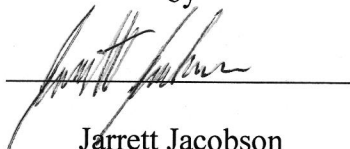


Reworking and Improving PH 2101. Principles of Thermodynamics

An Interactive Qualifying Project
Submitted to the faculty of
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
Degree of Bachelor of Science

by



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Report Submitted to:

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Abstract

This project addresses issues reported by students in the course evaluations for the PH 2101. Principles of Thermodynamics course at Worcester Polytechnic Institute. Data was collected from the 2014 and 2015 course evaluations. Course changes were proposed based on this course feedback. The changes were implemented in the 2016 and 2017 sections of the course and the effectiveness of the changes is gauged based on a comparison of the course evaluations from these years to the 2014 and 2015 evaluations.

Acknowledgements

I would like to thank Professor Germano Iannacchione for accepting my proposal for this Interactive Qualifying Project. I took the course that this IQP is auditing, PH 2101. Principles of Thermodynamics, in 2015, and I appreciate that Professor Iannacchione listened to the course experience from my perspective as a student and was willing to allow me to propose changes.

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1 Introduction

Thermodynamics is concerned with the study of energy transformations involving heat, work, and entropy. Thermodynamics has many applications in engineering disciplines involving air compression and expansion, heat transfer, power generation, and HVAC systems. Fundamental thermodynamic concepts affect engineering design decisions and analysis. As such, a strong background and understanding of the practical applications of thermodynamic concepts is imperative to the success of engineering students in their future courses and careers.

Thermodynamics courses are offered by three departments at Worcester Polytechnic Institute (WPI): Department of Engineering Science, Department of Chemistry and Biochemistry, and Department of Physics. Several majors that list a course in thermodynamics as a degree requirement offer flexibility in the choice of the thermodynamics course that students take. For example, the Aerospace department allows students to choose a thermodynamics course offered by any of the three departments. Many students strategically choose a thermodynamics course from a particular department to more easily pursue a double major or a minor by counting the credit in multiple degree requirements, or for satisfying a basic science requirement and thermodynamics requirement with one class.

The focus of this study is to evaluate the effectiveness of the thermodynamics course offered by the WPI Department of Physics, PH 2101. Principles of Thermodynamics, and generate a series of recommendations to improve course effectiveness and better actualize the course goals.

2 Background

In this chapter, the importance and background of thermodynamics courses at WPI is discussed.

2.1 Importance of Thermodynamics in an Engineering Curriculum

Thermodynamics teaches important scientific and engineering concepts and principles that students will need to use in their future classes and careers. Several majors require students to take a thermodynamics course to prepare them for courses in fluid dynamics, power generation, and heat transfer. The following majors at WPI explicitly list a 1/3 credit or more requirement in a thermodynamics class as a degree requirement:

- Aerospace Engineering—Aeronautical
- Aerospace Engineering—Astronautical
- Architectural Engineering—Mechanical
- Architectural Engineering—Structural
- Environmental Engineering
- Mechanical Engineering

In addition to these majors, many students at WPI majoring in chemical engineering take a thermodynamics course at some point of their college career to fill other requirements and prepare them for future chemistry and chemical engineering courses.

To illustrate the importance of thermodynamics courses in the engineering curricula at WPI, an analysis of the number of undergraduate graduates that were required to take a course in thermodynamics is performed. WPI publishes a Post-Graduation Report every year showing the breakdown of graduates per degree. This data is used to illustrate the number of students that require a strong background in thermodynamics for their major.

Table 1 shows the number undergraduate graduates in 2014-16 with bachelor degrees that require a thermodynamics course. The total number of bachelor degrees awarded is used to calculate the percentage of students that needed to take a thermodynamics course to graduate. This number is slightly larger than the total number of graduates due to some graduates pursuing a double major. As a result, the percentages of students with a thermodynamics course as a graduation requirement may be slightly off due to graduates using their thermodynamics course credit to satisfy the requirement for both degrees. The percentage of students graduating with double majors in 2014-16 averaged at 6.87%. This percentage can largely be ignored however, as there was only one instance of double-majoring between these four majors in the 2014-16 period (Koppi, 2014, 2015, 2016).

Table 1: Breakdown of Degrees Awarded Requiring a Thermodynamics Course

Year	2014	2015	2016
Aerospace	34	47	29
Architectural	6	3	17
Environmental	22	7	16
Mechanical	181	196	203
Total Number of Bachelor Degrees Awarded	911	1033	986
Percentage of Degrees Awarded Requiring a Course in Thermodynamics	26.67%	24.49%	26.88%

Based on the 2014-16 data, an average of 26% of graduates took a thermodynamics course as part of their degree requirement, and thus 26% of students at WPI will need a strong background in thermodynamics in their future courses and careers. This is a significant portion of the student body at WPI. It is thus vital that each thermodynamics class adequately instills the principles and concepts of thermodynamics in the students to prepare them for their future work.

2.2 Thermodynamics Courses offered at WPI

Each department offering thermodynamics course takes a slightly different approach to the topic by focusing on different areas. A review of these courses is provided in this section.

The Engineering Science department offers ES 3001. Introduction to Thermodynamics. The following is the course description taken from the 2014-15 course catalogue:

This course emphasizes system and control volume modeling using conservation of mass and the First and Second Laws of Thermodynamics. Topics include an introduction to heat, work, energy, and power, properties of simple substances, and cycle analysis for power production and refrigeration. Recommended background: basic physics, elementary differential and integral calculus. (WPI, 2014)

This course is designed for engineering students, and is particularly relevant to mechanical engineering and aerospace engineering students, as the topics covered prepare students for applying thermodynamic concepts to turbomachinery, HVAC systems, internal combustion engines, and refrigeration.

CH 3510. Chemical Thermodynamics is offered by the Chemistry and Biochemistry department. In addition to covering the basic laws and concepts of thermodynamics, this course focuses on the applications of thermodynamics to the analysis of chemical reactions and systems.

The course description reads:

The content of this course will be the development of the principles of classical thermodynamics. The laws of thermodynamics will be developed by using a series of increasingly complex model systems and a universal equation of state is formulated which incorporates the relationships illustrated by these model systems. Using this equation it will be possible to appreciate that thermodynamic laws are applicable to all systems of matter, regardless of their complexity. Finally, the principles developed are applied to problems of a chemical nature, focusing on predicting the spontaneity of chemical reactions. The material in this course will be of greatest interest to those students enrolled in the basic sciences including biology, chemistry, and physics, and in applied fields such as chemical engineering, materials science and biotechnology. Recommended background: Students

should be familiar with the material covered in the general chemistry sequence CH 1010-1040, and calculus including multi variables. (WPI, 2014)

This course is useful for students in chemical engineering, mechanical engineering, and aerospace engineering that will go on to perform work with fuels and combustibles. Biology and biochemistry students will also find this course useful to better understand the chemical reactions and processes that occur in living things.

Lastly, PH 2101. Principles of Thermodynamics is offered by the Physics department. This course takes a more fundamental and theoretical approach to thermodynamics to allow students to fully understand and appreciate the laws and physical meanings of different thermodynamics processes and parameters. The course description is as follows:

The course provides fundamental preparation for any specialized application of thermodynamics. The material covered includes a general description of large number systems, states, canonical state variables, state functions, response functions, and equations of state. Focus will be given to the physical meanings of free-energies, enthalpy, chemical potential, and entropy. Connections will be made to equilibrium states, reversible versus irreversible processes, phases and phase transformation, as well as the arrow of time as applied across disciplines. Recommended background: introductory mechanics and multi-variable calculus. (WPI, 2014)

This course is beneficial for physics and all engineering students that want a more fundamental understanding of thermodynamics and appreciation of the physical meaning behind the parameters and processes. This allows engineering students to better apply thermodynamic concepts to engineering design and analysis.

2.3 PH 2101. Principles of Thermodynamics Course Objectives

The PH 2101. Principles of Thermodynamics syllabus outlines the following as goals that students will meet by the end of the course:

- Define the term thermodynamics within the context of their specific discipline.
- Use microscopic and macroscopic variables to describe the state of any system.

- Apply conservation laws of mass/energy to any system.
- Define Equations of State and canonical (or best practice) use of state variables and apply them to arbitrary systems.
- Apply the Laws of Thermodynamics to the processer/disciplines/projects of choice.
- Calculate conditions for equilibrium and stability for phases of matter and describe phase transformations in the context of their specific discipline.
- Describe arbitrary thermodynamics processes as they pertain to the availability to extract work.
- Qualitatively and quantitatively describe reversible versus irreversible processes connecting them to the “arrow of time.”
- Apply math methods (differential relations, dimensional analysis, Legendre transforms, etc.) important in thermodynamics.
- Presentation of results of a project work applying thermodynamics performed in single and multidisciplinary teams in a formal paper format.

2.4 PH 2101. Principles of Thermodynamics Course Structure Breakdown

The 2014 and 2015 offerings of PH 2101. adhered to the following grading breakdown:

Table 2: Breakdown of Grades

SOURCE	NO.	TOTAL	WEIGHT
Quiz (100 points each)	2	200	50%
Homework	6	100	25%
Final Project	1	100	25%
TOTAL:		400	100%

Two in-class quizzes each contributed 25% to each student’s total grade. These quizzes lasted the entire class period and covered all material leading up to them. There were approximately 6 weekly homework assignments that totaled 25% of each student’s final grade. The homework allowed each student to demonstrate his or her understanding of the material to the professor and teaching assistant. The final project, in which an individual or team completed a detailed report or study on a topic of personal interest or within the scope of their major, comprised the remaining 25% of each student’s grade. The final project grade was individually assigned to each team member based on the overall grade and a mandatory statement of individual student

contributions to the project. Lastly, all course grading was performed using the “O’Neil Scale” as follows:

<u>Score</u>	<u>Rating Description</u>
5	<i>Demonstrates Mastery</i> = answer correct and presented flawlessly leaving no doubts, easy to follow.
4	<i>Demonstrates Competence</i> = answer correct with only 1 or 2 <i>very minor</i> mistakes in either the calculations or the presentation, not hard to follow.
3	<i>Suggests Competence</i> = overall correct but with troublesome errors, e.g. physically incorrect reasoning or several calculation/derivation errors, somewhat hard to follow.
2	<i>Suggests Incompetence</i> = answer incorrect with pervasive calculation/derivation errors, generally hard to follow.
1	<i>Demonstrates Incompetence</i> = answer incorrect and/or unphysical with multiple errors or glaring omissions, hard/impossible to follow
0	<i>Nothing Submitted</i>

3 Methodology

The main tool used to evaluate the effectiveness of the PH 2101. Principles of Thermodynamics course is a review of the course evaluations from the previous years that the course has been offered. A survey for data collection and analysis of the course is proposed for future study.

3.1 Course Evaluations

Anonymous course evaluations forms are provided to students during the last few days of every course at WPI. Students rate the course based on questions about the instructor, material, difficulty, and amount learned. Additionally, students are encouraged to answer several free response questions regarding what they liked and disliked about the course, what could be improved upon, and if they would recommend the course to other students. WPI archives the results of these evaluations and returns the results and free response answers to the professors so that they can use the results constructively to improve their teaching. An example of a WPI course evaluation is shown in Appendix A.

As PH 2101. Principles of Thermodynamics was only offered to students two times before the recommendations outlined in the report were implemented, the only data available for proposing changes is the 2014 and 2015 course evaluations. The comments regarding complaints and issues with this course expressed by students in these evaluations were categorized and counted to identify areas in need of improvement or overhaul. Several of the question asked students to provide a rating on a scale of 1-5. These numerical ratings are used to compare the effectiveness of the implemented changes from the 2014 through 2017 course offerings. The results of the evaluations are compared to the goals laid forth in the Course objectives

3.2 Course Survey

A course survey is proposed for use in collecting data on the key issues expressed in the course evaluations. This survey would be given to students in the course towards the end of the term to collect evaluate the effectiveness of the proposed changes. A sample of the proposed survey is available in Appendix B.

4 Findings

This chapter presents the data collected from the 2014 and 2015 PH 2101. Principles of Thermodynamics course evaluations. This data will be used to propose a series of suggested changes to improve the course.

4.1 Review of Course Evaluation Written Comments

Course evaluations from the 2014 and 2015 PH. 2101 classes were reviewed to find areas for improvement for the 2016 course offering. The comments written by students are categorized and the number of times each category was mentioned is counted. The course evaluation data for each year is shown in Table 2 and Table 3. Table 4 shows the combined data from both years that the course has been offered.

Table 3: 2014 Course Evaluation Data

Feedback Topic	Number of Mentions
Textbook incomprehensible	9
More/practical examples	12
Lecture/HW disconnect	3
Homework feedback/not returned in timely fashion	1
Homework too difficult	6
Course too theoretical	3
Did not like grading system	N/A
Project goals unclear until end	1
TA Inaccessible/Need more help sessions	5

Table 4: 2015 Course Evaluation Data

Feedback Topic	Number of Mentions
Textbook incomprehensible	8
More/practical examples	16
Lecture/HW disconnect	5
Homework feedback/not returned in timely fashion	3
Homework too difficult	7
Course too theoretical	2
Did not like grading system	2
Project goals unclear until end	1
TA Inaccessible/Need more help sessions	2

Table 5: Combined 2014 and 2015 Course Evaluation Data

Feedback Topic	Number of Mentions
Textbook incomprehensible	17
More/practical examples	26
Lecture/HW disconnect	8
Homework feedback/not returned in timely fashion	4
Homework too difficult	13
Course too theoretical	5
Did not like grading system	2
Project goals unclear until end	2
TA Inaccessible/Need more help sessions	3

The most common issue with the course expressed by students was a lack of practical examples to help guide them in completing their work. It is difficult for learners to go directly from a set of postulates, definitions, and equations to solving complex problems. Example problems help ease the transition between theory and problem solving.

The second most common issue reported by students was the difficulty in understanding the textbook, *Thermodynamics and an Introduction to Thermostatistic 2nd edition*. This text is an

important reference widely cited in physics research literature. The author claims to “have attempted to improve the pedagogical attributes of the book for use in courses from the junior undergraduate to the first year graduate level, for physicists, engineering scientist and chemists” (Callen, 1985). Based on the author’s goal of the book, it would seem that this text is inappropriate for a thermodynamics course at the introductory level. Course evaluations show that students found the text too challenging to comprehend.

Branching from the previous issue, the third most common student complaint was that the homework was too difficult. Students commented on the difficulty in understanding what was being asked by the homework problems taken from Callen’s book, and felt that the chapters did not adequately prepare them for completing these problems.

Fourth, students felt that the material being taught in lectures did not align with the homework being assigned, further making the homework difficult for them. A disconnect between material being taught during lectures and the knowledge-base required to complete the homework makes completing the assigned problems very difficult.

The fifth issue students expressed was that the course was excessively theoretical. While the goal of this course is to provide a deep understanding of thermodynamic theory and the mathematical relationships and definitions involved, students felt too disconnected from physical systems. Most of the student taking the course are pursuing degrees in engineering, and thus need to be able to apply these theories to real systems.

The remaining issues are of lesser importance and are more easily fixed. The recommendation in the following chapter aim to fix the big issues expressed by students while simultaneously mending the smaller issues, such as homework not being returned in a timely fashion.

5 Recommendations

Based on the course feedback of students, the following changes to the course design and structure are suggested to better actualize the goals outlined by the course objectives given in the syllabus. A revised course syllabus and course calendar reflecting these changes are shown in Appendix C and Appendix D respectively.

5.1 Textbook

Many students found Callen's *Thermodynamics and an Introduction to Thermostatistics 2nd Edition* too difficult to understand as an introductory text. The textbook is inappropriate for use as the main textbook for an introductory undergraduate course. In its place, I recommend Young and Freedman's *University Physics 13th Edition* as the main textbook for the course. This textbook is designed to be used as an introductory tool for many areas of physics. Chapters 17 through 20 delve into the topics of thermodynamics in a manner more accessible than Callen's text. Topics from Callen's text will still be taught to supplement the material from *University Physics 13th Edition*, but the text will not be required by students. *University Physics 13th Edition* has the added benefit of being a book that most students at WPI taking this course will already own, as it is the required text for the introductory physics courses PH 1110. General Physics-Mechanics and PH 1120. General Physics-Electricity and Magnetism.

In addition to *University Physics 13th Edition*'s clarity and readability, the text offers many practical examples relating the concepts being taught to real-world systems. Students will find this helpful in transitioning from a set of theories and principles to problem solving. A breakdown of the topics covered in *Univeristy Physics 13th Edition* is shown in Appendix E.

For the second half of the course, more advanced topics from Callen's *Thermodynamics and an Introduction to Thermostatistics 2nd Edition* will be taught. I worked with Professor Iannacchione to choose the most important topics from this text. Topics from following chapter sections were chosen for inclusion in the course:

- 3.1 The Euler Equation
- 3.2 Gibbs-Duhem Relation
- 3.3 Summary of Formal Structure
- 5.1 The Energy Minimum Principle
- 5.2 Legendre Transformation
- 5.3 Thermodynamic Potentials
- 5.4 Generalized Massieu Functions
- 6.1 The Minimum Principles for the Potentials
- 6.3 Helmholtz Potential
- 6.3 Enthalpy
- 6.4 Gibbs Potential; Chemical Reactions

It is suggested that these topics are taught in an easier and more fundamental way than is provided in the text. Professor Iannacchione requested having the final say in what material from these chapters will be taught in the course, and as such, no further details regarding this are suggested here.

5.2 Homework

Many students expressed that the homework was too difficult. As the homework questions were taken from *Thermodynamics and an Introduction to Thermostatistics 2nd Edition*, students had trouble interpreting the questions and utilizing the text to help them solve the problems. Additionally, several students reported that homework was not returned in a timely fashion further

hindering their ability to understand the material and their mistakes. To combat these issues, I propose several changes to the homework system of this course.

Firstly, I propose that Mastering Physics is used as part of the homework. Mastering Physics is an internet physics homework suite offered by Pearson Education, Inc. for use alone or in conjunction with Pearson's *University Physics* textbooks. Instructors can create highly customizable homework problems sets for students to complete and submit on the Mastering Physics website. A wide variety of problems with varying levels of difficulty are available, with options for providing hints, wrong-answer feedback, and customized grading schemes. Feedback is instantaneous, allowing students to see what they are doing correctly or incorrectly in real-time. Many of the problems available in Mastering Physics are numerical in nature. Students tend to be more comfortable with numerical problems rather than problems strictly involving variables. These types of problems provide a good starting point for students to practice new material they are learning, establishing a strong knowledge base.

For the next iteration of this course, a Mastering Physics problem set would be assigned every Friday and be due the following Wednesday at 11:59pm. This provides ample time for students to begin applying the concepts they have learned through textbook readings and lectures, and receive immediate feedback. Additionally, the problem sets will be designed such that they begin with several simpler problems to help solidify each student's understanding of basic principles and new concepts. Later problems will be chosen that help bring together and apply multiple concepts.

The second part of the renovated homework system is written homework. These assignments will be designed to challenge students and require them to organize and elegantly show their work and thought process. These problems will be designed to be more challenging than the Mastering Physics problems, but will build upon and utilize the simpler principles and problem solving

techniques used in the Mastering Physics problems. These problems will be more likely to be variable-based, requiring students to use thermodynamic definitions and multivariable calculus to solve them and illuminate the relationships and physical meaning behind the variables.

These written homework problems will act as a means for each student to demonstrate his or her understanding of the material. This allows the professor and teaching assistant to gauge the degree to which students are understanding and internalizing the course material. As all work and steps the student took to reach the final answer must be shown, the quality of work, thought process, and problem-solving steps that students use can be evaluated. This helps make up for the shortcoming of Mastering Physics only allowing for the input of final answers, and not the steps that the students took to get there.

5.3 Quizzes

The course's quiz structure will be changed from a system of two quizzes comprising 50% of each student's final grade, to a system of six weekly quizzes totaling 20% of each student's final grade. The remaining 30% of the final grade is redistributed between Mastering Physics assignments and the written homework assignments.

The final 20-25 minutes of lecture on each Friday will be reserved for the weekly quiz. The quiz will consist of one or two problems at or above the difficulty of the written homework assignments. The quiz questions will be projected in front of the class, and students will be provided with paper to work out the solution on. When students are finished with the quiz, they will staple it to the written homework assignment that they are submitting at the end of class.

This system accomplishes several goals. Firstly, it breaks up the course material into more digestible sections for students. The strict course schedule keeps the topics learned each week

contained to that week's Mastering Physics, written homework, and quiz. This will help alleviate the issue of students feeling that there is a disconnect between the material taught in lectures and the material covered on the homework. The schedule works out to roughly one textbook chapter per week, providing a strong course structure that is easy for the students and instructor to follow.

The proposed quiz protocol additionally helps lessen the time for the quiz and homework being returned. As they are stapled together, they can be graded at the same time. Quicker feedback allows students to more hastily fix their mistakes, leading to better success in future topics.

5.4 Examples and Sample Problems

The most common issue with the course expressed by students is the lack of practical example problems. Example problems are a key step in learning physics problems, as it bridges the gap between theory and application.

In addition to including more example problems in lectures, I suggest that the professor records video walkthroughs with voiceover of example problems and uploads them to a video hosting website. This is beneficial for both students and the instructor. Firstly, it frees up lecture time by requiring fewer examples to be performed during class, allowing for more discussion of theory. Secondly, it benefits students by allowing them to go through example problems at their own pace while working on homework or studying. Students will be able to pause, rewind, or re-watch as many times as necessary. Additionally, once recorded, these videos save time for the instructor in future years because the videos are reusable. It is recommended that these videos be recorded and organized in a similar fashion to the famous Khan Academy¹ videos. Many students find videos of this style very helpful.

¹ For examples of Khan Academy videos visit www.khanacademy.org.

Going further, these videos can be extended beyond just example problems. Short video lectures explaining particularly difficult concepts or methods can be provided as supplemental material for students to reference as needed.

5.5 Project Proposal

To help students better understand the goals of the final project, a project proposal will be due on the second Monday of the term. This will help clarify the goals of the project to students early on in the course so that they may properly prepare and organize their project. The proposal will allow the professor to review each team's ideas and provide feedback on the relevance, scope, and feasibility of the proposed projects. Additionally, by requiring students to decide on a project topic early in the course timeline, students will be better able to see how the course material relates to their chosen topic of interest, helping accomplish the course objective of “[applying] the Laws of Thermodynamics to the processer/disciplines/projects of choice.”

The project proposal assignment will require student to list the project team members, declare and describe of the project topic, and a discuss the project's relevance to their majors. The assignment is outlined in the *Project Paper Notes* in Appendix F.

5.6 Grading

To reflect the changes made to the course structure, a new grading system is necessary. The previous 400 total point system has been removed in favor of a weighted score of each source's final score. A breakdown of the new grading system is provided in Table 6.

Table 6: Breakdown of Suggested Grading System

SOURCE	NO.	WEIGHT
Mastering Physics	6	20%
Homework	6	35%
Quizzes	6	20%
Final Project	1	25%
	TOTAL:	100%

6 Results and Further Recommendations

The course evaluations from the 2016 and 2017 offerings of PH 2101, which implemented the proposed changes from chapter 5, are compared with the course evaluations from 2014 and 2015 to gauge the efficacy of the proposed changes.

6.1 Course Evaluation Score Comparisons

Each anonymous course evaluation asks twenty-four questions about the course that students rate on a scale of 1-5. WPI scans and archives the results of these questions. The results are made available to each professor to help them improve his or her teaching. The results of the six most pertinent questions from the course evaluations for each year from 2014 through 2017 are compared in Figures 1-6. The sample size is small, at only four years' worth of data. More data will need to be collected in future years to make a more realistic conclusion analysis.

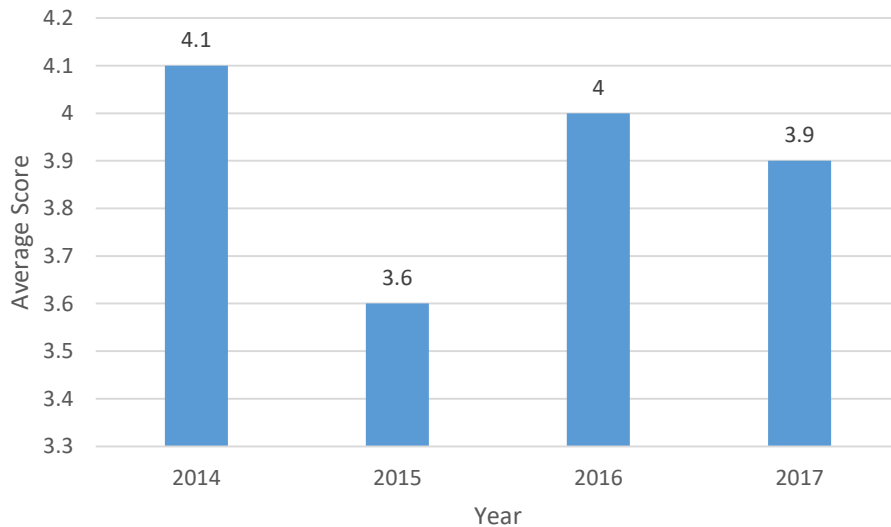


Figure 1: Average Scores of: "My overall rating of the quality of this course is"

Students rated this course consistently at around a 4 out of 5 every year except 2015. For unknown reasons, the 2015 offering of the course had low ratings for many of the question asked on the course evaluations.

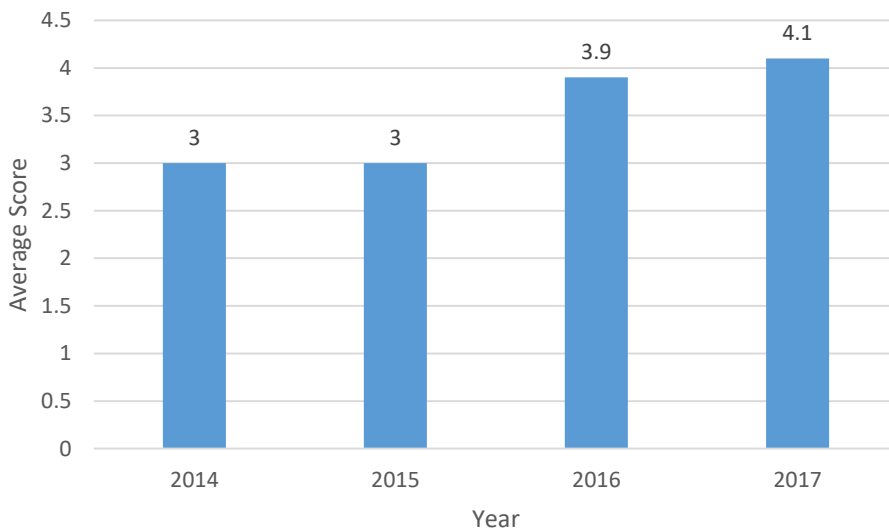


Figure 2: Average Scores of: "The educational value of the textbook and/or assigned reading was"

There is a dramatic change in how students viewed the value of the textbook after the changes were implemented. Students in the 2014 and 2015 course sections rated the education value of the textbook at a 3. After the proposed textbook change was implemented, students rated the educational value of the textbook at 3.9 and 4.1 in 2016 and 2017 respectively. This is likely due to *University Physics 13th Edition* being a more accessible and appropriate introductory text than Callen's book.

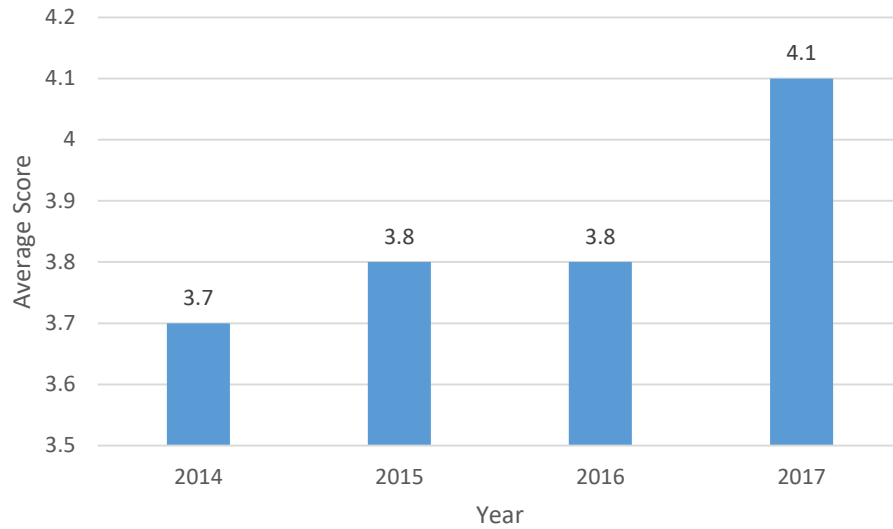


Figure 3: Average Scores of: "The educational value of the assigned work was"

The “educational value of the assigned work” was rated consistently from 2014-2016. There is a jump in this score in 2017, possibly due to Professor Iannacchione refining the Mastering Physics and homework questions to be more relevant to the course material.

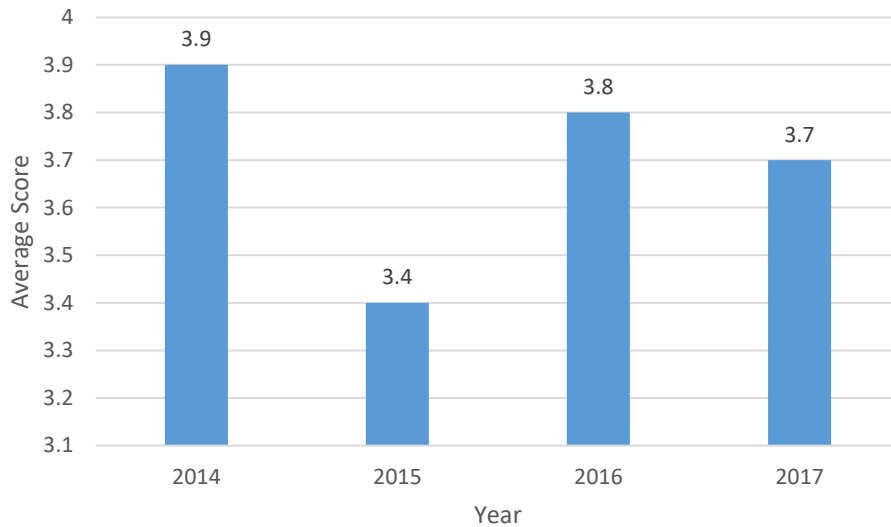


Figure 4: Average Scores of: "The amount I learned from this course was"

Students from the 2014 offering of the course rated the amount they learned as the highest in the four years that the course has existed. 2015 is once again an outlier due to unknown reasons. It is possible that the homework assignments and exams were made particularly difficult that year, and students felt as though they did not have a strong enough grasp of the material to succeed. Students in the 2016 and 2017 courses rated the amount they learned lower than that of 2014, likely due to the change to an easier to comprehend textbook and examples-based approach to the course.

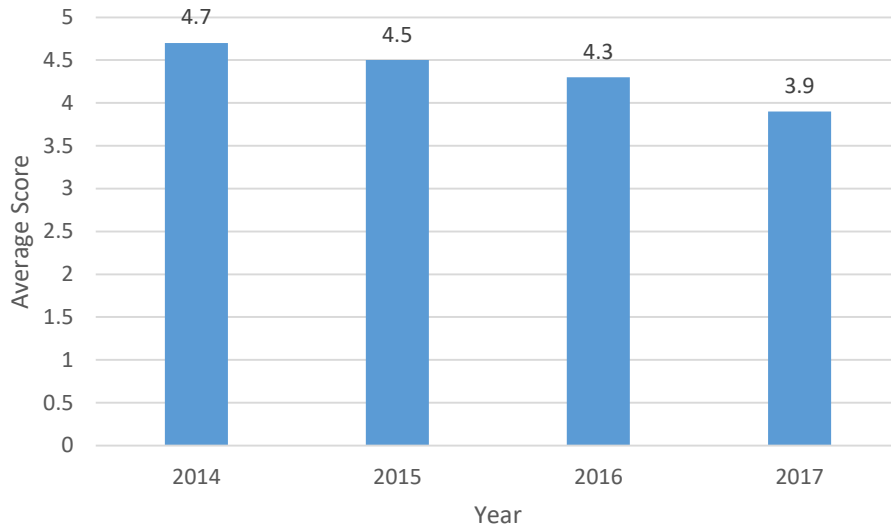


Figure 5: Average Scores of: "The intellectual challenge presented by the course was"

The average rating of the intellectual challenge presented by the course has decreased each year. It is not surprising that the two years that used Callen's book found the course more challenging than the 2016 and 2017 students who had a more approachable textbook and more example problems. The scores of 4.3 and 3.9 for intellectual challenge presented in the last two years seem more appropriate for an introductory level course than the 4.7 and 4.5 from 2014 and 2015.

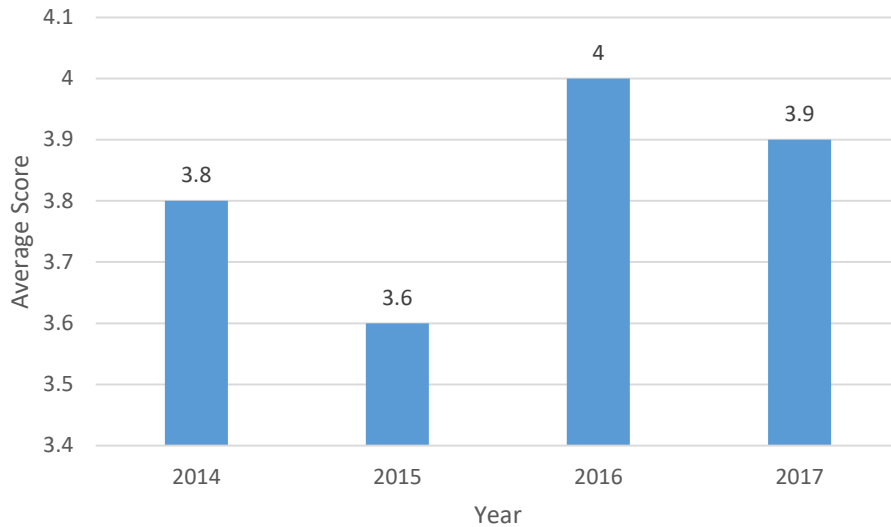


Figure 6: Average Scores of: "The instructor stimulated my interest in the subject matter"

Students in the 2016 and 2017 classes felt that their interest in thermodynamics was stimulated more than the students in the 2014 and 2015 classes. This is a good indication that the course changes were beneficial to students. Students were happier and more interested in the subject because they found it more approachable and less intimidating.

6.2 Course Evaluation Responses after Suggestion Implemented

The written responses from the 2016 and 2017 sections of the course are evaluated in this section in the same way as chapter 4 to judge the effectiveness of the changes. Table 7 and Table 8 categorize and total the written responses from 2016 and 2017 respectively. Table 9 combines the results from Tables 7 and 8.

Table 7: 2016 Course Evaluation Data

Feedback Topic	Number of Mentions
Dislike Mastering Physics	12
Like Mastering Physics	7
Not Enough Relevant Material Covered in Lecture	7
Not Enough Examples	9
Need Textbook or Reference for Material Covered in Callen's Book	3
Too Much Homework/Homework Too Long	6

Table 8: 2017 Course Evaluation Data

Feedback Topic	Number of Mentions
Dislike Mastering Physics	9
Like Mastering Physics	3
Not Enough Relevant Material Covered in Lecture	6
Not Enough Examples	14
Need Textbook or Reference for Material Covered in Callen's Book	4
Too Much Homework/Homework Too Long	5

Table 9: Combined 2016 and 2017 Course Evaluation Data

Feedback Topic	Number of Mentions
Dislike Mastering Physics	21
Like Mastering Physics	10
Not Enough Relevant Material Covered in Lecture	13
Not Enough Examples	23
Need Textbook or Reference for Material Covered in Callen's Book	7
Too Much Homework/Homework Too Long	11

The two main issues students had with the revised course was a lack of examples and a dislike for Mastering Physics. While more examples were provided during lectures compared to the 2014 and 2015 class sections, students still felt that there were not enough examples. It is difficult to balance lecture time between examples and new material, as each term at WPI is only seven weeks long and each lecture is 50 minutes. Professor Iannacchione only implemented two Khan Academy style videos with examples for students to watch outside of class. I recommend that more of these video examples are made and students are clearly instructed on where to watch them. A strong library of instructional videos with examples will alleviate the issue of not enough examples while maximizing the lecture time available for teaching new material. However, some amount of example problems should still be worked out in class to allow students to ask questions about the material and methodology.

The other main issue was a dislike for Mastering Physics, with twenty-one responses explicitly stating this. Few students provided reasons for disliking Mastering Physics other than a few responses that described technical issues that occurred with it. Ten students responded favorably to Mastering Physics, showing that a significant portion of the students appreciated its

utility. One student's response praising the use of Mastering Physics identified the reason why it is important and was implemented as a change: "Mastering Physics was helpful in figuring material out and getting a firm hold on the necessary steps in problems." I believe that the benefits of Mastering Physics and its utility in providing immediate feedback and hints as a way for students to practice the basics of the material taught outweighs some students' aversion to it.

Eleven students reported that there was too much homework and that it took too long to complete. With a Mastering Physics problem set and a written homework assignment due each week this is understandable. I recommend the Mastering Physics problem sets be shortened slightly and the difficulty of the problems be shifted to the written homework. This will shorten the amount of hours the students need to put into their homework while still achieving the goals of the assignments. With this change, the Mastering Physics will still allow students to practice the basics of the material, and the written homework assignments will challenge the students and require them to think critically.

The last issue reported by students was a need for a reference text for the later sections of the course which are not covered in *University Physics 13th Edition*. Students did not have a place to look for additional information and alternative explanations for the topics taken from Callen's book. I recommend that Professor Iannacchione makes his notes on these sections available for students to reference on the course website. Additionally, at least one copy of Callen's book should be put on reserve at the WPI Gordon Library for students to read.

7 Conclusions

PH. 2101. Principles of Thermodynamics sets out to take a different approach to thermodynamics than that of the other thermodynamics courses offered at WPI, focusing on the mathematics, definitions, and physical meaning of the relevant concepts, values, and processes. The changes outlined in this report reflect the goals of the course and the need for making the class an approachable introduction. The results of the changes show a general increase in student satisfaction and interest in the topic. Additionally, Professor Iannacchione commented on a significant rise in average grades after the changes were implemented. I believe that the changes were effective, as students felt the new textbook was more a more valuable learning tool, the value of the assigned work was more beneficial to learning, and their interest in the topic of thermodynamics was stimulated more.

Future work on the efficacy of these changes and the proposal of new changes to further refine this course can be accomplished through the evaluation of future surveys and course evaluations. The limited amount of data available for the analysis of the effectiveness of the proposed changes makes the conclusions reached in this report uncertain. I recommend that this topic is revisited in future years to further refine the course and provide students with the optimal introductory thermodynamics learning experience.

References

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- Koppi, Steve. 2015. *WPI Post Graduation Report: Class of 2015*. Worcester, MA. Worcester Polytechnic Insitute. Retreived on May 4, 2017 from <https://www.wpi.edu/sites/default/files/docs/Offices/Career-Development-Center/post-grad-report-2015.pdf>
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- Worcester Polytechnic Institute. 2014. *Undergraduate Catalog 2014-15*. Retrieved on April 30, 2017 from <https://web.wpi.edu/Images/CMS/Pubs-Catalogs-Ugrad/UGCat14-15FinalWEB.pdf>
- Young, Hugh & Freedman, Roger. 2014. *University Physics 13th Edition*. San Francisco, CA. Pearson Education, Inc.

Appendix A: Sample Course Evaluation

Class Climate	WPI Student Course Report	

Mark as shown: Please use a ball-point pen or a thin felt tip. This form will be processed automatically.
 Correction: Please follow the examples shown on the left hand side to help optimize the reading results.

You can help improve the quality of teaching at WPI by providing your responses on this form. Please consider each reply thoughtfully. These reports are used by the instructor for self-improvement, by students during course selection and by members of the administration and faculty committees. Your responses are anonymous and optional. Your comments will not be returned to your instructor until after the grading deadline.

- | | | | | | | | |
|--|---------------|--------------------------|--------------------------|-------------------------------------|-------------------------------------|-------------------------------------|---------------|
| 1. My overall rating of the quality of this course is | Very Poor (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) Excellent |
| 2. My overall rating of the instructor's teaching is | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 3. The educational value of the textbook and/or assigned reading was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 4. The educational value of the assigned work was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 5. The instructor's organization of the course was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 6. The instructor's clarity in communicating course objectives was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 7. The instructor's skill in providing understandable explanations was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 8. The instructor's skill in speaking clearly and audibly was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |

Relative to other college courses I have taken:

- | | | | | | | | |
|--|---------------|--------------------------|--------------------------|--------------------------|-------------------------------------|-------------------------------------|---------------|
| 9. The amount I learned from the course was | Much less (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) Much more |
| 10. The intellectual challenge presented by the course was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 11. The instructor's personal interest in helping students learn was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 12. The instructor stimulated my interest in the subject matter | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 13. The instructor encouraged communication outside of regular contact hours | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 14. The amount of reading, homework, and other assigned work was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 15. My attendance and participation for this course was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 16. The amount of effort I put into this course was | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |

How frequently were the following statements true in this course?

- | | | | | | | | |
|--|-----------|--------------------------|--------------------------|--------------------------|-------------------------------------|-------------------------------------|------------|
| 17. The instructor was well prepared to teach class. | Never (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) Always |
| 18. My instructor used course time effectively. | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 19. The instructor encouraged students to ask questions. | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 20. The instructor treated students with respect. | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 21. Instructor feedback on exams/assignments was timely and helpful. | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | (5) |
| 22. The exams and/or evaluations were good measures of the material covered. | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |
| 23. My grades were determined in a fair and impartial manner. | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | (5) |

24. What grade do you think you will receive in this course?
- | | | |
|---------------------------------|---|----------------------------|
| <input type="checkbox"/> A | <input checked="" type="checkbox"/> B | <input type="checkbox"/> C |
| <input type="checkbox"/> NR/D/F | <input type="checkbox"/> Other/Don't know | |
25. Which of the following best describes the role of this course in your academic program?
- | | | |
|--|--|--|
| <input type="checkbox"/> In your major field | <input checked="" type="checkbox"/> Required for major | <input type="checkbox"/> Free elective |
| <input type="checkbox"/> Required for minor | <input type="checkbox"/> Other Requirement | |
- 26A. On average, how many hours of the formally scheduled hours for lecture, conference, and labs did you ATTEND each week?
- | | | |
|--|---|----------------------------------|
| <input type="checkbox"/> 3 hr/wk or less | <input checked="" type="checkbox"/> 4 hr/wk | <input type="checkbox"/> 5 hr/wk |
| <input type="checkbox"/> 6 hr/wk | <input type="checkbox"/> 7 hr/wk or more | |
- 26B. On average, what were the total hours spent in each 7-day week OUTSIDE of formally scheduled class time in work related to this course (including studying, reading, writing, homework, rehearsal, etc.)?
- | | | |
|--------------------------------------|---|---|
| <input type="checkbox"/> 0 hr/wk | <input type="checkbox"/> 1-5 hr/wk | <input type="checkbox"/> 6-10 hr/wk |
| <input type="checkbox"/> 11-15 hr/wk | <input checked="" type="checkbox"/> 16-20 hr/wk | <input type="checkbox"/> 21 hr/wk or more |



For courses with laboratories only:

- | | | | | | | | |
|--|---------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|---------------|
| 27. The instructor showed me how to use lab equipment properly. | Never (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) Always |
| 28. The lab and/or computer equipment was in good operating condition. | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| 29. Good laboratory procedures were emphasized | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| 30. Relative to other lab experiences, the intellectual challenge presented by the lab assignments was | Much less (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) Much more |
| 31. Relative to other lab experiences, the clarity and specificity of lab assignment objectives was | Much less (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) Much more |

Your thoughtful answers to the following questions would be helpful to your instructor. (Please answer in the space provided underneath each question.)

What did you particularly LIKE about this course/lab?

Strong foundation for thermodynamics

What did you particularly DISLIKE about this course/lab?

Too much physics theory, but to be expected (personally, for me)

Can you suggest anything that the instructor could do to improve the quality of teaching?

Would you encourage a friend to take a course from this instructor? Why or why not?

Yes, absolutely knowledgeable, willing to help students during⁺ after class, very enthusiastic

Please use the following to answer additional question(s) that may be provided by your instructor:

- | | | | | | | | |
|--|----------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|-----------------|
| Instructor provided ranked question #1 | Low rating (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) High rating |
| Instructor provided ranked question #2 | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| Instructor provided ranked question #3 | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| Instructor provided ranked question #4 | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| Instructor provided ranked question #5 | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| Instructor provided ranked question #6 | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| Instructor provided ranked question #7 | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |
| Instructor provided ranked question #8 | (1) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | (5) |



Figure 7: Sample Course Evaluation

Appendix B: Sample Course Survey

PH. 2101 Principles of Thermodynamics Course Survey

Major: _____ Year and Term: _____ Year of Graduation _____

Please rate the following on a scale of 1-10 (10 being the highest).

1. The educational value of the textbook and/or assigned reading was:
2. The educational value of the assigned work was:
3. The instructor's skill in providing understandable explanations was:
4. The Amount I learned from this course was:
5. This course provided me a sufficient background in thermodynamics for future courses:
6. The instructor used course time effectively:
7. The amount of examples used in class was sufficient:
8. My overall rating of the quality of this course is:

Please provide short responses to the following questions:

- 1) What did you like or dislike about this course?

- 2) Explain how difficult/easy you found this course?

- 3) Please provide additional comments or thoughts on questions 1-8.

Appendix C: PH 2101. C16 Course Syllabus

PH 2101: PRINCIPLES OF THERMODYNAMICS

SYLLABUS

Lecturer

Logistics

Germano Iannacchione.
Office: Olin 212A (x 5631)
Email: gsiannac@wpi.edu

Days: M T Th F
Time: 2:00 – 2:50 pm
Room: FL - LWR

Constructive suggestions and comments are encouraged and always welcomed! There are no set office hours but I am available informally almost any time that is free in my schedule for questions. The best times are right after class. Students who wish to meet for extended help should arrange a specific meeting time by phone or email.

Description

Thermodynamics focuses on the universal principles governing the behavior of large ensembles of “things.” It answers the basic question, “how do chunks of the universe behave.” Because the important aspect is the large number and not the specific “things,” this discipline is universally applicable across all length scales and fields of study. The goal of this course is to provide fundamental preparation for any specific application of thermodynamics to multiple scientific and/or engineering fields.

This project-oriented course will support students to develop knowledge of a general description of large number systems, states, canonical state variables, state functions, response functions, and equations of the state. Through both traditional and project-based approaches, students will develop qualitative and quantitative skills for determining the physical meanings of free-energies, enthalpy, chemical potential, entropy, equilibrium states, reversible versus irreversible processes, phases and phase transformation, as well as the “arrow of time”. Team-based projects will allow students to integrate theoretical concepts learned to their specific disciplines. These projects will also allow students to develop written and oral communication skills.

Recommended background: introductory mechanics and multi-variable calculus

Assigned Text / Supplementary Text

Young and Freedman, University Physics 13th edition, Addison Wesley (2012).
(ISBN-13 978-0-321-69686-1)
We will be covering Chapters 17-20.

Additional supplemental text base on Callen’s Thermodynamics and an Introduction to Thermostatistics will be provided.

Other useful texts to consult:

H.B. **Callen**, Thermodynamics and an Introduction to Thermostatistics, John Wiley and Sons (1985).

J. **Chang Lee**, Thermal Physics, World-Scientific (2011).

E. **Fermi**, Thermodynamics, Dover Publications (1937).

A.B. Pippard, The Elements of Classical Thermodynamics, Cambridge University Press (1966).
E. Schmidt, Thermodynamics, Dover Publications (1966).
T. Greiner, L. Neise, H. Stocker, Thermodynamics and Statistical Mechanics, Springer-Verlag (1995).
H. Gould, J. Tobochnik, Statistical and Thermal Physics, Princeton University Press (2010).

Additional online resources that will be highlighted in lecture.

Homework

Each week will consist of one Mastering Physics (MP) problem set due on Wednesday at 11:59pm, and a homework set (HW) consisting of two problems assigned on myWPI due on Friday at the end of class. Homework problems will be posted to myWPI the Friday before they are due. There will be a total of 6 Mastering Physics problem sets and 6 Homework sets. Mastering Physics and Homework sets will contribute 20% and 30% respectively to your final grade.

Mastering Physics is used as a means to practice and apply what you are learning, and get immediate feedback. Although you do not turn in any physical work, it is suggested that you write out the problems and solutions clearly for practice.

The Homework Set is a means for you to demonstrate that you have a deeper understanding of the material and the methodologies involved. Your homework assignments must be readable and follow clearly and logically. Solutions will be handed out when the HW is due so **no late homework will be accepted.**

Quizzes

The last 20-25 minutes of each Friday lecture will be reserved for a quiz. Each quiz will consist of one question of similar difficulty and form to that of the homework problems. The problem will be shown on the projector. When you are finished, the quiz should be added and stapled to the homework assignment that you will be turning in at the end of class. Quizzes will contribute 25% to your final grade.

Final Project

A final project is due at the end of the term where a written report (fully annotated with figures and references) and 2-3 minute highlights oral presentation is delivered. The final project written report contributes 25% to your final grade. A project proposal outlining the team members, project topic, and relevance to your major will be due on the second Monday of the term.

The topic chosen must be an application of thermodynamics to your major or interests and should be developed right from the beginning of the course. Teams of students are allowed (up to 4) but with the added requirement that in the written report: (1) a detailed statement of individual student contribution to the project and (2) a clear discussion of the projects connection each team member's major. See *Project Paper Notes*.

Project grades are individually assigned to each team member, and not to the team as a whole, and will reflect on content as well as quality of the presentation.

Grading

In assigning grades at the end of the term, a number will be arrived at as follows:

<u>SOURCE</u>	<u>NO.</u>	<u>WEIGHT</u>
Mastering Physics	6	20 %
Homework	6	30 %
Quizzes	6	25 %
Final Project	1	25 %
TOTAL:		100%

In general, the class average and distribution will be used to determine the letter grade cutoffs. As a rule of thumb, the class average is set to a high C and each letter range is about 12 points wide. Hence, 2-3 points above the class average is about the C/B cutoff while 9-10 points below is about the C/NR cutoff. Finally, the A/B cutoff is about 12 + (2 to 3) points above the class average.

PH 2101: Principles of Thermodynamics – Scoring Scheme

Your scores for each deliverable are NOT determined by specific point deduction. Each activity is graded as a whole in terms of overall QUALITY. Thus, your deliverables are *rated* ... much like how you rate your instructors at the end of the course on a 0 to 5 scale (or multiples of 5).

The O'Neil Scale (named after a revered WPI physics professor):

Score Rating Description

- 5 *Demonstrates Mastery*
= answer correct and presented flawlessly leaving no doubts, easy to follow.
- 4 *Demonstrates Competence*
= answer correct with only 1 or 2 *very minor* mistakes in either the calculation or the presentation, not hard to follow.
- 3 *Suggests Competence*
= overall correct but with troublesome errors, e.g. physically incorrect reasoning or several calculation/derivation errors, somewhat hard to follow.
- 2 *Suggests Incompetence*
= answer incorrect with pervasive calculation/derivation errors, generally hard to follow.
- 1 *Demonstrates Incompetence*
= answer incorrect and/or unphysical with multiple errors or glaring omissions, hard/impossible to follow.
- 0 *Nothing submitted*

PH 2101: Principles of Thermodynamics – Course Objectives

By the end of the term, the students will be able to:

- Define the term thermodynamics within the context of their specific discipline.
- Use microscopic and macroscopic variables to describe the state of any system.
- Apply conservation laws of mass/energy to any system.
- Define state functions and response function and utilize their inter-relationships for characterizing a phase of matter.
- Define Equations of State and canonical (or best practice) use of state variables and apply them to arbitrary systems.
- Apply the Laws of Thermodynamics to the processes/disciplines/projects of choice.
- Calculate conditions for equilibrium and stability for phases of matter and describe phase transformations in the context of their specific discipline.
- Describe arbitrary thermodynamic processes as they pertain to the availability to extract work.
- Qualitatively and quantitatively describe reversible versus irreversible processes connecting them to the “arrow of time”.
- Apply math methods (differential relations, dimensional analysis, Legendre transforms, etc.) important in thermodynamics.
- Presentation of results of a project work applying thermodynamics performed in single- and multidisciplinary teams in a formal paper format.

2101: Principles of Thermodynamics – Course Schedule (also see course calendar)

<u>Week</u>	<u>Session</u>	<u>Topic</u>
		<i>Chapter 19: The First Law of Thermodynamics</i>
1	1	Course Introductions and Logistics
	2	Definitions of Thermodynamic Systems and Processes What is thermodynamics?
2	3	The First Law of Thermodynamics Heat and Work
	4	<i>p</i> v-diagrams The types of Thermodynamic Processes
[HW#1 due] [Quiz#1]	5	Internal Energy and Heat Capacities
		<i>Chapter 17: Temperature and Heat</i>
3	6	Introduction to Temperature, Temperature Scales, Zeroth Law of Thermodynamics
	7	Defining Quantity of Heat, Specific Heat, Molar Heat Capacity
	8	Phase changes, Heat Transfer
[HW#2 due] [Quiz#2]	9	Applications of Heat Transfer–Thermal Stress and Expansion

Chapter 18: Thermal Properties of Matter

4	10	Introduction to Equations of State Simple Ideal Gas and Multi-component Ideal Gas
	11	The van der Waals Equation p - v -diagrams and Ideal Gases
	12	Kinetic-Molecular Model of Ideal Gases Defining Pressure and Molecular Energies
[HW#3 due] [Quiz#3]	13	Heat Capacities C_v and C_p

Chapter 20: The Second Law of Thermodynamics

5	14	Directions of Thermodynamic Processes Reversible vs. Irreversible Processes
	15	Entropy and the Second Law of Thermodynamics
	16	Entropy in Different Thermodynamic Cycles
[HW#4 due] [Quiz#4]	17	Heat Engines, Otto Cycle, and Refrigerators

6	18	Continuing Heat Engines, Otto Cycle, and Refrigerators
	19	Engine Efficiency and Carnot Cycle
[HW#5 due] [Quiz#5]	20	The Generalized Massieu Functions

7	21	The Minimum Principle for the Potentials
	22	The Helmholtz Potential and Enthalpy
	23	Gibbs Potential and Chemical Reactions Other Potentials
[HW#6 due] [Quiz#6]	24	Compilations of Experimental Data: The Enthalpy of Formation The Maximum Principles for the Massieu Functions

Chapter 7: Maxwell Relations

8	25	Maxwell Relations Thermodynamic Mnemonic Diagram
	26	Intrinsic Stability of Thermodynamic Systems Stability Conditions for Thermodynamic Potentials
	27	Entropy and why time moves from past to future
[Project due]	28	Big Questions, Big History

Appendix D: Proposed 2016 Course Calendar

JANUARY

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SAT/SUN
WEEK 1	11	12	13	14 First Day of Class	15	16/17
WEEK 2	18	19	20 Mastering Physics #1 Due	21	22 Homework #1 Due Quiz #1	23/24
WEEK 3	25 Project Proposal Due	26	27 Mastering Physics #2 Due	28	29 Homework #2 Due Quiz #2	30/31

FEBRUARY-MARCH

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SAT/SUN
WEEK 4	1	2	3 Mastering Physics #3 Due	4	5 Homework #3 Due Quiz #3	6/7

WEEK 5	8	9	10 Mastering Physics #4 Due	11	12 Homework #4Due Quiz #4	13/14
	notes					
WEEK 6	15	16	17 Mastering Physics #5 Due	18	19 Homework #5 Due Quiz #5	20/21
	notes					
WEEK 7	22	23	24 Mastering Physics #6 Due	25	26 Homework #6Due Quiz #6	27/28
	notes					
WEEK 8	29	1	2	3	4 Project Due	5/6
	notes				Last Day of Class	

Figure 8: Proposed Course Calendar for 2016

Appendix E: Topics Covered in Young and Freedman Ch. 17-20

Chapter 17: Temperature and Heat

- Temperature
- Thermal equilibrium
- Insulators
- Zeroth Law of thermodynamics
- Temperature scales and conversion between
- Thermal expansion
- Thermal stress
- Quantity of heat dQ defined
- Specific heat derived mathematically
- Molar Heat capacity
- Heat Transfer, conduction/convection/radiation and associated equations.

Chapter 18: Thermal Properties of Matter

- Equations of State
- Ideal gas equation
- Van der Waals Equation
- pV -diagrams, isotherms
- Kinetic energy of gases
- Molecular Speeds, Maxwell-Boltzmann Distribution
- Mean free path
- Heat Capacities
- Phases of matter, phase equilibrium, phase diagrams, triple point.

Chapter 19: The First Law of Thermodynamics

- Definition of Thermodynamic System
- Definition of Thermodynamic Process
- Heat Q and Work W
- $Dw = Fdx = pAdx$
- $W = \int_{V_1}^{V_2} pdV$
- Paths in a thermodynamic process
- Internal energy
- First Law of Thermodynamics: $Q = \Delta U + W$
- First Law of Thermodynamics in differential form: $dU = dQ - dW$
- Types of Thermodynamic Processes and their pV diagrams:
 - Adiabatic
 - Isochoric
 - Isobaric
 - Isothermal

- Internal energy
- Heat capacities, C_p and C_v , and their derivations
- Ratio of heat capacities, γ

Chapter 20: The Second Law of Thermodynamics

- Directions of thermodynamic processes
- Reversible processes/equilibrium processes
- Heat engines
- Working substance
- Heat reservoirs
- Thermal efficiency
- Energy-flow diagrams
- Internal combustion engines
- Otto Cycle
- Refrigerators
- Second Law of Thermodynamics
- Carnot Cycle
- Entropy
- Entropy in reversible/cyclic/irreversible processes

Appendix F: Project Paper Notes

Project Paper Notes

A fully annotated final project with figures and references is due at the end of the term. A project proposal will be due on **Monday, January 25**. This proposal will briefly outline the topic, methods, and scope for your project, as well as provide brief discussion of how the chosen topic relates to your major or personal interests. It should also include a list of all group members (up to 4), your majors, and emails addresses. The topic chosen must be an application of thermodynamics to your major or interests.

Upon submission of your final project, a detailed statement outlining each individual student's contribution to the project and a clear discussion of the project's connection to each team member's major must be submitted. This project contributes 25% to your final grade, and grades will be individually assigned to team members.

Your project must follow the format:

- Title Page
- Abstract
- Introduction
- Methods
- Results
- Discussion
- Conclusion
- References