench method as well as calculate the clamping force using the strain in the bushing using the turn-of-nut method. For two sets of data students prepare plots showing the clamping force vs. torque and plots showing the clamping force vs. angle, and interpret the results.

## 8. Go-Kart Design

In this semester-long design challenge, students are given the following information:

*A customer has requested assistance in designing a go-kart. The customer has provided general specifications and design considerations although there is freedom in the final design. The best design will be one that meets the customer's needs, remains within budget, and is simplest in design and functionality.*

*Design a custom, inexpensive, four-wheel go-kart to be used by a single driver on an ordinary go-kart track. Its most demanding performance requirement is that it be able to drive up a 20 deg slope at no less than 20 mph. An  $L_{10}$  life of 5 years at 50 weeks/year, 5 days/week, and 3 hours/day is desired for all components except for maintenance items such as tires, air filters, spark plugs, etc. The vehicle weight is limited to 300 lb (not including the driver) and the budget is \$1500.*

The project focuses on the powertrain and related components of the go-kart. The suspension, steering, and braking systems are excluded. The project is divided into five deliverables: (1) Design loads, (2) Engine/motor and clutch selection, (3) Drive/transmission selection, (4) Rear axle design, and (5) Final Report, including CAD model of the rear axle and final components (including powertrain design.)

Each student was required to complete the project, and fully justify all design decisions. The project served as a capstone experience, bridging many of the concepts of the course. One strong message that students drew from the experience was the reality of multiple designs – each with its own tradeoffs – that satisfied the challenge.

### **Feedback and Assessment in the Machine Design Laboratory**

This section of the paper summarizes some of the feedback from students who conducted the experiments in the Machine Design Laboratory. The “Design of Machine Elements” course has been run only once with the new experiments. There are no results of a longitudinal assessment study. In addition to direct questions to students (following each experiment), we solicited feedback through anonymous formal survey forms multiple times through the semester. Student comments were consistent with the feedback from the Teaching Assistants and directly expressed to the faculty.

Many students reported their enthusiastic reception to the laboratory activities and challenges, and felt it was the “driver” for the course. Some students with industrial coop and internship experience were elated to have “hands-on” laboratory experiences and enjoyed the open-ended challenges. A few students were much less comfortable working with tools and touching hardware (getting their hands dirty.) Even though they exhibited a more passive reaction to the experience during the laboratory sessions, their end-of-semester comments were overwhelmingly supportive. Many expressed thanks for the opportunity to have conducted the experiments, through which they became familiar with current practice in machine design and gained real-world experience, including the use of tools.

The Teaching Assistants provided valuable insight into the students’ work during the experiments and based on the laboratory deliverables. They reported several interesting quotes

from students about their reactions. They were mostly positive; some expressed frustration with the open-ended design challenges, especially the reality of multiple right answers.

Students performed better in experiments that required relatively few calculations during the laboratory sessions and leaned heavily towards open-ended hands-on activities (and liked those involving data acquisition). They preferred more quantitative analysis and design challenges pushed to post-lab deliverables. Accordingly, later experiments were modified to reflect this approach, with most of the required calculations supporting design decisions reserved for post-lab exercises.

The anecdotal comments do not represent a formal assessment based on student comprehension and assimilation of fundamental concepts. Toward this end, we look forward to the coming semester to acquire such information.

## Conclusion

This paper describes the details of the experiments and pedagogical approaches to student learning employed in a new Machine Design Laboratory at Marquette University. The educational benefits to students include (1) hands-on learning in a laboratory environment with real-world hardware, (2) directed and open-ended machine design challenges that promote active-learning and force out-of-the-box thinking, and (3) experience working in teams. The experiments provide students the opportunity to apply classroom learning in a real, functioning environment. The laboratory activities attempt to teach students the importance of logical thinking as well as develop intuition for the selection of different machine element components. The experiments are predicated on student-centered learning methods that are the cornerstone of modern engineering education practice.

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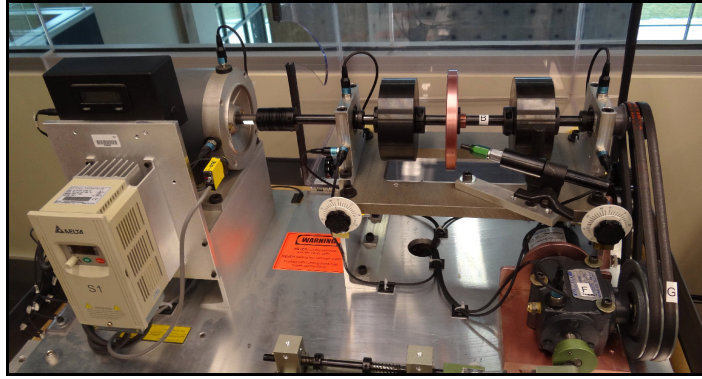


Figure 1: Machine Fault Simulator (SpectraQuest, Inc.)



Figure 2: Investigating the operation of a drill-press in Experiment 1.



Figure 3: Understanding the transmission in a motorcycle engine in Experiment 1.



Figure 4: Chainless bicycle in Experiment 1.



Figure 5: Go-Kart chassis in Experiment 1.

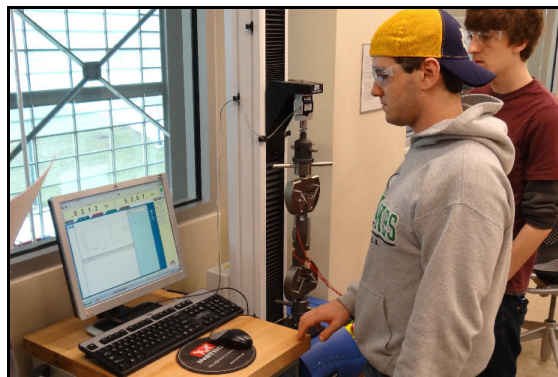


Figure 6: Measuring strain in flat bar with stress concentration in Experiment 2.





Figure 7: Measuring bending and torsional strain in Experiment 2.



Figure 8: Measuring strain in round stock with stress concentrations in Experiment 2.

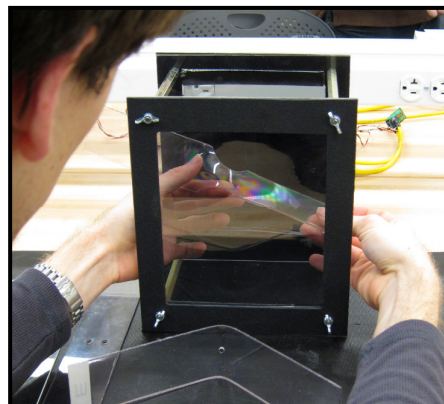


Figure 9: Photoelastic method to study strain of loaded components in Experiment 2.

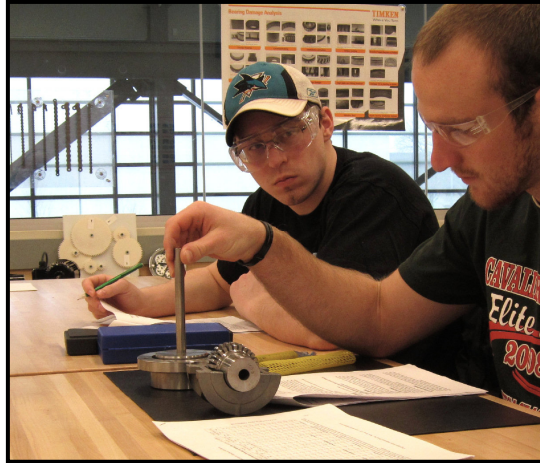


Figure 10: Checking fit of ground rod in Experiment 3.



Figure 11: Press fit using an arbor press in Experiment 3.



Figure 12: Investigating operation of an RV leveler in Experiment 4.



Figure 13: Counting gear teeth in HVAC baffle drive in Experiment 4.

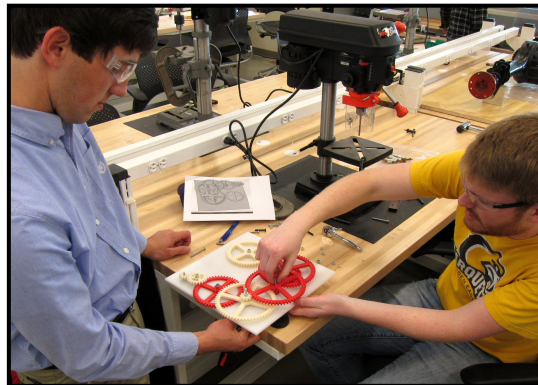


Figure 14: Assembling gear-driven clock mechanisms in Experiment 4.



Figure 15: Classifying wire rope in Experiment 5.



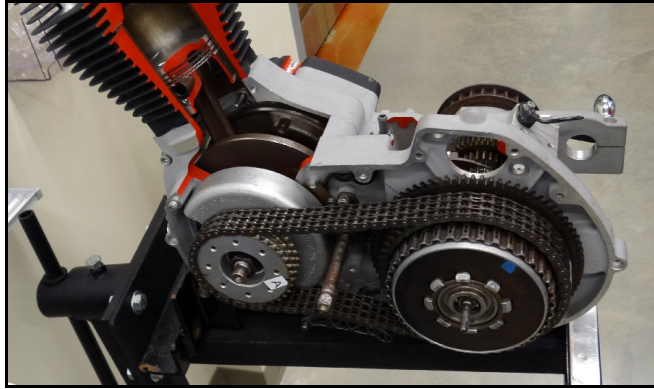


Figure 16: Sectioned motorcycle engine showing chain drive in Experiment 5.

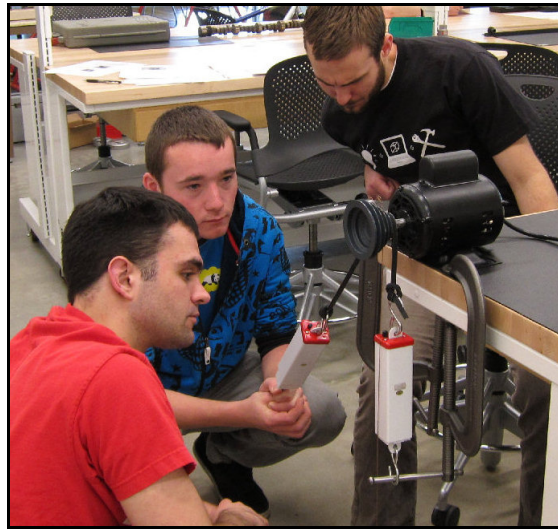


Figure 17: Investigating belt tension in Experiment 5.

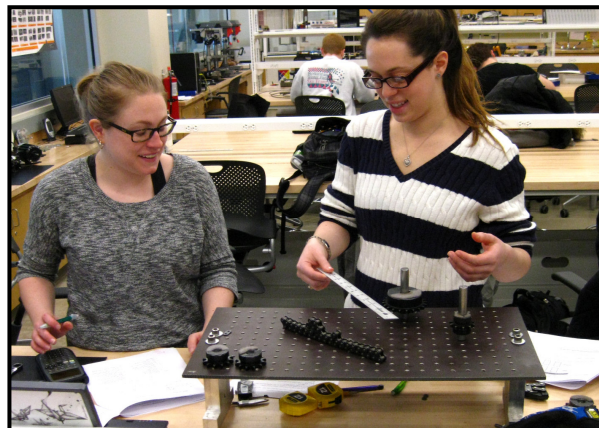


Figure 18: Designing and assembling a chain drive in Experiment 5.

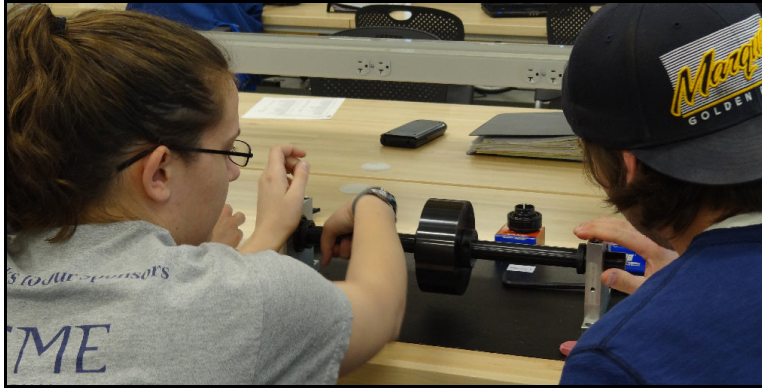


Figure 19: Investigating bearing operation in Experiment 6.

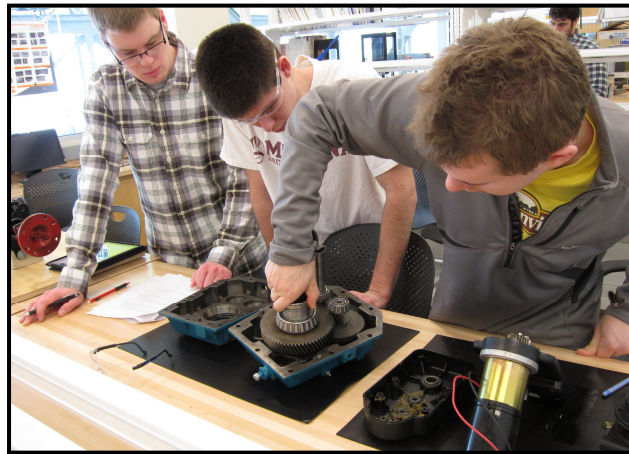


Figure 20: Bearing identification and selection in Experiment 6.



Figure 21: Measuring bolt clamping force in Experiment 7.