The Tinkerer's Pendulum for Machine System's Education: Creating a Basic Hands-On Environment with Mechanical "Breadboards"

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Abstract

The pendulum of engineering education is swinging from an emphasis of theoretical material to a balance between theory and hands-on activities. This transformation is motivated, in part, by the changing students entering engineering programs. Instead of a tinkering background with the dissection of machines and use of tools, students are now entering with computer, video games, and other "virtual" experiences. This focus has left a void in the ability to relate engineering principles to real-world devices and applications. In this paper, we introduce a new approach for filling this void in a mechanical engineering curriculum. In particular, we describe modifications and extensions to machine design courses to include hands-on exercises. Through the application of "mechanical breadboards," clear relationships between machine design principles and the reality of machine components are established. These relationships reduce the number of topics covered in the courses, but greatly increase the interest of the students and their potential retention of the material.

1. OVERTURE: INTRODUCTION

1.1 Motivation:

Engineering education is transforming from a theoretical emphasis to a balance between applied mathematics and science material and hands-on activities. Design components in courses are helping to provide this balance. Instead of relegating design courses to the last two semesters of an engineering program, many universities are spreading the experiences across the entire 4-5 year curriculum.

An example of this distribution of design courses is shown in Figure 1. This figure illustrates a spectrum of the current design education at The University of Texas (UT), Department of Mechanical Engineering. As shown in the figure, five-core courses of the curriculum include substantial design components. These begin with a freshman Introduction to Mechanical Engineering course. Students study a range of topics in this course, including survival skills (using library and internet resources, email, ethics, team skills, etc.); the engineering design process; engineering graphics, drawings, and solid modeling; the role of engineering analysis; and others. The topics in this course are integrated with a reverse engineering experience where student teams choose a mechanical toy or other device (e.g., a mechanical clock), predict how the device works, dissect it, analyze the functionality and simple physical principles, predict how it was fabricated, and suggest possible redesigns and improvements.
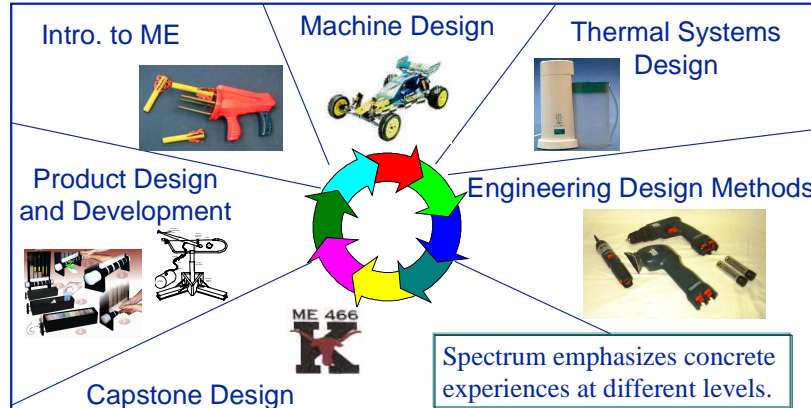
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Figure 1. Spectrum of engineering design activities at UT,
Dept. of Mechanical Engineering

Following the freshman year, students enroll in a number of basic and major sequence courses. Two courses, in particular, are Machine Design (or Machine Elements) and Thermal Systems Design, usually taken during the second-semester sophomore or junior years. These courses include fundamentals in machine components, solid mechanics, and thermodynamics, but they also focus on open-ended design activities to apply the material to real systems.

Besides the development of design components in supporting electives of these core courses, the design sequence at UT closes with two courses during the senior year. The first course covers design processes and methodology. Students learn fundamental product design principles and supporting techniques. They also apply the results to a more sophisticated reverse engineering and redesign project (Otto and Wood, 1997-2000.). In the second course, students complete a capstone experience on industrially sponsored design projects. Teams of 3-4 individuals carry a design problem from initial problem definition through to working drawings and initial prototypes. The results are presented and delivered to the industrial sponsors.

This description of the design sequence at UT illustrates one case where the pendulum has swung to include more physical interaction with the technology being studied. Much more work is needed to integrate design even more fully in the curriculum while still achieving a good balance. Yet, this case does illustrate a significant effort toward this goal.

One of the key motivating factors behind this effort is the changing student population entering engineering programs. In the recent past, a majority of the students could be expected to enroll with a significant history of "tinkering" with devices. This tinkering might include the dissection of devices just to see how they work, or the fabrication of tree houses, go-karts, etc. using basic tools and materials. Today's engineering student can't be expected to have this background or even to have ever even nailed two pieces of wood together. Our global society is much more information based, translating into significant computer and video experience on the part of the students. We are thus faced with the tinkerer's problem, i.e., how do we ground the students in engineering fundamentals while tying these fundamentals to actual physical hardware so that they may be retained and applied?

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In this paper, we discuss the evolution of the machine design courses at The University of Texas and the United States Air Force Academy (USAFA) to address this problem. These courses are usually taken during the junior year of a mechanical engineering program, and demonstrate an approach for including more of a hands-on emphasis.

1.2 Background and Issues:

Most universities that teach mechanical engineering include a machine design or machine elements course as part of the curriculum. Such courses usually focus on the material covered in classical texts such as those of Spotts (1997), Shigley (1989), or Juvinall (1991). These textbooks, for the most part, cover the fundamentals of solid mechanics, factors of safety, and the analysis of discrete machine components.

At the University of Texas, undergraduate mechanical engineering students enroll in a machine design class during the early part of their junior year. This course, known as ME 338 – Fundamentals of Machine Elements, focuses on a balance between solid mechanics theory and a survey of machine elements, such as gears, bearings, and springs. At USAFA, cadets in mechanical engineering take their machine design course during the first semester of their senior year. This course is referred to as EM 470 – Machine Design, and it also divides the course material between basic theory and a survey of elements. Thus, classically, emphasis of machine design courses has been on solid mechanics principles applied to individual machine elements.

The emphasis of machine design courses has its roots in material from the 1950's. These roots are important and have been evolved from the research in the field of mechanisms and machines. However, the classical emphasis of teaching machine design raises a number of issues in the contemporary engineering curriculum. For example, students are no longer tinkerers, by default. This characteristic results in a disconnect between the theory in the course and the reality of implementing machine elements in a device. Due to this disconnect, students are not successful in implementing the knowledge in follow-up design courses.

Likewise, students are not given many opportunities for making assumptions and performing estimation. While textbook problems may be repeated and solved by the students, they do not demonstrate an ability to apply the material to simple machines, such as mechanical toys or electromechanical kitchen appliances. The skills of taking a "real world" device, dissecting and filtering the information, and simplifying the results are not overtly fostered in the classical approach.

Another issue arising in machine design instruction concerns the coverage of different learning styles. Past student evaluations at UT and USAFA show that the interest in our machine design courses is not as high as we would expect. Machines are fundamental to mechanical engineering. We would thus expect machine design to be one of the most popular courses in the curriculum. The student evaluations do not support this expectation. An analysis of the evaluations shows that students are seeking a more hands-on approach, one in which they experience, hypothesize, and test actual machine systems, not just the theory of how they are designed.

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Figure 2 illustrates further motivation for promoting hands-on activities. The figure shows Kolb's model of learning, embodied by a cycle that begins with concrete experience, proceeds with reflective observation and conceptualization, and ends, before restarting, with active experimentation. By studying and dissecting current machines, the physical components may be directly experienced with all senses. Design methods may then be used to hypothesize current functions, and conceptualize new functions and/or solutions to the current configuration. Observation and active experimentation with the current and refined concepts may then be executed, realizing mental ideas into physical embodiments. The process may then begin again, where further iteration enhances and cements learning, as well as actual product improvements.
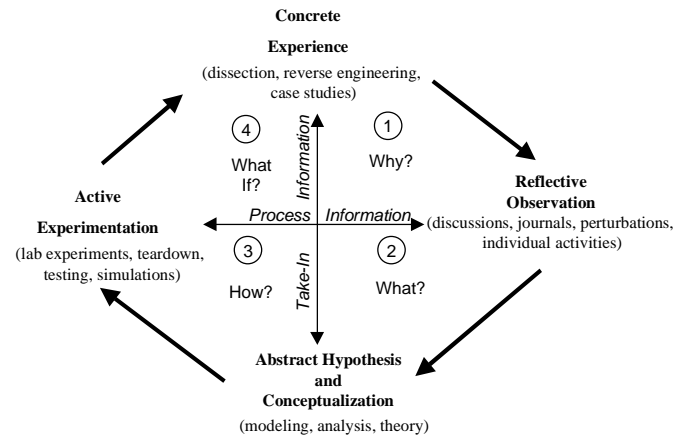

Figure 2. Kolb's Model of Learning (Stice, 1987)

The Kolb model, as shown in Figure 2 swings the pendulum of learning engineering from an emphasis of generalization and theory to a balance with all modes of learning (Stice, 1987). Engineering becomes equally focused on hands-on activities. Without this approach, we have no concrete experience to ground our learning and build a solid understanding. Nowhere is this truth more pronounced than in machine design. The grounding in current machines helps nurture our interest for understanding the way things work and for making devices work better.

1.3 Need:

These issues in our machine design courses lead to the following statement of need: "create a hands-on environment for ME 338 and EM 470 instruction, evolving the purely analytical focus in the past." Supporting goals for this need include the following: develop activities where students manipulate the components they are studying, especially in everyday devices the students are familiar with; add design components in the course, both machine layout and analysis; add team assignments (without going to level of pure design courses), where students learn actively through peer interaction and questioning; and implement a systems approach for studying machine design, where elements are not studied in isolation. The remainder of this paper addresses the goals for our curriculum.

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2. NEW COURSE DESIGN

In this section, we present the skeletal structure of our new course design at UT and USAFA. Our fundamental premise is not to revolutionize machine design instruction; it has a long and rich history within mechanical engineering. Instead, the goal is to evolve the curriculum in machine design to address the contemporary needs and goals of our students.

2.1 Development History:

The development of an evolved machine design course occurred, first, at the United States Air Force Academy during the Fall of 1997. Three faculty members were involved in the new course design, and the design was carried out in the summer of 1997. Because most cadets at USAFA have a heavy course load (18-21 hours), and because a majority seek to be pilots after graduation, special emphasis was placed on designing the course within the cadet's constraints. Three sections of the course were initially offered, with a total of 36 cadets. Figure 3 shows cadets testing their systems project, the analysis and redesign of a radio-controlled (RC) car, during the course's first offering.
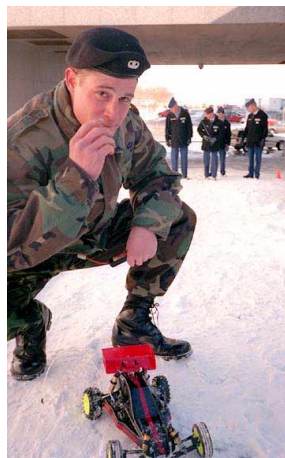

Figure 3. RC Car Testing on the
Obstacle course at USAFA

After implementing the new course in the Fall of 1997, the new course, with some modifications, was first taught at UT during the summer of 1998 (20 students). It has since been taught in each semester from the Fall 1998 through the Fall of 1999 (150 students). The following sections provide a brief description of the primary course components.

2.2 Course Organization:

The new course seeks to address the issues identified in previous offerings of machine design. It also seeks to complete the full cycle of Kolb's learning model. Hands-on activities are the primary addition to the course to complete the cycle. In addition, a systems approach to machine design is the focus. Because of the additions and new focus, some of the material previously taught is removed from the course. The idea is to teach the covered material to interest and

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motivate the student, with the expectation of retention and connection to the concepts. The students did not retain the removed material on any account.

Table 1 shows the new course structure. The first three lessons review critical concepts learned in previous solid mechanics courses. Subsystems of machines are then covered sequentially, beginning with the powertrain subsystem (shafts, bearings, gears, fatigue, and gear trains). The subsystems of fasteners (threaded connectors and welds), energy storage (springs and flywheels), energy dissipation and transfer (brakes and clutches), and motion control (mechanisms) are then presented and integrated. From these fundamentals, the end of the semester is devoted to the study of entire systems through project work.

Table 1. Simplified Course Syllabus.

LSN	TOPIC	LSN	TOPIC
1	Introduction, Admin, Prin. Stress	22	Welds
2	Principle Stresses	23	Springs
3	Prone Stresses; Failure Theories	24	Springs
4	Failure Theories; Shafts	25	Project Time - Welding
5	Journal Bearings	26	Project Time - Welding
6	Journal Bearings	27	Clutches and Brakes
7	Rolling-Element Bearings	28	Clutches and Brakes
8	Spur Gears	29	Clutches & Springs
9	Spur Gears, Gear Trains	30	Machine element summary
10	Gear Trains, GR Review	31	GR Review
11	Graded Review #1 (M-11)	32	Graded Review #3 (T32)
12	Fatigue	33	Introduction to Mechanisms
13	Project Time	34	4-Bar Linkages; Vel. Diagrams
14	Project Time	35	Velocity Diagrams
15	Threaded Fasteners	36	Project Time
16	Bolted Joints	37	Inertial Force Analysis
17	Bolted Joints	38	Project Time
18	Fastener Lab	39	Project Time
19	Welds	40	Project Test & Evaluation
20	GR Preview	41	Project Test & Evaluation
21	Graded Review #2 (M-21)	42	Wrap-Up and Evaluation

Besides a new course structure, the following features are added to the course:

1. A defocus of repeated solid mechanics instruction; an emphasis on fundamentals and applications of machine elements as subsystems
2. A balance between homework exercises and hands-on projects (Kolb's Model); a move toward active learning through multiple, team-based projects
3. "Show-and-Tell" and product dissection activities
4. Implementation of a mechanical breadboard (Kolb's Model) to incrementally construct, analyze, and redesign machine systems
5. A supplemental reverse engineering project
6. Addition of motors as a topic to the course using new multimedia education software developed by Professor Sheri Sheppard's group at Stanford University.

These features replace some the extensive, survey material originally covered in the course. In the first case, homework exercises on fundamentals and machine element analysis are used to understand the rudiments of basic concepts (just as in the original courses); however, team projects (two to four persons) are added to study real-world devices for each subsystem and complete Kolb's cycle.

In conjunction with projects, students obtain hands-on experiences with machines through a "show-and-tell" activity and the use of a "mechanical breadboard." After studying each major subsystem, students are asked to bring in one to two real-world devices from home or work. Students must predict the internals in the devices, dissect them before class, and write a ½-1 page summary of each device, how it operates, and how the analysis from class applies to the components. A subset of the class is asked to summarize their findings to their classmates during the first ten minutes of a lesson.

This show-and-tell activity has a dramatic impact on the students. They become familiar with the technical terminology. They are introduced to the world of "tinkering," using tools, and analyzing how products are constructed. They also connect classroom material directly with products they have used on countless previous occasions.

This impact is further elaborated through the introduction of mechanical breadboards into the course. The concept of a mechanical breadboard is analogous to breadboards in electrical engineering. Basic building-block components, such as gears, bearings, connectors, and so on are provided with a flexible support structure. These components may be configured on the support structure depending on the system being emulated, prototyped, or designed.

A mechanical breadboard is used in the new course to incrementally construct a system as the subsystems are being studied. After each construction exercise, machine-component analysis is applied to the subsystem, and at the end of the course, a systems analysis is performed to redesign and improve the overall device. A mechanical breadboard, in this case, represents the final epitome project for the course.

Many options exist for meeting the need of a mechanical breadboard for the course. These options include Lego™ or other construction kits, commercially available precision-metal breadboards, household products, or hobby kits, such as radio-controlled cars. The next section discusses our choice of mechanical breadboards for the Fall 1997 semester.

The remaining two features for the new course include a reverse engineering project and the study of electric motors. As a supplemental, extra-credit, or main project, students can choose a household device to dissect and reverse engineer. Such devices include kitchen appliances, mechanical toys, and power tools. Students should dissect the project, choose a set of customer needs (such as durability, low weight, etc.) to study, setup the analysis for 2-3 subsystems, measure geometric, power flow, and material data from the product, perform the analysis compared to the customer needs, and make recommendations for redesign. This project provides a wonderful forum for exciting the senses of the student, for improving modeling and assumption skills, and for closing the loop of the Kolb learning model.

As a final feature for the new course, electric motors are studied. A systems approach to machine design requires a source of power or prime mover. Electric motors are prevalent in many of the systems used by the students. To teach this new topic, an experimental multimedia tool can be used from Stanford University. This tool, developed under support from the National Science Foundation, uses an interactive game to analyze the fundamentals of electric and magnetic fields. It applies these fundamentals to a systems game where students must set the parameters on a Lego™ cart, powered by an electric motor, to travel up a hill as fast as possible.

2.4 Course Niche: Breadboard Alternatives

Considering the features added to the new machine design course, the concept of a mechanical breadboard intrigued and excited both the faculty and students to the greatest extent. Machine design is a very difficult topic area due to the large number of components, complex analyses, three-dimensional geometry, variety of connection methods, and required creativity. Utilizing a mechanical breadboard, as an analogy to an electrical breadboard, has the potential to overcome many of the difficult features. Students will be able to connect the studied theories with hardware. They will also have a reconfigurable media for trying and testing their ideas.

A number of options exist for implementing the concept of a mechanical breadboard. Five options are considered below, balancing the tradeoffs of cost, complexity, and utility.

Precision Mechanical Breadboard Kits

A number of suppliers exist that sell high-end mechanical breadboards. These breadboards include precision metal components and actuators that attach to configurable structures with slot-set-screw connectors. Many kits are available from the vendors, and the kits can be used to architect a variety of machine layouts. For a set of *basic* kits, the cost would be approximately $20-30,000 for ten teams. Figure 4 shows the application of a mechanical breadboard as a prototype for a printer product.
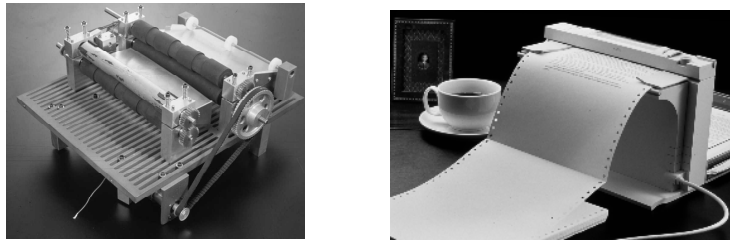
Figure 4. Mechanical Breadboard Prototype Printer

Household Consumer Products

Consumer products are a possible option for a mechanical breadboard. Products, such as power tools, lawnmowers, mechanical toys, and kitchen appliances, may be initially dissected and disseminated to students in kits. These kits may then be assembled in part or in whole from complete or partial assembly diagrams. Such kits would not be easily reconfigurable, and the cost would range between $10 and $100, depending on the products chosen. Figure 5 shows example consumer products that could be used in this exercise.

Figure 5. Consumer Product Examples

Children's Construction Kits

Viable options for a mechanical breadboard are children's construction kits, such as Lego™ and erector sets. These kits can be designed into a number of machine configurations. The new kits, that include actuators and sensors, also provide the ability to design controllers and dynamic subsystems. The costs of these kits range between $25 and $500, and they have a severe limitation in the ability to apply many of the solid mechanics analyses (due to the plastic material properties and methods for fastening).

Radio-Controlled (RC) Car Kits

Another option is to purchase commercially available RC vehicle kits. These kits include many types of vehicles, such as cars (road racers, formula, and trucks), helicopters, and airplanes. Such kits provide scale versions of actual vehicles. They also provide the capability for the use of tools, the study of a wide variety of components and mechanisms, testing, and limited reconfigurability. The cost of these kits range from $150-$1000. Figure 6 shows an example RC car.

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Figure 6. Remote-Controlled Car

Automobile/Aircraft Subsystems

Automobile and aircraft subsystems are also an option for the concept of a mechanical breadboard. Example subsystems include suspensions, doors and hoods, steering, motors, and others. Such subsystems can be dissected and reassembled (but with significant effort). They also provide good cases for solid mechanics analyses, and relate significantly to the future job market for both USAFA and UT graduates. The cost for such subsystems range from $500 to $4000, reconfigurability is greatly limited, and they are difficult to transport and use in the classroom due to size and weight considerations.

As an alternative to automobile and aircraft subsystems, go-kart kits may be purchased. These kits provide small-scale on-road or ATV vehicles with 5-10 Hp motors. The cost ranges from $750 to $2500 per kit, and the kits provide limited reconfigurability.

Choice/Compromise

For the UT and USAFA courses, the final choice amongst these options is the combination of RC car kits, in-class product examples, show-and-tell product examples, and supplemental reverse engineering projects of consumer products. This choice represents a good compromise in cost, scale, viability of measurements, and viability of analyses. This choice also satisfies the hands-on requirements of the new courses, in addition to the variety component and the possibilities to make design modifications. RC car kits have the potential to be great fun and introduce a potential for racing competitions at the end of the semester. Likewise, they use state-of-the-art materials, and they are challenging (open-ended, no obvious answer exists by inspections, and uncertainties exist in performance). The primary disadvantages of this choice include their limitations in reconfigurability (not completely analogous to electrical breadboards), the need for replacement parts, and the use of limited energy supplies (batteries or nitro fuel).

3. EXAMPLE APPLICATIONS AND EXERCISES WITH THE RC CAR BREADBOARD AND SUPPLEMENTAL PROJECTS

The study of machine design and/or machine elements can be a difficult learning experience for students as it is often presented as a series of independent concepts with the only common thread the general principles of mechanics and kinematics. The use of mechanical breadboards offers the opportunity to integrate more effectively the knowledge of the design of machine elements and offers the student an increased exposure to hands-on experiments, which reinforce the theoretical knowledge base. In addition, the experience with a simple but integrated system also better prepares the students for their follow-on capstone design course. Machine design courses

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normally cover the analysis of common mechanical components, e.g. shafts, gears, bearings, springs, clutches, fasteners, etc., but fall short of synthesizing the components into a working system.

The incorporation of a remote-controlled (RC) car to use as a mechanical breadboard allows the student to experience many of the commonly studied machine elements in a single system. Although simple in design, the RC car allows basic analysis and design of the following systems and components:

- Transmission: gears, bearings, shafts, fasteners
- Drive train: motors, clutches, shafts, belts
- Suspension: spring variations (e.g. length, stiffness, diameter)
- Steering: motors, levers, linkages, fasteners

This section describes a selection of projects introduced in the course specifically to allow the students an opportunity to both analyze and design, in an integrated system, different components of the RC car. These projects were supplemented with additional homework problems used to reinforce basic theoretical concepts.

3.1. Engineering Design:

Early in the course the students were introduced to the topic of bearings, both journal and rolling-element, followed by an introduction to gears and shafts. To supplement their understanding of the design aspects, as well as the interdependence, of these components, the project shown in Figure 7 was assigned.

Project 1: Designing a Gear Train and Supporting Shafts

For this assignment, you may work only with your assigned partner and instructors in EM 470. Do not use any materials produced by another student, except your assigned partner.

Create a spreadsheet to design and analyze a gear train. Allow the user to provide the input and output speeds (and directions), the input torque, the diametral pitch of the gears, the pressure angle of the gear teeth, the coefficient of friction, and the design life (in hours). As a minimum, your spreadsheet must calculate and display the numbers of teeth and the diameters of all gears in the train, the output torque, the gear train efficiency, and the total width of the gear train. Also, the spreadsheet must determine the bores of the appropriate bearings to support the shaft of each gear in the train. All values in the spreadsheet must be clearly labeled and the spreadsheet should include error-trapping to prevent inappropriate input values.

The gear train must consist of simple spur gears and must have the minimum number of gears. The maximum gear ratio for the entire train will be 12:1. However, the gear ratio from one gear to the adjacent gear must not exceed 6:1. Assume a separate shaft supports each gear, and that all the shafts are parallel. Include the effects of friction losses in the gears when calculating forces and torques, but ignore friction losses in the shaft bearings.

The bearings must be selected from the 200 series radial ball bearings in Table 14.2 in the course text. Assume each shaft is supported by two bearings and that each bearing supports one half of the load on its gear. Select bearings based on 95% reliability.

Figure 7. Gear Train Design Project

This project enabled the students to perform parametric design of various gear train combinations and observe the effects of frictional losses, gear ratios, power transmission, gear

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train efficiencies, etc., and would become a tool for subsequent design and analysis of the RC car transmission. Figure 8 shows a representative solution for this project.

User Input:

Input Speed (rpm)	20
Output Speed (rpm)	180
Input Torque (lb-in)	500
Diametral Pitch (teeth/in)	20
Diam of Gear 1 (in)	100
Coeff of Friction	0.01
Pressure Angle (Deg)	25
Bearing Design Life -L (hrs)	40000

Worksheet Output:

Overall Gear Ratio (Out/In)	0.11	
Output Torque (lb-in):	55.04	
Efficiency:	99.07%	
# Gears in Train	3	Idler gear not required
Gear Ratio - G2/G1	0.17	
Gear Ratio - G3/G2	0.67	
Gear Ratio - G4/G3	NA	Only 3 gears required
Gear Train Width (in)	127.78	

Gear Size Design

Gear Diameter -

Diameter - Gear 1 (in)	100
Diameter - Gear 2 (in)	16.67
Diameter - Gear 3 (in)	11.11
Diameter - Gear 4 (in)	NA

 # Teeth/Gear -

# Teeth, Gear 1	2000
# Teeth, Gear 2	333
# Teeth, Gear 3	222
# Teeth, Gear 4	NA

Shaft Bearing Design

Bearing Loads -

Load/Bearing - G1 (lb)	5.52
Load/Bearing - G2 (lb)	9.95
Load/Bearing - G3 (lb)	5.47
Load/Bearing - G4 (lb)	NA

Adj Bearing Loads (Creq) -
(Life, reliability, appl.)

Adj Load/Bearing - G1 (lb)	5.25
Adj Load/Bearing - G2 (lb)	16.21
Adj Load/Bearing - G3 (lb)	10.05
Adj Load/Bearing - G4 (lb)	NA

Required Bearing Bore -

Bore - Gear 1 (mm)	10
Bore - Gear 2 (mm)	10
Bore - Gear 3 (mm)	10
Bore - Gear 4 (mm)	NA

Assumptions:

Application Factor - Ka	1
Reliability Factor - Kr	0.63

200 Series Bearing Required -

Bearings - Gear 1	200
Bearings - Gear 2	200
Bearings - Gear 3	200
Bearings - Gear 4	NA

BEARING TABLE
(Table 14.2 - Juvinall & Marshek)
200 Lt Radial Ball Bearings

Rated Load		Bore	
lb	kN	mm	in
10679	47.5	140	5.51
9218	41	130	5.12
8431	37.5	120	4.72
7869	35	110	4.33
7194	32	105	4.13
6857	30.5	100	3.94
6183	27.5	95	3.74
5621	25	90	3.54
5058	22.5	85	3.35
4137	18.4	80	3.15
3934	17.5	75	2.95
3822	17	70	2.76
3597	16	65	2.56
3058	13.6	60	2.36
2698	12	55	2.17
2181	9.7	50	1.97
2113	9.4	40	1.57
2046	9.1	45	1.77
1911	8.5	35	1.38
1214	5.4	30	1.18
821	3.65	25	0.98
753	3.35	20	0.79
607	2.7	17	0.67
351	1.56	15	0.59
319	1.42	12	0.47
279	1.24	10	0.39

Figure 8. Example Solution to the Gear Train Design Project

Spring elements also play an important part in machine design and are a major component in the suspension system of the RC car. The class project shown in Figure 9 offered the students the opportunity to design springs for their RC car based on design criteria contrived from operating conditions and geometrical constraints from the car structure. The students then compared their results with the front and rear springs provided with the car kit and also with experimentally determined spring stiffness coefficients. Figure 10 provides a representative solution for this project.

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We wish to design the rear shock springs for the RC-10B2 Sport Car. Our design will consider fatigue-loading conditions, where the off-road impact load varies from 8.88 N to 35.52 N on each rear spring. Given D=14.23 mm, and δ = 57 mm (unloaded to fully loaded), assume that steel spring wire (ASTM A227) with shot peening (Fig. 12.16) is to be used.

(a)   Choose appropriate values of d, N for your spring design. Compare your calculated values to the actual rear springs in the car.

(b)   Calculate the spring rate for the design, and compare to the experimental values below:

1.   We wish to design the rear shock springs for the RC-10B2 Sport Car. Our design will consider fatigue-loading conditions, where the off-road impact-loading varies from 8.88 N to 44.4 N on each rear spring. Given D_o=15.25 mm, D_i = 13.2 mm, and δ = 57 mm (due to 1/10 scale shock constraints), assume that steel spring wire (ASTM A227) without shot peening (Fig. 12.16) is to be used.

    (a)   Choose appropriate values of d, N for your spring design. Compare your calculated values to the actual rear springs in the car.

    (b)   Calculate the spring rate for the design, and compare to the experimental values below:

RC Car Problem: Spring Design

Measured Spring Constants:

Silver				Green		
	Deflection	(in.)				
Mass (g)	Spr1	Spr2		Mass (g)	Spr1	Spr2
0	0	0		0	0	0
500	0.344	0.406		500	0.297	0.25
1000	0.844	0.875		600	0.359	0.375
1200	1.063	1.094		700	0.422	0.406
1300	1.172	1.203		800	0.484	0.469
1500	1.298	1.329		1000	0.609	0.594
(N/mm)	k_s1	k_s2			k_g1	k_g2
	0.561367	0.475641			0.650203	0.772441
	0.457607	0.441395			0.645494	0.617953
	0.435997	0.423642			0.64065	0.665897
	0.428402	0.417362			0.638381	0.658798
	0.446326	0.435915			0.634188	0.650203
Avg.	0.46594	0.438791			0.641783	0.673058
Grand Mean (N/mm):						
	0.452365				0.657421	

    (c)   Check for buckling and spring surge for your design (assume that the car encounters bumps every 100 mm at a speed of 25 mph during off-road driving). Conclude about the results.

(c)   Check for buckling and spring surge for your design (assume that the car encounters bumps every 100 mm at a speed of 25 mph during off-road driving). Conclude about the results.

Figure 9. Suspension Spring Design Project

Rear Spring				Front Spring			
User Input:				**User Input:**			
Given Values				*Given Values*			
Car Weight (N)	15.0	G (Pa)	7.9E+10	Car Weight (N)/(lb)	15.0	G (Pa)	4.1E+10
Force/spring (N)	5.4	D (m)	1.4E-02	Force/spring (N)/(lb)	2.1	D (m)	1.3E-02
delta (δ) (m)	5.0E-03	d (m)	1.4E-03	delta (m)	2.0E-02	d (m)	1.1E-03
delta_max (δ) (m)	5.0E-02	N	12.2	delta_max (m)	2.5E-02	N	27.2
Spring Constant (k) calculation using 2 methods:				Spring Constant (k) calculation using 2 methods:			
k = F/d (N/m)	1075.4			k = F/d (N/m)	104.3		
k = d^4G/8D^3N (N/m)	1075.4			k = d^4G/8D^3N (N/m)	104.3		
Constraints:				Constraints:			
C = (D/d)	1.02E+01			C = (D/d)	1.2E+01		
Length_Free (m)	7.5E-02			Length_Free (m)	3.0E-02		
Length_Solid (m)	2.0E-02			Length_Solid (m)	2.1E-03		

Figure 10. Example Solution to the Spring Design Project

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3.2. Engineering Analysis:

Mechanical "Breadboards" offer students the ability to perform an array of engineering analysis using a combination of hands-on experiments with analytical tools to reinforce concepts such as: torque/speed relationships, shaft and bearing load, failure, and fatigue, gear tooth stress and strength, steering system kinematics (four-bar linkages), fastener stress and strength, etc.

The RC car affords a unique opportunity for students to experiment with a simple, single friction disk clutch. The tension on the clutch disk can be adjusted by means of a single screw and allows for analysis of the axial force on the disk and resulting slippage of the drive mechanism. The following class project (Figure 11) was accomplished in parallel with class lectures on clutch and brake machine components.

Specifications for the RC10-B2's Reedy Firehawk electric motor indicate a maximum output of 0.25 hp at 15,000 rpm. This power is transferred through a pinion and drive gear to the car's clutch mechanism, which is a single molded Rulon disc with a coefficient of dynamic friction of 0.36.

(a)   Determine the initial (i.e. new) axial force setting required by the clutch's spring using a factor of safety of 1.0 with respect to clutch slippage.

(b)   After the clutch has been "broken-in", what adjustment will be required to the axial spring force to provide the same torque and factor of safety with respect to clutch slippage?

(c)   Is the clutch disk designed for maximum torque transfer? Why or why not?

Figure 11. Clutch System Analysis Project

During assembly of the RC car kit's transmission components, the students were tasked to analyze the power flow through the system and determine the stresses in the gear teeth using the project described in Figure 12 below. The assembly task involved the installation of gears, shafts, and bearings in the transmission housing and enabled the students to see and feel the interactions between the components as they analyzed the system.

The next system in the RC car drive train is the drive shaft, which delivers power from the transmission to the wheels. The following project (Figure 13) was introduced to demonstrate relationships between the most basic kinematical concepts (distance versus time) and advanced concepts of beam deflections, critical speeds, and factors of safety with respect to shear stress. The project also served to complete the flow of power in the form of torque from the electric motor to the wheels. A sample analytical solution to each part of the problem is also provided in Figure 14.
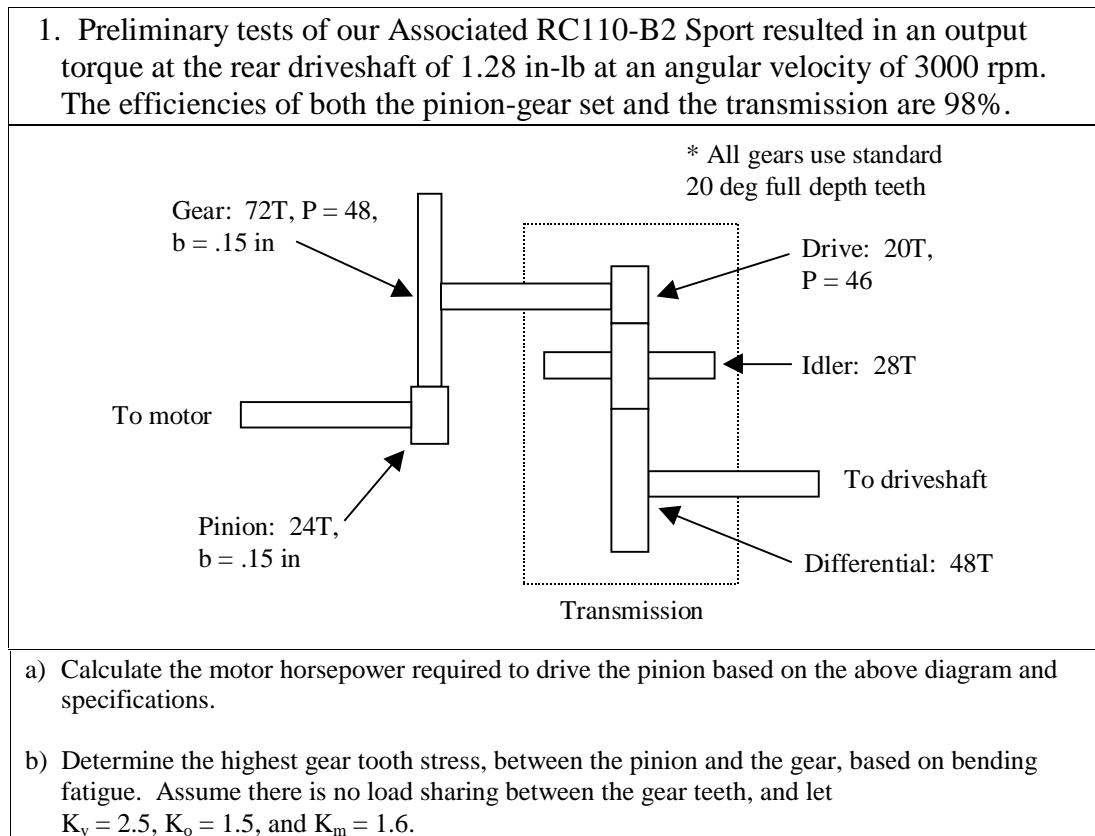
1. Preliminary tests of our Associated RC110-B2 Sport resulted in an output torque at the rear driveshaft of 1.28 in-lb at an angular velocity of 3000 rpm. The efficiencies of both the pinion-gear set and the transmission are 98%.

* All gears use standard 20 deg full depth teeth

Gear: 72T, P = 48, b = .15 in

Drive: 20T, P = 46

Idler: 28T

To motor

To driveshaft

Pinion: 24T, b = .15 in

Differential: 48T

Transmission

a) Calculate the motor horsepower required to drive the pinion based on the above diagram and specifications.

b) Determine the highest gear tooth stress, between the pinion and the gear, based on bending fatigue. Assume there is no load sharing between the gear teeth, and let $K_v = 2.5$, $K_o = 1.5$, and $K_m = 1.6$.

Figure 12. Transmission Analysis Project

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A preliminary speed test of the EM470 RC10-B2 Sport radio-controlled car produced the following results:

Time (sec)	Distance (ft)
1.85	28
3.1	56
4.2	84
5.25	112
6.3	140
7.35	168

The mass of the car was measured to be 1.53 kg and the tires have a diameter of 3.0 inches. The driveshaft properties and geometry are shown below.

Driveshaft
1020 HR Alloy Steel
Mass = 2.16 gr.

Diam. = .102 in

L = 1.97 in
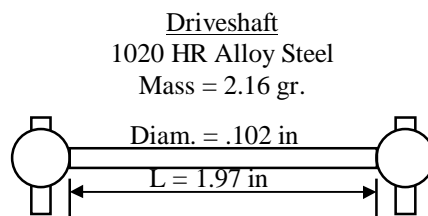
a. Determine the maximum lateral and angular deflections of one of the vehicle's driveshafts. State all assumptions made in your analysis.

b. Determine the critical speed of the driveshaft. In the test above, was the driveshaft anywhere near the resonant speed? What would be the speed of the vehicle at the resonant speed of the driveshaft?

c. Assuming the driveshaft is experiencing torsion only, determine the factor of safety in the design based on the theory of Maximum Shear Stress.

Figure 13. Kinematical Analysis of Drive Shaft

RC10-B2 Sport Driveshaft Analysis

Experimental Data:

Time (sec)	Dist (ft)	Vel (ft/s)	Accel (ft/s2)
0	0	0.00	0.00
1.85	28	15.14	8.18
3.1	56	22.40	5.81
4.2	84	25.45	2.78
5.25	112	26.67	1.15
6.3	140	26.67	0.00
7.35	168	26.67	0.00

Measured Data

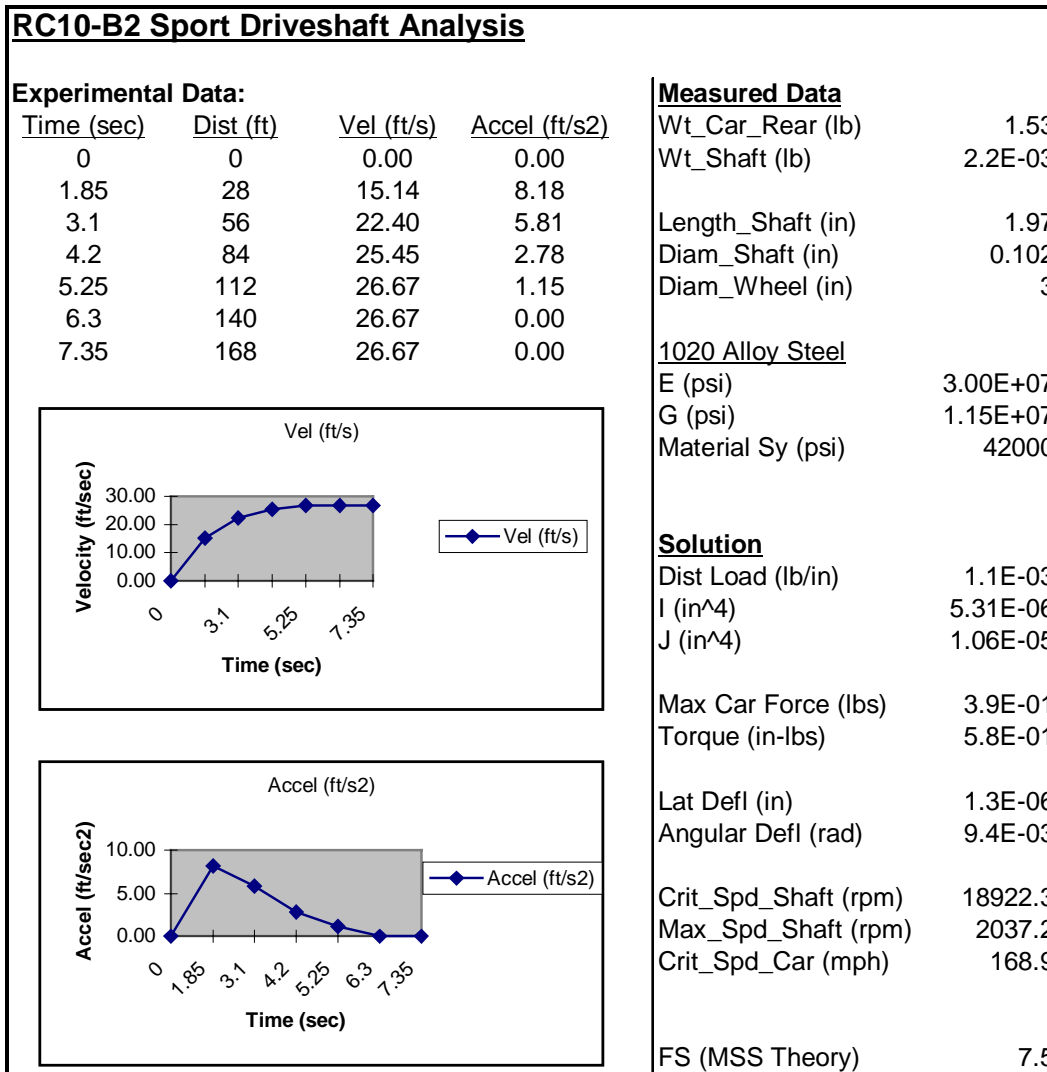|	
Wt_Car_Rear (lb)	1.53
Wt_Shaft (lb)	2.2E-03
Length_Shaft (in)	1.97
Diam_Shaft (in)	0.102
Diam_Wheel (in)	3
1020 Alloy Steel	
E (psi)	3.00E+07
G (psi)	1.15E+07
Material Sy (psi)	42000
Solution	
Dist Load (lb/in)	1.1E-03
I (in^4)	5.31E-06
J (in^4)	1.06E-05
Max Car Force (lbs)	3.9E-01
Torque (in-lbs)	5.8E-01
Lat Defl (in)	1.3E-06
Angular Defl (rad)	9.4E-03
Crit_Spd_Shaft (rpm)	18922.3
Max_Spd_Shaft (rpm)	2037.2
Crit_Spd_Car (mph)	168.9
FS (MSS Theory)	7.5

Figure 14. Example Solution of Drive Shaft Analysis

3.3. Fun Competition:

From the first day the course project was introduced in class, the students knew the day would come when they would put their RC cars, complete with modified clutches, suspensions, gear ratios, lubrication, etc. to the final test. Shown below (Figure 15) is the final course project. The intent of this final project was two-fold. First, the project tasked the students to analyze the performance of the car with respect to the steering system, the suspension system, and the drive train system. In each case the students were asked to state any and all assumptions in their analysis and also to explain their results, and comment specifically where their results differed from the current design of the car.

Secondly, the project introduced the final phase in the design and analysis effort – the end-of-course competition. As part of this effort, the students were tasked with documenting any modifications made to their cars components to increase performance including complete

engineering analysis to support the changes. At this point in the course, the students had a significant knowledge base and an array of analytical tools developed throughout the course with which to use to fine-tune their cars for the competition.

Part 1 [150 points]: Model the RC10-B2 Sport's steering mechanism using Working Model (R:\WM303). All necessary dimensions are to be measured directly from your car. Specifications for the steering servo are as follows: Torque = 2.78 in-lb, Speed = 0.72 rev/sec, Angular Displmt = +/- 37 °

    A. Turning Radius and Ackerman Angle –
        (1) Calculate the minimum turning radii "R" using the δ_i determined from Working Model. Investigate both left and right turning.
        (2) Calculate the minimum turning radii "R" based on the measured values of δ_i for your car. How do these values compare to the radii determined in part "1" above? Explain any differences.
        (3) Measure the minimum turning radii of your car. How do these values compare to the radii determined in part "2" above? Explain any differences.
        (4) Is your car's steering system designed with the correct Ackerman angle? Explain your answer.

    B. Steering Velocity –
        (1) Using Working Model, determine the angular velocity with which the wheels steer assuming maximum servo input and initial straight line motion of the car.
        (2) Using a velocity vector diagram, repeat the analysis in part "1" above. Compare the results and explain any differences.
        (3) Determine the mechanical advantage gained or lost between the steering servo and the wheels and explain its importance in the design.

Part 2 [50 points]: RC Car Traction and Speed Design

    A. Off-road RC10-B2 cars must maintain front-wheel traction to turn on varying terrains. Many parameters exist to adjust front- and rear-wheel traction. Two important parameters are the heights of the front and rear suspensions. These heights may be adjusted by setting the shock travel, or by choosing appropriate spring constants. Your task is to design new springs (i.e., spring constants) to maximize front-wheel traction. State all assumptions, where you need not verify the static or fatigue stress in the springs.

    B. For the sets of pinion and spur gears provided with your car kits, calculate the maximum IDEAL, straight-line speed, based on a motor speed of 20,000 rpm. Assuming the drive-train is not ideal, estimate a new maximum speed for gear-mesh losses only. Measure the actual maximum speed of the car, compare these measurements to your two estimates, and explain the differences.

Part 3 [100 points]: RC Car Race Competition

During Lessons 40 and 41, we will be holding intra-class race competitions. Each team should complete the construction and testing of their car before these lessons. It may be assumed that we will be competing on an oval track, a hill climb, and/or an obstacle course. The competitions will be organized by random draw and single elimination, where winners will receive 10 bonus points.

Each team will be expected to "tune" and adjust their cars for the best possible performance. Adjustments (besides maintenance, repair, and battery charging) will not be allowed after the beginning of Lesson 40. Teams must document their adjustments and provide justification for their choices in car configuration. No non-stock parts or permanent modifications may be used/made to the car or any of its components, except for the car's body.

Figure 15. Final Course Project

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4. COURSE ASSESSMENT

To assess our new machine design course, two instruments are employed: course ratings and the evaluation of specific course advancements according to the personality types of the students (Jensen, 1998). For the purpose of this paper, only the results of the course ratings are included due to space limitations.

Tables 2 and 3 list the results of the course ratings. The first table shows the results from UT during the first two semesters of implementing the new course, with a sample size of 65 students. It also shows the average ratings of the course (0-5 point scale) from 1995 through the spring of 1998. This average is across eight faculty members.

The second table shows the course ratings for USAFA during the inaugural semester of the course. The sample size is small (only 26 students) across two faculty members.

The results from the course ratings are very encouraging. The trends show an increase in reception by the students, especially regarding the ability to reason independently and the relevance of the content material. In the UT case, students especially resonated with the refined course. The course material was evaluated as very difficult and challenging, yet the students perceived that an active and project learning forum greatly added to their ability to understand and retain the material.

Table 2. UT Course Ratings (0-5 pt. Scale)

Question	Avg. Rating 95-98 (Spr.)	Rating 1998 Fall	Rating 1998 Sum.
Course Well Organized	3.3	4.5	4.8
Communicated Information Effectively	2.8	4.8	4.9
Helped to Think, Reason, and Evaluate	3.2	4.8	4.7
Overall Instructor Rating	2.9	4.8	4.8
Overall Course Rating	2.9	4.5	4.9

Table 3. USAFA Course Ratings (0-6 pt. Scale)

Question	Avg. Rating 95-96 (Fall)	Rating Fall 1997
Course Well Organized	4.1	4.2
Information Communicated Effectively	4.2	4.5
Intellectual Challenge & Independent Thought	4.5	4.5
Relevance of Content	4.6	5.0
Overall Instructor Rating	4.7	4.9
Overall Course Rating	4.1	4.1

5. DISCUSSIONS AND CONCLUSIONS

The move from the traditional lecture format course presentation to a more active learning environment has met with tremendous success at both USAFA and UT. The incorporation of mechanical breadboard projects like the RC car have enhanced the students ability to design and analyze mechanical systems resulting in students better prepared to enter their senior capstone design course(s). Although the transition does not come without cost, the reduction in course content and initial increased investment in faculty time and department resources has resulted in a significant increase in student interest and motivation and ultimately an improved retention of the course material.

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