HIGH-PERFORMANCE ENGINES

Fast Cars Accelerate Learning

"FEEL THE NEED FOR SPEED? If you think the sound of an F-1 engine cranking up to 18,000 rpm coming out of turn 8 at Hockenheim is up there with Vivaldi and Mozart, you're probably going to like this course. If you know there is no such thing as too much horsepower and torque under your right foot, this may just be the course for you. If you would rather go to an Auto Show than go to a casino to gamble, hop aboard. If you think that a car is really for getting between Bernalillo and the main campus, there are probably other courses you would enjoy more."

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The "High-Performance Engines" (HPE) course at The University of New Mexico integrates problem-[1,2] and simulation-based[3-5] learning approaches. The course encourages students to synthesize core chemical and mechanical engineering principles (*e.g.,* thermodynamics, transport phenomena, kinetics, catalysis, mechanics, and dynamics) to analyze historically famous racing engines. With independent analysis based on computer simulations, the students in groups of 3 or 4 get to understand engineering innovations that lead to the engines' superior performance in auto racing. The analysis transforms abstract engineering concepts into concrete, object-oriented outcomes.

The students also discuss the design parameters (*e.g.,* compression ratio, intake manifold geometry, and valve timing) to improve engine performance. The groups compete through modeling and simulation to achieve the best improvement. The educational competition augments students' interest in the course subjects and promotes their active participation.[1]

The format of the HPE course is a problem-based learning environment centered on case studies of specific engines, many with great historical significance.

To compare the improvement, students rely on WAVE, an engine design software provided by Ricardo Software. It enables custom engine design and performance simulation by simultaneously solving momentum, energy, and mass balance equations. Since auto manufacturers such as Ford Motor Company use the software to design production engines, the software training advantageously increases students' career potential in automotive design engineering.

The course also prepares a group of University of New Mexico students for the collegiate Formula Society of Automotive Engineers (FSAE) Competition.[6] The participating

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students optimize the competition car design by using WAVE. Figure 1 illustrates how the course exploits the racing engines as the centerpiece to integrate core chemical and mechanical engineering concepts while promoting active learning and preparing our students for the national FSAE Competition.

COURSE DEVELOPMENT

A technical elective course such as High Performance Engines provides a convenient venue to explore problem-[1,2] and simulation-based[3-5] learning. These learning approaches have been proven to promote active student participation and enrich students' learning experience.[7] We introduced the course in the fall of 2001 and taught it again in the fall of 2002 to the upper division students in the departments of chemical engineering and mechanical engineering.

During the conception of the course, our strategy was to exploit high performance engines as the centerpiece to draw students' interest and integrate the two learning approaches around a central topic. If the course became successful, we anticipated that it might lead to additional courses that explore the rest of the automobile.

Our first task was to identify the potential audience and to promote the course. We advertised that the course would be about what makes automobiles go, and in particular, what makes them go *fast*. We also placed the focus of the course squarely on high-performance internal combustion engines. Although much more goes into an automobile or a racecar to make it perform well (*e.g.*, transmission, suspension, steering, tires, brakes, many forms of electronic instrumentation, and controls), our perception was that the high-performance engine would be a good place to start. After all, the engine is the power source, or more precisely the "transformer," of chemical energy into mechanical energy.

The HPE course appeals largely to students who view cars as more than just transportation and who regard an engine as the soul of an automobile. Since the course is geared toward car enthusiasts, these students are highly motivated to learn the subject matter. The course also reflects local history and general public interest. Albuquerque is the hometown of the legendary auto racing family, the Unsers. Auto racing is a tradition in Albuquerque and has a loyal following, including Formula 1 (F-1) and National Association for Stock Car Auto Racing (NASCAR) circuits. Because the University of New Mexico serves largely in-state students deeply rooted in the local community, the HPE course certainly appeals to a wide audience, including some of the alums who wish to return for continuing education.

With the target audience clearly identified, our intention was to help students see how fundamental engineering principles come to life in internal-combustion, spark-ignition engines. The engine operation and design require integrative understanding of thermodynamics, transport phenomena, kinetics, catalysis, mechanics, and sound wave dynamics. Students get to capitalize on the application of these engineering fundamentals to engine operation and design and see how they come to life. The course relies heavily on computational tools and information technology for modeling, simulation, visualization, and design of historically famous racing engines.

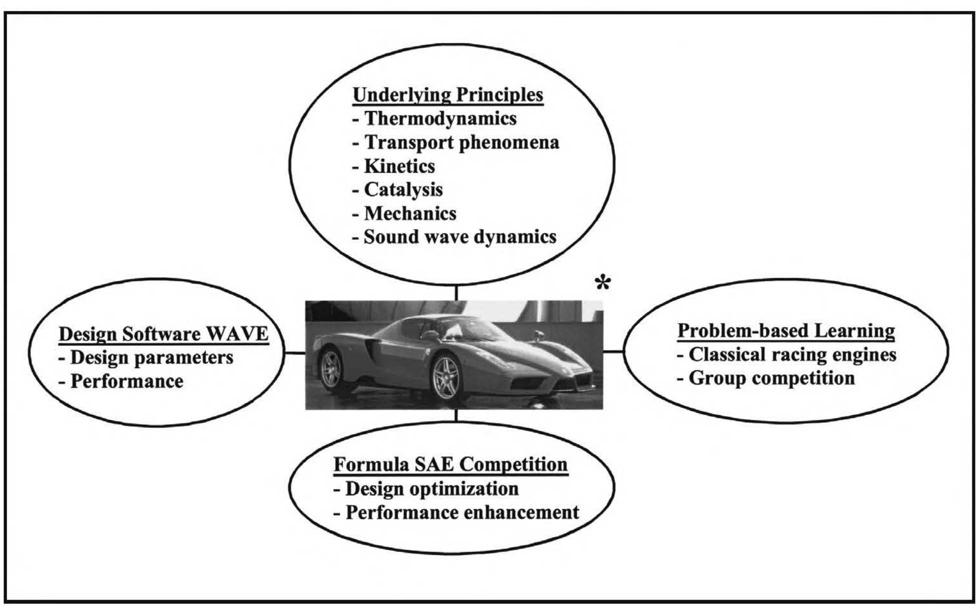

Figure 1. *A conceptual diagram of the HPE course that exploits students' interest in concrete objects to integrate core chemical and mechanical engineering principles via problem/simulation-based, active learning while preparing them for national FSAE competition. (Picture of Ferrari FX is available via <http://www.ferrari.com>).*

TEXTBOOKS

We chose Lumley's *Engines: An Introduction*[8] and Heywood's *Internal Combustion Engine Fundamentals*[9] as the main textbooks for the course. Lumley's book surveys the relevant topics of engine operation and carries enough depth for the students with limited hands-on experience in auto engines. This simplicity allows students with very basic mathematics to appreciate the engineering fundamentals behind engine operation. Overall, Lumley's book is an excellent option to broaden the potential audience by lowering the barriers for those who may not have extensive knowledge of auto engines. It also uses the Stanford Engine Simulation Program (ESP) available via <http://esp.stanford.edu>. This freeware lets students explore the engine's operating characteristics and thermodynamic performance as a function of geometric parameters of engines. The program is a straightforward and effective way to visualize methods for improving engine performance. We discuss other software tools later in this paper.

In comparison, Heywood's textbook thoroughly discusses operating principles with in-depth rigor. The topics in both books range from ideal models of engine cycles, to engine breathing, to engine heat transfer, to engine operating characteristics. These topics naturally lead to a discussion of subjects that are largely familiar to chemical and mechanical engineers, such as pressure vs. volume (P-V) diagrams of ideal Otto cycle, flow separation, thermal boundary layer, combustion, and mechanical vibrations and balancing. We added Heywood's book as a response to improve the course, based on a student survey conducted in the fall of 2001. The students expressed a need to see more rigorous analysis of engine operation in addition to the cursory demonstrations in Lumley's book.

ENGINEERING TOPICS FOR CLASS DISCUSSION

The first topic discussed in HPE is the Otto engine cycle. Although the ideal Otto cycle is reviewed in numerous engineering thermodynamics courses, students often fail to appreciate its engineering significance. Our goal is to relate the P-V diagram to tangible engine performance so that students depart from abstract understanding of the diagram. We achieve this realistic understanding by first visualizing how each stroke (*i.e.,* intake, compression, ignition, expansion, blowdown, and exhaust) corresponds to the piston position between the top dead center (TDC) and the bottom dead center (BDC) of the cylinder, as illustrated in Figure 2.

We simultaneously introduce students to a concept of mean effective pressure (mep) as an artificial measure of thermodynamic performance of an engine. The mep value is intimately related to the P-V diagram. The product of mep and total engine displacement (V_d) is work done by the engine per power cycle, and the product is simply the shaded area carved out by the piston trajectory in the P-V diagram.

The power generated by the engine, a number that we all look at before purchasing a vehicle, is merely a product of the work produced per power cycle and the engine speed (N) in revolutions per second. This proportionality explains precisely why the brake horsepower (bhp) increases more-or-less linearly with the engine speed, often given in revolutions per minute (rpm), until the engine breathing becomes the limiting factor at high rpm.

This example demonstrates how an abstract concept can come to life by associating it with concrete objects and visualization. We expand on this approach with subsequent course materials by leading the students to make such associations. For instance, students directly relate intake manifold tuning, intake runner design, intake/exhaust valve size and number, intake/exhaust valve lift and overlap control by cam, and super/turbo charging to the engine performance figures. Making such connections requires fundamental understanding of sound-wave dynamics, turbulence and combustion, continuum fluid flow, mechanics, and advanced thermodynam-

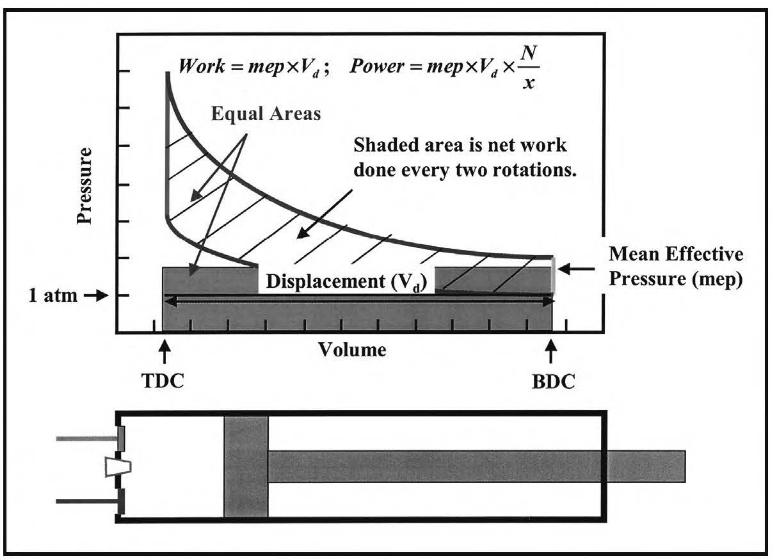

Figure 2. P-V diagram of ideal Otto engine cycle. Mean effective pressure (mep) is an artificial measure of an engine's thermodynamic performance intimately related to the P-V diagram. The generated power is simply a product of mep, total engine displacement (V_d), and engine speed (N) in revolutions per sec divided by the number of cycles per power stroke (x).

ics. When the abstract engineering concepts are closely linked to tangible parts and concrete engineering outcome (*e.g.*, horsepower and torque), students become capable of retaining the learned information, and their desire to understand the engineering subjects remains strong throughout the course.

> *The course encourages the students to synthesize core chemical and mechanical engineering principles (e.g., thermodynamics, transport phenomena, kinetics, catalysis, mechanics, and dynamics) to analyze historically famous racing engines.*

LOGISTICS OF THE COURSE

The instructors formulate the case studies that will be the focus of class discussion. These case studies require students to investigate the engineering topics mentioned previously. The instructors act primarily as *facilitators* to provide some degree of continuity and structure for the course. They essentially provide a forum for the extensive participation of students in this learning process.

Each case study starts with a brainstorming session moderated by the instructors. Students identify relevant engineering topics and areas that they wish to focus on. From time to time, the instructors themselves may be resources of knowledge in helping to explain concepts, but the faculty do not lecture in the conventional manner. They are, however, responsible for introducing modeling software (*e.g.*, ESP, WAVE, and Working Model 2D) and ensuring that students have adequate access to running these codes. The faculty members are expected to seek productive feedback from the students and to act on the feedback to improve the course.

Finally, the faculty evaluate student learning based on measures that truly reflect what students have gained in knowledge and competence. Some of the evaluation criteria are

- *The team's understanding of newly acquired concepts*
- *The depth and diversity of learning resources provided by the students*
- *The students' active participation during each case study*
- *Thorough documentation of quoted references*

Students are expected to have taken engineering thermodynamics before enrolling in the HPE course and instructor approval is required for those who have not taken it. Students are expected to attend all classes and to be thoroughly prepared.

At the beginning of the course, students form teams of 3 to 4 members each, and all activities during the semester are team-produced. Students can name their teams, for instance, after F1, IRL, and NASCAR race teams and compete during each case study. They are expected to participate extensively and fully in all aspects of working out the cases. This may include initial brainstorming sessions, concept identification, problem solving, and resource discovery. Teams are responsible for developing their own case study with guidelines provided by the faculty.

Although no one taking this course should be concerned about his or her grade, for the record, the grade is based on classroom participation, creative contribution to analyzing case studies, production of creative materials and learning resources, and the quality of case studies on performance engines, each of which is approximately equally weighted. For instance, students can bring real mechanical components to class, such as superchargers or camshafts, to demonstrate their working principles relevant to the corresponding case studies. Such participation reflects not only initiative, but also the students' creative approach to classroom presentation.

Since individual performance needs to be weighed appropriately in addition to the overall team performance, each team is responsible for a self-assessment of the performance of each team member. The grade for each student is based on overall team performance, peer evaluation, and self-assessment. The evaluation metrics chosen for the HPE course is available from <http://www.departments.bucknell.edu/projectcatalyst/Finalized%20Materials%20for%20CD/cats.htm>. the "Peer Rating Factor"[10] on this website is particularly useful in formulating the evaluation metrics.

CASE STUDIES AND GROUP COMPETITION

The case studies used in the course are based on historically famous racing engines with significant engineering innovations of the period. These engines provide very successful examples of excellent engineering design. The posed problems generally require analyzing engine design parameters and their impact on performance. A few case studies are listed here as examples.

► **1954 Jaguar XK 3.4 L Inline Six**

1. *Provide additional background information and reference(s) for the XK engine.*
2. *Estimate the indicated mean effective pressure for*

this engine.

3. *Estimate the peak power.*

► **Honda RA122E/B 3.5-Liter V12**

1. *Provide additional historical and technical information on the Honda engine.*
2. *Estimate cylinder wall, piston crown, and exhaust valve temperatures as a function of engine speed (rpm).*
3. *Estimate the cycle-averaged heat loss rate in the given engine as a function of engine speed (rpm).*
4. *Discuss how the thickness of the cylinder wall and piston crown affects the heat loss.*
5. *Show semi-quantitatively how the exhaust valve diameter would affect valve temperature.*
6. *Provide an alternate way of estimating the cycle-averaged gas temperature and the exhaust gas temperature.*

► **Timing and Camshaft Design of 1989 Mustang GT**

1. *Provide nomenclature for main parts of the camshaft.*
2. *Relate cam profile and phasing to valve actuation and ultimately engine performance.*
3. *Select a commercially available cam for the 1987 Mustang and provide reasons for selection.*
4. *Use available software to simulate the engine performance.*

The third case is a primary example that can easily lead to group competition to produce the best performing engine. The group competition brings *fun* back to class, while at the same time promoting students' active participation.[1] "Who can produce an engine for the best quarter-mile time?" has proven to be an all-time motivator.

For those instructors who wish to implement a case study strictly limited to chemical engineering principles, the key points of the second case study are discussed in detail for illustration. The Honda F-1 engine case study focuses on heat transfer from the engine cylinder to the surrounding environment when chemical energy is released from the combustion process. The students are encouraged first to gather relevant information on gasoline, such as average molecular weight, specific gravity, heat capacity, and heat of combustion. For instance, one can assume complete combustion of octane to estimate the upper limit on the released chemical energy

$$C_8H_{18} + \frac{25}{2}O_2 \xrightarrow{\Delta H_c} 8\,CO_2 + 9\,H_2O \qquad (1)$$

For the adiabatic complete combustion, the students can calculate the exhaust gas temperature within the cylinder. The adiabatic gas temperature translates to the first estimate on the actual exhaust gas temperature since in the real situation, the released heat flows from the exhaust gas to valve assembly, cylinder wall, and piston head. The instructors must simultaneously guide the students to recognize that the amount

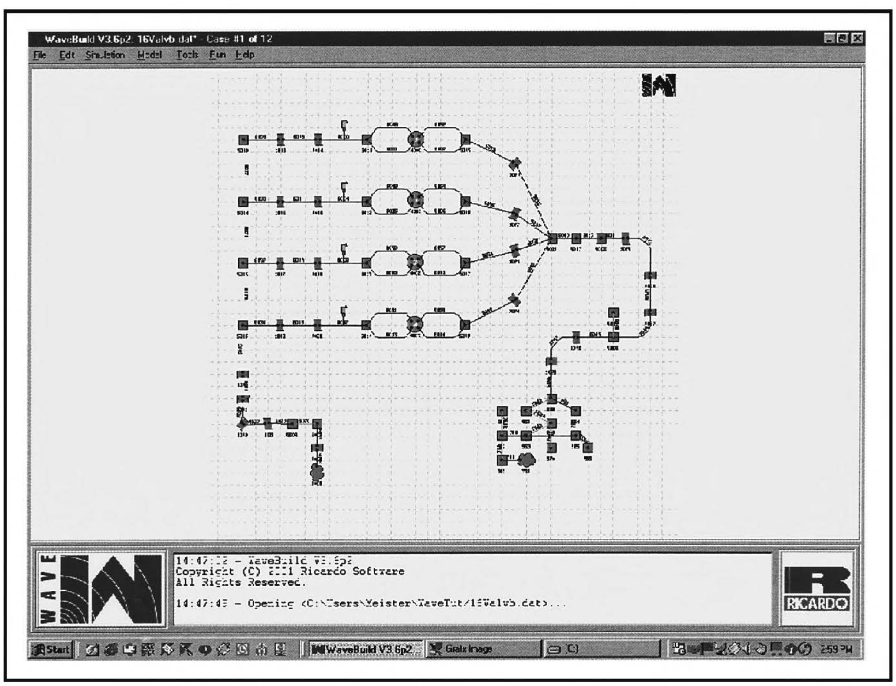

Figure 3. *Screen Shot of WAVE simulation software. The image shows modular components of a four-cylinder engine with complete intake and exhaust systems.*

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of released chemical energy per unit time increases as the engine speed increases and that the heat transfer coefficient (h_e) for the turbulent flow of gasoline and combustion products in the cylinder also increases with increasing engine speed. That is, the increasing engine speed equals increasing Reynolds number (Re) for the working fluid in the cylinder, which in turn increases h_e according to

$$\frac{h_e b}{k_g} = 10.4\left(\frac{Gb}{\mu_g}\right)^{0.75} \qquad (2)$$

where b, k_g, and μ_g denote cylinder bore, thermal conductivity of working fluid, and viscosity of working fluid.[8] G is defined as $\dot{m}_a / A_p$, where $\dot{m}_a$ and A_p denote mass flux per unit time through the cylinder and piston area. Gb/μ_g essentially equals Re. The heat transferred from the working fluid to the surrounding mechanical parts by forced convection is subsequently conducted through mostly metal engine components. In the case of the cylinder wall, the heat is finally transferred to the cooling jacket, whose temperature can be fixed for the purpose of calculations at a cycle-averaged temperature. By equating the heat flux from the convective heat transfer to the heat loss by conduction to the surrounding engine components, one can determine the surface temperature of valve assembly, cylinder wall, and piston head.

The remaining task is to account for the heat loss to the surroundings. The initial approximation on the exhaust gas temperature by adiabatic combustion no longer holds true. Thus, the students need to solve reiteratively for the exhaust gas temperature, which in turn affects both convective and conductive heat transfer. The students can consider additional complexity of heat conduction based on the varying cross-sectional areas of engine components available for the conductive heat transfer.

LEARNING TOOLS

We introduce a number of software tools in the course. Although the effectiveness of introducing more than one software tool in a semester is still in debate, students often find their favorite from a selection of available tools, depending on their level of willingness to learn increasingly more complex software. For instance, ESP allows students to quickly grasp the key design parameters to improve engine performance with much ease and simplicity. For this reason, ESP is introduced in the early stages of the course.

The next software that we have considered introducing is Dyno/Drag 2000 by Motion Software, Inc., which contains an extensive list of commercially available engines and their components to simulate engine performance. The level of complexity comparatively increases from ESP to Dyno/Drag 2000. Dyno/Drag 2000 tests students' ability to choose the "right" components based on sound engineering decisions.

In comparison, WAVE (manufactured by Ricardo Software) is the most comprehensive and flexible software for simulating engine performance by simultaneously solving momentum, energy, and mass balance equations with a Wiebe-based combustion model. The software requires approximately a month of training to bring students to the point of simulating their own engines. Figure 3 shows a screen shot of WAVE simulation that students initially work on as a part of the training. The image illustrates four cylinders placed in the center with a full intake system on the left and a full exhaust system on the right. The user can specify details such as choice of fuel, exact geometry and operating temperature/pressure of all components, intake/exhaust valve lift as a function of crank shaft angle, rate and amount of heat release during combustion, and even complex muffler arrangements. Because some auto manufacturers use WAVE to design and optimize production engines, this training improves students' potential to pursue a career in auto design and manufacturing.

The last tool introduced is Working Model 2D by MSC Software. This tool allows students to construct moving components of an engine such as the cam and analyze their dynamic mechanical behavior. The exposure to mechanics helps students see that constructing a working engine requires more than understanding its thermodynamics, transport phenomena, and combustion.

The software tools additionally benefit the students who belong to the FSAE team. Using WAVE, these team members optimize their racecar design. The design rules of FSAE competition[6] are comprehensive, including chassis rules, crash protection, safety rules, and power-train restrictions. Among these rules, the design constraint of a 20.0-mm-diameter intake flow restrictor is the most limiting factor for engine breathing and hence, for its performance. The team members have been using WAVE to optimize the intake manifold to overcome this constraint and to maximize the engine

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performance of Yamaha R6.

In addition to the software tools, we use WebCT, a web-based teaching tool. It enables prompt distribution of course materials, fast real-time communication with students via chat rooms, immediate feedback on student evaluation, and compilation of research topics and information relevant to the discussion topics. Although creating and improving a WebCT site requires more hours of preparation than conventional lectures, it proves an effective medium to keep the course more accessible and malleable for improvement.

COURSE OUTCOME ASSESSMENT AND STUDENT EVALUATION

We expect the students to be able to perform the following tasks during the course of the semester:

- *Construct ideal Otto as well as nonideal P-V diagram describing each stroke of the internal combustion engine*
- *Identify key elements that contribute to the nonideality and how the nonideality impacts engine efficiency*
- *Recognize the importance of engine breathing and propose the methods of improving engine breathing based on full understanding of fluid mechanics*
- *Compare supercharging and turbocharging to natural aspiration and draw the piston trajectory on the P-V diagram*
- *Perform convective and conductive heat transfer calculations to approximate the temperature of mechanical components surrounding engine cylinders*
- *Design and virtually build a mechanically stable camshaft/valve assembly, using Working Model 2D*
- *Design a working 4- to 8-cylinder engine, using WAVE, and baseline the performance compared to commercially available production engines*

The majority of students are capable of performing the above tasks, evidence of which is based on their classroom presentation and full discussion of case studies, including the mathematical calculations. The narrow final grade distribution, ranging from 80% to 96% in cumulative scores based on the evaluation criteria described previously, support that the student groups collectively meet the expected course outcomes better than the majority of engineering classes.

The latest student course evaluation (Fall 2002) rates the course at 6 on a scale of 1 through 6, where 6 is the most favorable rating. The main categories of evaluation are course content, instructors, and effectiveness in learning. Overall, students enjoy the introduction to industry-developed software such as WAVE, the seminar format of the course that gets everyone involved, and the assignments that lead to good discussions. Students request lessening the gear head talk, however, and increasing the availability of instructors to answer the questions in regards to the case studies.

SUMMARY

The format of the HPE course is a *problem-based learning environment* centered on *case studies of specific engines,* many with great historical significance. Students and faculty jointly explore the fundamental chemical and mechanical engineering aspects that govern the operation of the internal combustion engines, leading to an understanding of how engines work, how to model them, and how to design them for maximum performance. While engineering rigor is not sacrificed, the course is about applying good engineering and its tools to high-performance engines, and in the process, making engineering fundamentals come to life.

This course is not primarily about plugging numbers into formulas, although students do some extensive calculations at times, but rather about understanding, through implementation of computing and information technology for modeling, simulation, visualization, and design. The set of resources compiled over the semester, with contributions from all faculty and students, represents a rich legacy that will be useful to those who have taken the course as well as students who follow.

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