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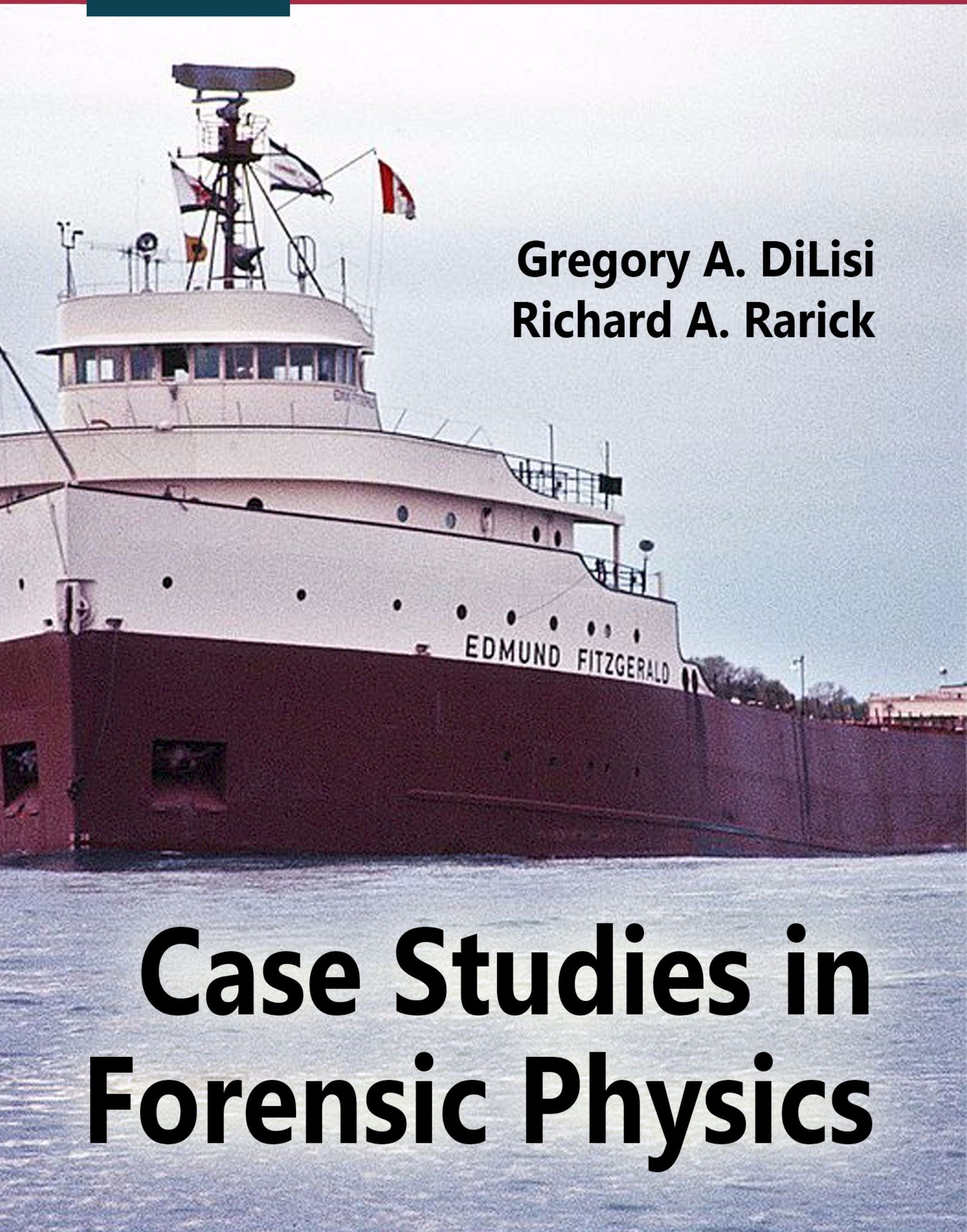

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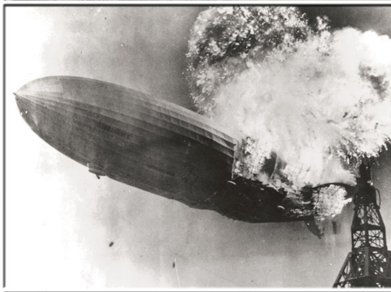
Case Studies in Forensic Physics



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Case Studies in Forensic Physics

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SYNTHESIS LECTURES ON ENGINEERING, SCIENCE, AND TECHNOLOGY #9

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ABSTRACT

This book focuses on a forensics-style re-examination of several historical events. The purpose of these studies is to afford readers the opportunity to apply basic principles of physics to unsolved mysteries and controversial events in order to settle the historical debate. We identify nine advantages of using case studies as a pedagogical approach to understanding forensic physics. Each of these nine advantages is the focus of a chapter of this book. Within each chapter, we show how a cascade of unlikely events resulted in an unpredictable catastrophe and use introductory-level physics to analyze the outcome. Armed with the tools of a good forensic physicist, the reader will realize that the historical record is far from being a set of agreed upon immutable facts; instead, it is a living, changing thing that is open to re-visitation, re-examination, and re-interpretation.

KEYWORDS

forensic physics, applied physics, forensic analysis, introductory physics

This book is dedicated to my family:
to my grandparents, Tommaso and Carmela Frate,
to my parents, Richard and Mary DiLisi,
to my siblings, Rick DiLisi, Carla Solomon, and Jennifer Newton,
to my wife, Linda,
to my daughter, Carmela,
and
to the wonderful creatures who inhabit our home.

Gregory A. DiLisi

Contents

Preface

INTRODUCTORY REMARKS

My interest in case studies and forensic physics came about by accident. As I will discuss in Chapter 9, I was at a department meeting when one of my colleagues described his part-time job as a referee for local high school football games. He had me spellbound as he described his involvement in a controversy surrounding a hotly contested playoff game. A quarterback had completed a spectacular pass that would have won the game; however, my colleague ruled that the quarterback's airborne knee and foot were *beyond* the line of scrimmage when the ball was released, thus negating the play. In the parlance of referees, the play was "an illegal forward pass" [1]. After a series of official protests were lodged against him, my colleague was adamant that he had called the play correctly and that a videotape of the play would vindicate him. He made his case: "I have a videotape of the play. If only someone could scientifically analyze it for me." That kind of talk gets a physicist's blood pumping! Rest assured, my analysis of the video proved my friend had indeed made the correct call but, more importantly, it was my first taste of using forensic physics to re-examine an actual historical event (albeit a local high school football game). I was hooked!

Today, I use case studies as a way to teach not only physics, but topics in engineering, problem-solving, critical thinking, and even ethics. Indeed, the pedagogical utility of case studies is a growing and well-researched area of physics education [2–4]. For example, the University at Buffalo, with support of the National Science Foundation, hosts the National Center for Case Study Teaching in Science [5]. The Center's site contains a searchable database of over 750 peer-reviewed cases studies, encompassing all areas of science and engineering. Likewise, the American Physical Society and American Association of Physics Teachers have prepared guidelines for structuring case studies to assist teachers in achieving their desired student learning outcomes [6]. Furthermore, the American Physical Society's Forum on Education provides a nice summary of the rationale and benefits of using case studies in the physics classroom [7]. For example, in addition to re-examining historical events, case studies allow teachers to incorporate the reverse engineering of products into their classroom activities and make for powerful senior-level capstone projects in which students must build prototypes of newly conceived devices to address specific concerns of a client. The list goes on. On a final note, I should point out that lumping together the various formats in which case studies are utilized is somewhat problematic since each has its advantages/disadvantages and addresses different types of learning outcomes. However, I want to create a single label to represent the set of pedagogies that implement an up-close, in-depth investigation of a single event as a means of teaching content. Therefore, in this text, I use the phrase "case studies" in its most generic sense.

FORMAT OF THIS BOOK

Since analyzing that controversial football play, my colleagues and I have written several articles which focus on a forensics-style re-examination of other controversial historical events. In each article, we presented a case study as a pedagogy for teaching topics from both introductory- and advanced-level physics courses. Capitalizing on these articles, I recently assembled our works into a series of *"MythBusters-style"* modules for pre-service teachers enrolled in a science education course where we trial-tested the activities presented in each chapter of this book (Chapter 10 discusses the reactions of the pre-service teachers to our material). The goal of these modules was to widen the pedagogical viewpoint of the pre-service teachers by exposing them to case studies as a means of teaching physics, problem-solving, and critical-thinking. Combining our previous articles, the classroom modules for pre-service teachers, the best practices from the literature, and the lessons learned from the implementation of our prior works, we identified nine advantages of using case studies as a pedagogical approach to teaching. Each of these nine "pedagogical advantages" is the focus of a chapter of this book. Within each chapter, a case study is used as a way to highlight the "pedagogical advantage," although we emphasize that each chosen case study could be used to highlight any of the identified advantages. Each case study uses physics to analyze a controversial historical event and attempts to resolve the historical debate. Given the format just described, you might say that this book is a case study in case studies.

The advantages which are highlighted in each chapter and the accompanying case studies are summarized below.

1. **Case studies allow teachers to emphasize that scientists now take a forensics-approach to historical events.** Scientists no longer adopt a strictly passive approach to history. Instead, they bring sophisticated analytical tools to scrutinize why certain events happened. The 2015 American Football Conference Championship game between the New England Patriots and the Indianapolis Colts, better known as *"Deflategate,"* is a powerful example of how the historical record is open to re-examination and re-interpretation [8].

2. **Case studies are interdisciplinary, have broad appeal, and make personal connections to students.** Case studies were first used in the 1820s as a way of teaching the social sciences and quickly became associated with teaching anthropology, history, sociology, law, medicine, and psychology. Today, however, case studies are used in business, education, and all sub-disciplines of the STEM-fields. Our analysis of a spectacular scene from the movie *Black Panther*, demonstrates how case studies have been used to make broad, interdisciplinary appeal [9].

3. **Case studies, more so than traditional pedagogies, raise historical awareness in students and bring historical contexts to new generations of students.** By presenting stu-

dents with relevant background information, comparative timelines, and leading theories as to why events unfolded as they did, we can bring sometimes forgotten events to new generations of students. The tragic story of the *Lady Be Good*, a World War II B-24 bomber that mysteriously disappeared in 1943, is a riveting tale of courage that can be handed down to the next generation of students while simultaneously tackling multiple topics in physics and engineering [10].

4. **Case studies highlight the importance of operational definitions in scientific experiments.** With a case study, students see, perhaps for the first time, how operational definitions compare phenomena of interest against known standards or accepted protocols. Our article on the *Hindenburg* disaster provides an excellent case study to illustrate this point. On May 6, 1937, the German zeppelin *Hindenburg* caught fire while preparing to dock at the Naval Air Station in Lakehurst, New Jersey. The ensuing fire destroyed the massive airship in 35 seconds. We present the historical debate as: *"What was the source of fuel for the fire that destroyed the* Hindenburg?" [11].

5. **Case studies demonstrate the phenomenon of "Normalization of Deviance" that plagued several notorious engineering disasters.** Often, groups of scientists and engineers go to extreme lengths to test and re-test various design concepts and construction techniques. Immersed in an isolated and high-stress environment, these groups develop a false sense that their products are "fail-safe," "full-proof," and "invincible." Over time, the group accepts a lower and lower standard of performance until that standard becomes the new "norm." This phenomenon is known as "Normalization of Deviance," since the departure from a higher, more robust standard has been normalized. For this topic, a case study was designed to honor the crew of Apollo 1. On January 27, 1967, a fire swept through the interior of NASA's *"AS-204"* Command Module and killed American astronauts Roger Chaffee, Virgil "Gus" Grissom, and Edward White II during a rehearsal of their upcoming space flight. We present the historical debate as: *"What was the source of fuel for the Apollo 1 fire?"* [12].

6. **Case studies demonstrate the *"perfect storm scenario"* — how a progression of events often results in an unlikely or unforeseen outcome.** Our article on the sinking of the *S.S. Edmund Fitzgerald* provides the basis of this case study. On November 10, 1975, the Great Lakes bulk cargo freighter *S.S. Edmund Fitzgerald* suddenly and mysteriously sank during a winter storm on Lake Superior. All 29 men onboard perished. Students see that an unlikely cascade of conditions (*i.e.*, the *"perfect storm scenario"*) were met, thus placing the ship at the wrong place at the wrong time. We present the historical debate as: *"Why did the S.S. Edmund Fitzgerald sink in Lake Superior on November 10, 1975?"* [13].

7. **Case studies showcase that scientists and engineers must often develop simulations or test analog materials in lieu of actual substances — especially if those substances are**

prohibitively rare, precious, expensive, or dangerous to test. To illustrate this point, we examine the conditions of the Indian Ocean Tsunami following the Sumatra–Andaman earthquake of December 26, 2004. As a result of the earthquake, a 1,200-km × 900-km area of the ocean floor slipped 15 vertical meters where the Indo-Australian plate subducts under the smaller overriding Burma microplate. The ensuing tsunami led to the deaths of more than 200,000 people and devastated parts of Indonesia, Sri Lanka, India, Thailand, Somalia, and Burma. We present the historical debate as: *"What factors contributed to the formation of the Indian Ocean Tsunami of 2004?"* [14].

8. **Case studies allow teachers to discuss active areas of research and ask complex questions while still covering the appropriate content and maintaining the appropriate level.** Teachers are often handcuffed to teach predetermined, district-, or department-prescribed curricula. Case studies allow front-line research to be brought into the classroom. Teachers can emphasize to students the importance of staying current with recent developments in scientific research and demonstrate how this informs teaching. The sinking of the "unsinkable" R.M.S. Titanic on its maiden trans-Atlantic voyage is the hallmark example of such an opportunity. On April 14, 1912, the massive British passenger liner struck an iceberg and sank in under three hours. Over 1,500 passengers and crew perished. We present the historical debate as: *"Why did Titanic hit the iceberg in the first place?"* [15].

9. **Case studies offer teachers and students the opportunity to explore and re-examine local events.** Not all case studies have to involve historical events from the national- or international-scenes. Re-examining local events, or events that transpire at school, can bring content directly into students' lives. Thus, case studies personalize the curriculum while emphasizing how content can be used to treat a wide range of events. For this topic, we revisited a well-known controversial football play between two Cleveland-area high school football powerhouses. The play is legendary in Cleveland lore. A video analysis of the play opens up the historical debate to, *"You make the call!"* and asks students to determine if the referee indeed made the correct ruling [16].

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July 2020

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My friend, co-author, and the finest engineer walking the planet today, **Richard Rarick**. Rick's craftsmanship as an engineer and dedication to the art of teaching manifest themselves in several sections of this text. Rick's attention to detail is simply unparalleled.

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Gregory A. DiLisi
July 2020

CHAPTER 1

Taking a Forensics Approach to History

Case studies allow teachers to emphasize that scientists now take a forensics approach to historical events

Scientists no longer adopt a strictly passive approach to history. Instead, they bring sophisticated analytical tools to scrutinize why certain events happened. Far from being a set of agreed upon immutable facts, the historical record is now open to re-examination and re-interpretation. The 2015 American Football Conference Championship game between the New England Patriots and the Indianapolis Colts, better known as *"Deflategate,"* is a powerful example of how the historical record can be re-opened time after time. At halftime of this game, officials determined that 11 of the 12 footballs being used by the Patriots on offense were significantly underinflated. The team was immediately accused of intentionally using underinflated balls to give its offense an advantage. We present the historical debate as: *"Did the New England Patriots cheat during the AFC Championship game of 2015?"* Although our laboratory activity could focus on the ideal gas law and the effects of temperature on pressure, a simple analysis of the sound of bouncing balls resolves the debate. Sound waves from various professional-grade sports balls are analyzed as they bounce off of the floor. Discussions of projectile motion, conservation of energy, and linear impulse/momentum support the analysis.

1.1 BOUNCING BACK FROM "DEFLATEGATE": A CASE STUDY IN THE PHYSICS OF A BOUNCING BALL

Gregory A. DiLisi, *John Carroll University, University Heights, Ohio*
Richard A. Rarick, *Cleveland State University, Cleveland, Ohio*

1.1.1 INTRODUCTION

Halfway through the National Football League's 2015 American Football Conference (AFC) Championship game between the New England Patriots and Indianapolis Colts [1], game officials discovered that the Patriots were using under-inflated footballs on their offensive snaps (see Figure 1.1). A controversy ensued because the Patriots had actually supplied these balls

Figure 1.1: Even today, controversy surrounds the 2015 AFC Championship game between the New England Patriots and the Indianapolis Colts. The Patriots won the contest, 45 to 7, but the game quickly became known as “Deflategate.” Special thanks to Carmela DiLisi for designing this graphic.

to the game’s Referee just hours before kick-off. In a rare but touching display of solidarity, athletes and physicists have since agreed that using under-inflated footballs gives an unfair advantage to the offensive team since its players can improve their grip on the ball. Media outlets focused their attention on two possible culprits behind the deflationary debacle: either the Patriots had intentionally under-inflated their supply of footballs … or the climatic conditions, coupled with the various impacts to which the balls were subjected during the course of the game, had somehow altered the internal air pressure of the balls. This controversy soon became known as “Deflategate.”

The purpose of this case study is to analyze the physics of “Deflategate” using the basic principles of physics covered in a typical introductory physics courses. First, we provide some background information on the actual 2015 AFC Championship game and subsequent media-blitz surrounding the controversy. This information will help us contextualize “Deflategate” as a real-word application of “physics in action.” Next, we recast the spotlight on “Deflategate” from its traditional focus, the Ideal Gas Law, to a new one—the physics of a bouncing ball. We then use this scenario as a motivation for a fun but informative set of experiments that can be carried out using equipment already found in most high school or college laboratories. The subsequent data analysis relies on three basic principles: **Projectile Motion**, **Conservation of Energy**, and **Linear Impulse/Momentum**. The analysis showcases the application of introductory physics to the world of sports and demonstrates how multiple problem-solving strategies can be used to examine different aspects of a single controversy. Finally, some experimental results are presented and discussed.

1.1.2 THE CONTROVERSY

Throughout the 2014–2015 NFL football season, several teams (most noticeably the Indianapolis Colts and Baltimore Ravens) suspected that the New England Patriots were playing with under-inflated footballs while on offense. Media reports confirm that as early as November 2014, NFL officials had been alerted to the possibility that the Patriots were routinely using under-inflated footballs on offensive. With a history of alleged violations of League rules, suspicion immediately fell upon Patriots head coach, Bill Belichick, as the mastermind behind the *intentional* use of under-inflated balls. *Had Belichick purposely supplied under-inflated balls for some nefarious purpose?* Both athletes and physicists agree that the primary benefit of using an under-inflated football is that the reduced air pressure in the ball makes it easier to grip. Presumably, increasing the grip on the ball gives an advantage to the offense since the ball is now easier to throw and catch and less likely to fumble, especially in the cold and wintry conditions that often dominate the games of the NFL's post-season. Starting in 2006, the National Football League's rules require that each team supply the Referee with 12 footballs that will be used by that team while on offense. According to the 2013 Official Playing Rules of the National Football League: Rule 2 — "The Ball," Section 2 — "Ball Supply:"

Rule 2 The Ball
Section 2
BALL SUPPLY

- *Each team will make 12 primary balls available for testing by the Referee two hours and 15 minutes prior to the starting time of the game to meet League requirements. The home team will also make 12 backup balls available for testing in all stadiums. In addition, the visitors, at their discretion, may bring 12 backup balls to be tested by the Referee for games held in outdoor stadiums. For all games, eight new footballs, sealed in a special box and shipped by the manufacturer to the Referee, will be opened in the officials' locker room two hours and 15 minutes prior to the starting time of the game. These balls are to be specially marked by the Referee and used exclusively for the kicking game.*

- *In the event a home team ball does not conform to specifications, or its supply is exhausted, the Referee shall secure a proper ball from the visitors and, failing that, use the best available ball. Any such circumstances must be reported to the Commissioner.*
- *In case of rain or a wet, muddy, or slippery field, a playable ball shall be used at the request of the offensive team's center. The Game Clock shall not stop for such action (unless undue delay occurs).*

  Note: It is the responsibility of the home team to furnish playable balls at all times by attendants from either side of the playing field.

Using this process, quarterbacks get to use footballs that they have repeatedly handled and for which they have developed a "feel" that suits them. Also, the rule ensures that teams do not play with a football supplied by another team except after recovering a fumble or interception. The rules further stipulate that two hours and 15 minutes prior to every game, the Referee must measure the pressure of each of the 24 game-balls (using a pump or gauge supplied by the home club) and verify it to be between 12.5 and 13.5 PSI. Again, according to the 2013 Official Playing Rules of the National Football League: Rule 2 — "The Ball," Section 1 — "Ball Dimensions:"

Rule 2 The Ball
Section 1
BALL DIMENSIONS

- *The Ball must be a "Wilson," hand selected, bearing the signature of the Commissioner of the League, Roger Goodell.*
- *The ball shall be made up of an inflated (12 1/2 to 13 1/2 pounds) urethane bladder enclosed in a pebble-grained, leather case (natural tan color) without corrugations of any kind. It shall have the form of a prolate spheroid and the size and weight shall be: long axis, 11 to 11 1/4 inches; long circumference, 28 to 28 1/2 inches; short circumference, 21 to 21 1/4 inches; weight, 14 to 15 ounces.*
- *The Referee shall be the sole judge as to whether all balls offered for play comply with these specifications. A pump is to be furnished by the home club, and the balls shall remain under the supervision of the Referee until they are delivered to the ball attendant just prior to the start of the game.*

As a side note, the acceptable pressure of 12.5 to 13.5 PSI for each football, as mandated by NFL Rule 2 — Section 1, can be a bit misleading. Obviously, with atmospheric pressure typically accepted to be 14.7 PSI, a football would collapse if its inside pressure were truly less than one atmosphere. Instead, the League rule refers to the "gauge pressure" (or "pressure difference" between the inside and outside of the ball), not the "total pressure." Pressure gauges typically measure the pressure relative to the surrounding atmosphere. Thus, if ever using the Ideal Gas Law to tackle the physics of "Deflategate," be sure to use total pressure by adding 14.7 PSI to the gauge pressure.

Once the pressures are verified, the Referee is to store the balls until handing them over to a game-attendant just prior to kick-off. Other attributes of the footballs such as their dimensions and weights are specified by League rules, but are not required to be verified by any of the game officials. Finally, regarding the supply of game-day footballs, League rules also dictate the following: only the Referee is required to verify that the 24 game-balls comply with League specifications; the home team is to supply a set of 12 back-up balls for pressure-testing; and a separate set of 8 balls directly mailed to the Referee by the manufacturer is to be used for all aspects of the kicking game.

On Sunday, January 18, the New England Patriots routed the Indianapolis Colts, by the score of 45 to 7, in the NFL's 2015 American Football Conference championship game. The game proved to be one of the most lop-sided championship games in the history of the AFC. The game was held at Gillette Stadium, home of the Patriots, in Foxboro, Massachusetts. Air temperatures were recorded as: 52°F at kick-off (6:50 pm), 52°F at halftime, and 46.9°F at the final gun. Though the game ended in a rout, the halftime score suggested a more even contest at 17 to 7 in favor of the Patriots. Before the half ended, with the game's outcome still very much in question, a controversy erupted that continues to be the debate of athletes, sports writers, and physicists around the world. During the first half of the game, the Patriots quarterback Tom Brady, threw an interception to Colts defensive linebacker D'Qwell Jackson (see Figure 1.1).

Jackson, suspecting that the Patriots might indeed be using under-inflated balls, immediately handed the football to the Colts equipment manager for inspection. Once alerted by the Colts, game officials noticed that 11 of the 12 footballs being used in the game by the Patriots, were "significantly under-inflated." The exact measurements of pressure, as well as the temperature and time at which these measurements were taken, were not logged. News reports indicate that when checked by the Referee at halftime, the 11 balls in question were 1.4–2 PSI under the minimum pressure; however, these values of differentials in pressure have been debated. During the halftime intermission, the 11 under-inflated balls were re-inflated to proper pressure (though again, exact values of time, temperature, and pressure were not logged). Further confusion exists as to whether the set of footballs used by the Patriots to play the second half were the re-inflated balls or their set of backup footballs.

… and so began what soon became known as: "Deflategate" (the moniker makes an obvious connection to the 1970s "Watergate" scandal of political corruption). Had the Patriots *pur-*

posely under-inflated the footballs to give the team an advantage on offense … or could physics be the culprit? Perhaps the balls had simply deflated due to the changing weather conditions between the indoor location where the balls were inflated and the outdoor conditions of Gillette Stadium in mid-January. Additionally, perhaps the conditions to which the balls were submitted during the course of the first half, (i.e., throwing, fumbling, bouncing, etc.) also contributed to the change in air pressure inside the footballs? **Thus, the controversy of "Deflategate" was launched and the question on everyone's mind became: "Who was the culprit … Patriots Coach, Bill Belichick? … Patriots Quarterback, Tom Brady? … or physics?"**

1.1.3 THE MEDIA BLITZ–PHYSICS TO THE RESCUE

Within hours of the final gun, reports began to flood news outlets with speculation about the physics of "Deflategate." Op-ed pieces by columnists, bloggers, current and former athletes, and physicists are too numerous to cite; however, some of the highlights include the following.

- On Saturday, January 24, Bill Belichick held one of the most tongue-tied, pseudo-scientific press conferences since "The Professor" first lectured Gilligan on the subtleties of quantum mechanics. Attempting to deflate "Deflategate," Belichick fumbled through an explanation of how the footballs naturally became under-inflated. A particular highlight of the press conference was when Belichick mentioned that he wasn't the "Mona Lisa Vito" of air pressure (Vito refers to Marisa Tomei's Academy Award winning performance as a know-it-all auto mechanic in the movie "My Cousin Vinny."): "I would not say that I'm the Mona Lisa Vito of the football world as she was the car expertise area. All right?" In his press conference, Belichick theorized that the changing pressures in the footballs were the manifestations of two phenomena. First, "climatic conditions:"

> *"We found that once the footballs were on the field over an extended period of time, in other words, they were adjusted to the climatic conditions and also the fact that the footballs reached an equilibrium without the rubbing process, that after that had run its course and the footballs had reached an equilibrium, that they were down approximately one-and-a-half pounds per square inch. When we brought the footballs back in after that process and re-tested them in a controlled environment as we have here, then those measurements rose approximately one half pound per square inch. So the net of one and a half, back to a half, is approximately one pound per square inch, to one and a half."*

Next, Belichick offered the second of his two phenomena, "the rubbing process:"

> *"Now, we all know that air pressure is a function of the atmospheric conditions. It's a function of that. If there's activity in the football relative to the rubbing process, I think that explains why when we gave them to the officials and the officials put it at, let's say 12.5, if that's in fact what they did, that once the football reached its equilibrium state, it probably was closer to 11.5. But again, that's just our measurements."*

- Saturday, January 24, "Saturday Night Live" opened its show with a sketch on the controversy.
- On Sunday, January 25, Bill Nye, appearing on "Good Morning America" took to the air and took the air out of Belichick's explanation stating that it "didn't make any sense." Nye explained: "Rubbing the football, I don't think you can change the pressure. To really change the pressure you really need one of these …" Nye then produced an inflation needle and held it in front of the camera and said: "… the inflation needle!"
- On Tuesday, January 27, League sources confirmed that the focus of the "Deflategate" investigation was on a Patriots locker room attendant who was seen on surveillance camera to take all 24 game-balls into a restroom for 90 seconds. Speculation then arose that Belichick had inflated the balls two and a half hours before game time in a heated sauna so that the Referee would indeed measure a proper air pressure at the appropriate designated time. Inflating the balls in a sauna would increase the temperature-differential, and thus the pressure-differential, to which the balls were subjected once exposed to the colder climatic conditions of Gillette Stadium.
- Throughout the time between the AFC Championship game and Super Bowl XLIX, several media outlets called for the Patriots and/or Belichick to be expelled from the Super Bowl.
- Media speculation continued to swirl as more and more reports were released confirming the propensity for professional football teams to push the letter of the law in order to gain even the slightest advantage during a game. For example, during the same time "Deflategate" was unfolding, media reports confirmed that for the last two seasons, the Atlanta Falcons had been piping in artificial crowd noise into their home field to disrupt opponents' during their offensive snaps. Also at this time, the Cleveland Browns front office was found to be repeatedly violating League rules by texting coaches during games. As lifelong Cleveland sports fans, the authors can attest to the futility of the Browns' efforts to gain a competitive edge during a game—since resuming operation in 1999, the Browns have a record, as of 2019, of 101–234. That is a winning percentage of 30%

1.1.4 A NEW FOCUS FOR "DEFLATEGATE"

In general, analyzing the physics of "Deflategate" has focused exclusively on grip—namely, that the sole advantage to using an under-inflated football is that it affords the offensive team with an improved grip on the ball. The scientific analysis has therefore focused on using the Ideal Gas Law (or the Gay-Lussac portion of the Law, $P \propto T$) to determine if the air pressure of a football inflated in a "warm," interior room can in fact decrease enough, when taken to a "cool," exterior stadium, to account for the measurements observed in the 2015 AFC Championship game (52°F in Foxboro in the middle of January can hardly be considered "frigid," as some pundits and commentators have stated). Physics laboratory activities and homework problems soon popped-up in which students use the Ideal Gas Law to either confirm or discount the alleged pressure measurements taken during "Deflategate."

Although activities involving the Ideal Gas Law make for an obvious extension of "Deflategate" into the physics classroom or laboratory, the purpose of this article is to pose an alternate scenario that allows us to focus on other aspects of mechanics. Specifically, we shift the focus of "Deflategate" from the Ideal Gas Law to the physics of a bouncing ball. At the very least, our activities can be used in conjunction with activities involving the Ideal Gas Law as a means to showcase how multiple problem-solving techniques can be used to examine different aspects of the same controversy. The intention of the authors is in no way to denigrate the reputations of the New England Patriots or their head coach Bill Belichick. Instead, our intention is simply to provide an alternative approach to discussing "Deflategate" and to pilot an accompanying set of experiments that allows us to unify basic principles of mechanics while examining an interesting, real-world application of physics to sporting events. To trial-test our activity, we presented the following problem to a small group of students enrolled in an introductory physics laboratory. After stating the problem and discussing its solution, a set of experiments was conducted by the students, under the supervision of the two authors, with the hope of incorporating this scenario into our physics laboratory sequence in later semesters.

1.1.5 STATEMENT OF THE PROBLEM

Since the controversy of "Deflategate" first erupted during the 2015 AFC Championship game, most physicists have concluded that weather and game conditions were simply not the culprit. In other words, changing climatic conditions and the typical impacts to which a football is subjected during the course of a game cannot account for a drop of 2 PSI in the internal air pressure of the ball. Therefore, we posit, for instructional purposes only, that the New England Patriots *intentionally* under-inflated their game-supply of 12 footballs to the 2015 AFC Championship game. The goal of this laboratory exercise is to find out *why might the Patriots have intentionally under-inflated their supply of game-day footballs?* In a more general sense, the purpose of this laboratory exercise is to determine *why the National Football League finds it necessary to specify the internal air pressure of the footballs used in its games.*

Until now, the leading theory has focused on grip. No one doubts that under-inflated footballs are easier to grip and therefore easier to throw and catch and less likely to fumble. So a clear advantage exists for the offensive team using under-inflated footballs. However, one might also ask: *"Is an altered grip the only advantage to using under-inflated footballs?"* What other phases of the game might be impacted by the air pressure inside the ball? An immediate thought is the kicking game—the impulse delivered by a kicker's foot to a football will certainly be affected by the ball's elasticity, (i.e., a less elastic ball will remain in contact with the kicker's foot for a longer period of time, thus increasing the energy dissipated during impact and reducing the kinetic energy delivered to the ball). However, the NFL's Rule 2, Section 2 (see above) clearly states that footballs used for the kicking game are to be directly mailed to the Referee by the manufacturer and are not supplied by either team—so the Patriots would not have under-inflated their supply of game-day footballs with the hope of altering the kicking game. The only remaining phase of the game affected by a football's internal air pressure involves its ***bounce***, or ***rebound***, after impact. The "rebound" of a ball refers to how it bounces after colliding with another object, like another ball, the ground, or a player's shoulder pads. Therefore, we now turn our attention to the physics of a bouncing ball. In the upcoming laboratory activity, we will determine how the internal air pressure of a ball affects its rebound. For fun, we will examine the performance of several common sports-related balls, with special attention to the professional-grade football. Our analysis relies on the application of basic principles covered in a course on basic *Classical Mechanics*.

1.1.6 THE PHYSICS OF A BOUNCING BALL

As most of us grow up playing sports, we develop an intuition of how particular types of sports-related balls rebound. We expect a super-ball to be very elastic and to rebound close to the original height from which it was dropped. Conversely, we expect a baseball to be much less elastic after impacting a hard surface such as a baseball bat, since much of the incoming energy is dissipated in the loud "crack of the bat." Many sports use a ball that must be inflated with air to some recommended pressure. Aside from the incoming velocity, this air pressure plays the most important role in determining how the ball will rebound after impact. Clearly, using an improperly inflated ball will significantly disrupt a player's ability to anticipate how that ball will recover from an impact. Examples from the world of sports are numerous: if you have ever tried to dribble an under-inflated or over-inflated basketball, you know how difficult controlling the ball can be. Since soccer players often use their heads to alter the trajectory of the ball, several studies have focused on the correlation between inflation pressure and the incidence of head injuries and concussions after impacting a player's head. In football, the rebound of the ball from the ground after a punt or fumble would be significantly altered if the football were not adequately inflated.

We intuitively understand that the combination of a ball's internal air pressure and the velocity with which it impacts a hard surface, originating from the height from which it was dropped, (i.e., the drop-height), accounts for the height of its rebound, (i.e., the rebound-height). Obviously, we expect that increasing the drop-height will increase the rebound-height. Likewise, we expect that increasing the internal pressure of the ball lowers both the energy dissipated at impact and the duration of the impact, thereby increasing the rebound-height. Therefore, the same rebound-height can be achieved with a given ball by altering various combinations of its internal air pressure and drop-height—that's why both parameters must be specified when characterizing an acceptable range of rebound-heights to which a particular ball must rebound. Although most experienced athletes develop an instinctive sense of a ball's rebound, most athletes do not know that the ball used in each sport is designed specifically to perform best in the range of heights that occur most often in that sport. For example, most NBA basketball players are 6–7 feet tall. When impacting the court (on a dribble, for example), an official NBA basketball's internal air pressure of 7.5–8.5 PSI was chosen because at that pressure, the ball dissipates very little energy and is very elastic when dribbled in this range of drop-heights. Likewise, a football is designed to perform optimally in the 12.5–13.5 PSI pressure-range. If a football is significantly under-inflated, the amount of energy it dissipates when rebounding from a surface can be greatly increased; thereby confounding the trajectory of the ball's rebound. If the Patriots practiced with under-inflated footballs, they certainly would have developed a better sense of how these footballs would rebound after impact, thus giving them an unfair advantage over their opponents.

1.1.7 PHASES OF A BOUNCING BALL AND THE COEFFICIENT OF RESTITUTION

Consider dropping a ball, from rest, from a known height. We will consider the recovery of the ball from a hard surface, but additional surfaces (like grass or artificial turf) can be added as "further explorations" to our laboratory activities. Like all good physicists, we need to make some simplifications.

- The rebound of a football off of a hard surface is complicated by its distinct shape, called the "prolate spheroid." This shape introduces a number of complicating parameters to the analysis: namely, the incoming spin, angle, and orientation of the ball relative to the surface. Unpredictable bounces are observed when elongated or non-spherical objects rebound off a hard surface [2]. This unusual behavior differs from that of a spherical ball since the normal reaction force between the ball and ground at the point of contact does not usually act along a line through the ball's center of mass. Consequently, the torque applied to an elongated ball when it rebounds depends on its orientation at impact and can be significantly larger than that on a spherical ball [3]. Our analysis is greatly simplified if we neglect the shape, spin, and orientation of the ball at impact and instead focus on a non-rotating spherical ball impacting a hard surface like the ground. Although this three-pronged approximation might seem overly simplistic at

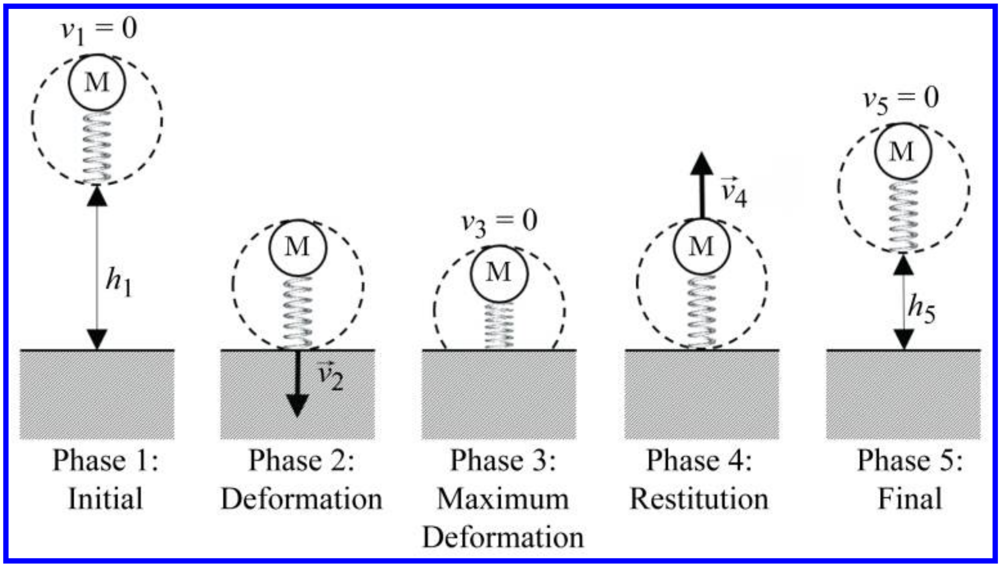

Figure 1.2: Cross-sectional view (along the long-axis of the ball) of a football rebounding from a hard surface. When viewed along its long-axis, the cross-sectional view of a football is spherical.

first, we will take steps in our experimental-design to ensure that this simplification is valid, even for the rebound of a football.

- In his head-scratching press conference, Bill Belichick referred to "the rubbing process"—his term for describing the expansion of the football over time and after repeated impacts. Many sports-balls, (i.e., soccer, football, tennis, etc.) become bigger after being used for a period of time. The football is made from a Urethane bladder enclosed in a pebble-grained, leather case. After the ball has been used, the material and stitching of the cover and linings stretch out. Additionally, stitching will loosen. Thus, the cover and linings become less capable of resisting the pressure of the air inside the bladder causing the ball to expand over time. We further simplify our analysis by making no attempt to account for the expansion of the ball after each of our experimental trials.

- Finally, we neglect air resistance.

To analyze a bouncing ball, we break up a single bounce into five distinct phases, as shown in Figure 1.2.

- *Phase 1 — Initial:* The football is released from rest from height h_1 and free-falls vertically downward under the influence of only gravity. The instant before impacting the ground, the velocity is downward as is the acceleration.

- *Phase 2 — Deformation:* The ball makes initial contact with the ground. The velocity is downward at v_2 as the ball begins to deform; however the acceleration is now upward since the ground is pushing upward on the ball with some force greater than mg. At this point, most models assume that the deformation of the ball obeys Hooke's law, (i.e., the restoring force is proportional to the displacement of the spring from equilibrium) and ignore the negligible change in gravitational potential energy that occurs over the very small distance over which the ball is deformed. Some of the kinetic energy of the ball is converted into elastic potential energy when the ball hits the ground; however, some of the kinetic energy is also dissipated during the impact due to either the internal friction of the ball, sound, vibration, or the heating of the surface.

- *Phase 3 — Maximum Deformation:* The ball continues to push the ground with a restoring force proportional to its displacement from the equilibrium position. In consequence, the ground pushes back on the ball with a force equal in magnitude but opposite in direction. The ball eventually stops as it reaches its maximum deformation. Thus, its velocity is zero, (i.e., $v_3 = 0$) while its acceleration remains upward.

- *Phase 4 — Restitution:* The ball is no longer at maximum deformation and is now pushing against the ground with a force greater than mg. The ball begins to recover and rebound into the air. The ball's velocity is upward at v_4 and the acceleration is still upward. Again, we ignore the negligible changes in gravitational potential energy in this phase.

- *Phase 5 — Final:* The ball bounces back in the upward direction. During the rebound, the stored elastic potential energy was released as kinetic energy which in turn is converted to gravitational potential energy as the ball moves up. Eventually, the ball fully rebounds and reaches its maximum height, h_5. The velocity v_5 is zero, and the acceleration is now pointing downward since the only force acting on the ball is gravity.

Often, when two objects collide (like a ball striking the ground), little information is available about the forces or processes involved in the loss of energy. For example, is the energy loss due to internal friction, the creation of sound, the generation of vibrations, or the permanent deformation of the ball or surface? Sometimes, the energy may even be stored in the ball as a result of its compression and may not be released until well after the rebound by a slow recovery of the ball to its original shape [4]. Therefore, when describing the rebound of a ball, in an effort to quantify the momentum-efficiency of the collision, physicists and sports technologists often define a coefficient e, called the "Coefficient of Restitution" (or "COR"), that measures how the linear impulse of the ball changed during its impact with the ground. Using the five phases shown in Figure 1.2, the vertical impulse experienced by the ball between phases 2 and 4 is given by:

$$\int_{t_2}^{t_4} \vec{F}(t)dt = m\left(\vec{v}_4 - \vec{v}_2\right) \Rightarrow \bar{F} \cdot \Delta t_{\text{impact}} = mv_4 + mv_2,$$

where $\bar{F}$ is the average magnitude of the impulsive force, and Δt_{impact} is the duration of the impact, (i.e., the time that the ball stays in contact with the ground). A positive sign results since the directions of $\vec{v}_4$ and $\vec{v}_2$ are opposite. The term mv_4 is called the "restitution impulse" while the term mv_2 is called the "deformation impulse." In general, the COR is defined as the ratio of the relative speeds of the two colliding objects A and B, before and after impact:

$$e = (v_B - v_A)_{\text{after}} / (v_A - v_B)_{\text{before}} .$$

Values of e have been measured for many objects striking various types of surfaces. For a perfectly elastic collision, $e = 1$ and for a completely inelastic collision, $e = 0$. Obviously, the COR depends on the elastic properties of both objects involved in a collision; however, if a relatively soft ball is dropped on a rigid surface like a hard floor, the resulting value of e provides a measure of the elastic properties of only the ball, provided there is no deformation of the surface on which it bounces [5]. Therefore, for our situation, our definition for the COR simplifies to the ratio of the restitution impulse to the deformation impulse: $e = (mv_4) / (mv_2)$. For the bounce of a generically shaped ball, including an elongated ball like a football, the COR is actually defined by the ratio of the speeds of outgoing-to-incoming contact points, (i.e., the ratio of the normal velocity components at the point of contact), not the ratio of the speeds of the outgoing-to-incoming centers-of-mass, as we have done. However, because we have simplified our problem to neglect shape, spin, and orientation, the two definitions are equivalent [3, 6, 7]. The expression for the COR can be further simplified by balancing the total energy between phases 1 and 2 as well as between phases 4 and 5. Since no non-conservative forces are involved in these phases:

$$mgh_1 = \frac{1}{2}mv_2^2 \Rightarrow v_2 = \sqrt{2gh_1}, \quad \text{and} \quad mgh_5 = \frac{1}{2}mv_4^2 \Rightarrow v_4 = \sqrt{2gh_5}.$$

Combining these results, we now have a common expression for the COR, for use with non-rotating spherically-shaped balls, impacting a hard surface: $e = \sqrt{h_5/h_1}$.

1.1.8 EXPERIMENTAL RESULTS AND DISCUSSION

To measure the height of a rebounding ball and the duration of its impact with a hard surface, one might first try simply filming a single bounce and analyzing the footage frame-by-frame. However, the speed of a typical digital camera is 30 frames per second, (i.e., 0.034 seconds per frame), while the duration of impact of a typical sports-ball with a hard surface is less than 0.01 seconds. Therefore, unless equipped with a high speed digital camera capable of film speeds greater than 100 frames per second, simple photographic analysis will not provide the temporal resolution needed for proper data analysis.

Instead, we employ a sound sensor and data acquisition software to record the sound of several types of sports-balls bouncing one time, after striking the hard cement floor of our laboratory. This technique has been commonly used in several experiments [8–10]. First, three professional-grade sports balls were purchased: a men's basketball, football, and soccer ball. These particular balls were chosen because of the popularity of their associated sports; are easy to find at common sporting goods stores; and obviously rely on some appropriate inflation pressure (unlike solid-core types of balls like a baseball or golf ball). The costs of these professional-grade balls turned out to be the most costly expense to our experiment: the men's basketball cost $199.99, the football cost $99.99, and the soccer ball cost $159.99. Non-professional-grade versions of these balls are available at much lower costs. Next, recalling our prior list of simplifications, we need to take steps in our experimental design in order to minimize the effects of spin, shape and orientation of the ball at impact. Minimizing these effects was achieved through carefully designing an electromagnetic release-mechanism to ensure that each ball was not spinning, and was properly-oriented, when striking the ground. For the basketball and soccer ball, a small (1/2 inch × 1/2 inch) piece of flat metal was fastened to the ball—thus allowing these balls to be suspended from the electromagnet and released from rest, without rotation. Since these balls are spherical, their shape and orientation at impact were not problematic. The football proved more difficult because of its elongated shape. To minimize the effects of shape and orientation at impact, our experimental technique had to ensure that the football impacted the ground with its long axis parallel to the ground. A lightweight string was woven under the stitches of the football to create a "hanger" for the football, as shown in Figure 1.3. The hanger was then attached to a small metal binder clip. The electromagnet held the paper clip and thus suspended the football. With a little practice, this experimental technique was quite successful at releasing the football so that it impacted the ground with little rotational motion and with its long axis parallel to the ground. Overall, by using a simple electromagnet as the release-mechanism, we minimized the effects of rotation, shape, and orientation on our experimental results. For all trials, the balls were released from a predetermined height of $h_1 = 4$ feet. (Recall from Figure 1.2 that the initial drop-height is denoted by h_1.) A height of 4 feet was chosen as an approximate average value of height at which the football would most likely be carried by a running back prior to fumbling.

Next, a *PASCO* sound sensor was placed on the cement floor at the approximate location where each ball would initially impact the ground and presumably strike after its first bounce. We used the *Data Studio*™ data acquisition software (set to sample at 10 kHz) to record each impact. To start, each ball was inflated to 5 PSI below its average recommended gauge pressure. The ball was then dropped while its initial impact and subsequent bounce were recorded. This recording was repeated five times and the "best" recording kept (note that an average was not used). The ball was then inflated to 4 PSI below its average recommended gauge pressure and the initial impact and bounce were recorded five times. Again, only the best recording, as judged by the students and faculty, was kept. This process was repeated until the ball was eventually inflated to 5 PSI *over* its average recommended gauge pressure—thus, each ball was tested at 11 pressures (using increments of 1 PSI, we varied the pressure from 5 PSI below the average recommended gauge pressure to 5 PSI above the average recommended gauge pressure) with the initial impact and first bounce recorded for 5 drops at each pressure. Figure 1.4 shows all

Figure 1.3: The hanger used to suspend the football is simply a lightweight string that has been woven under the stitches of the football. The string is then connected to a binder clip that is then suspended from the electromagnet.

of the equipment necessary to bring the physics of "Deflategate" to your home, classroom, or laboratory.

For each trial, data only needed to be recorded for a short time as each drop, initial impact, and bounce lasted less than two seconds. Very little practice was required to analyze the sound recordings. Since the recorded sound level makes a significant jump, relative to background noise, each time the ball impacts the ground near the sound sensor, identifying the portion of the recorded waveform corresponding to an impact is readily apparent. Typically, each recording shows: a brief interval of background noise as the ball is released from its initial height of 4 feet; a waveform corresponding to the initial impact of the ball with the ground; another brief interval of background noise as the ball arches through the air after its first bounce; and finally another waveform corresponding to the second impact of the ball with the ground. For each recording,

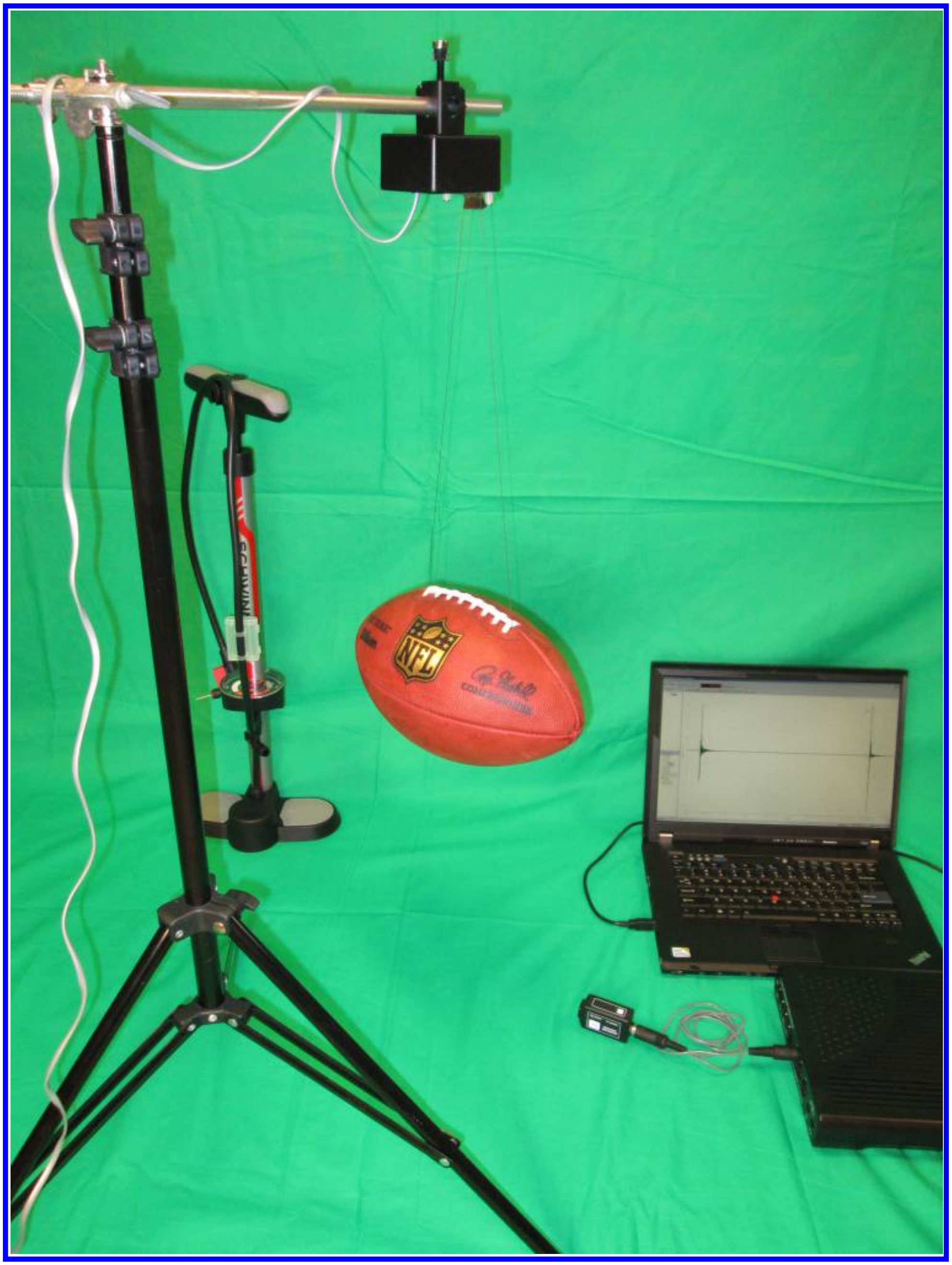

Figure 1.4: Equipment used in our experimental design. During the trials, the football was released from a height of 4 feet. The football has been lowered to fit it in the photograph.

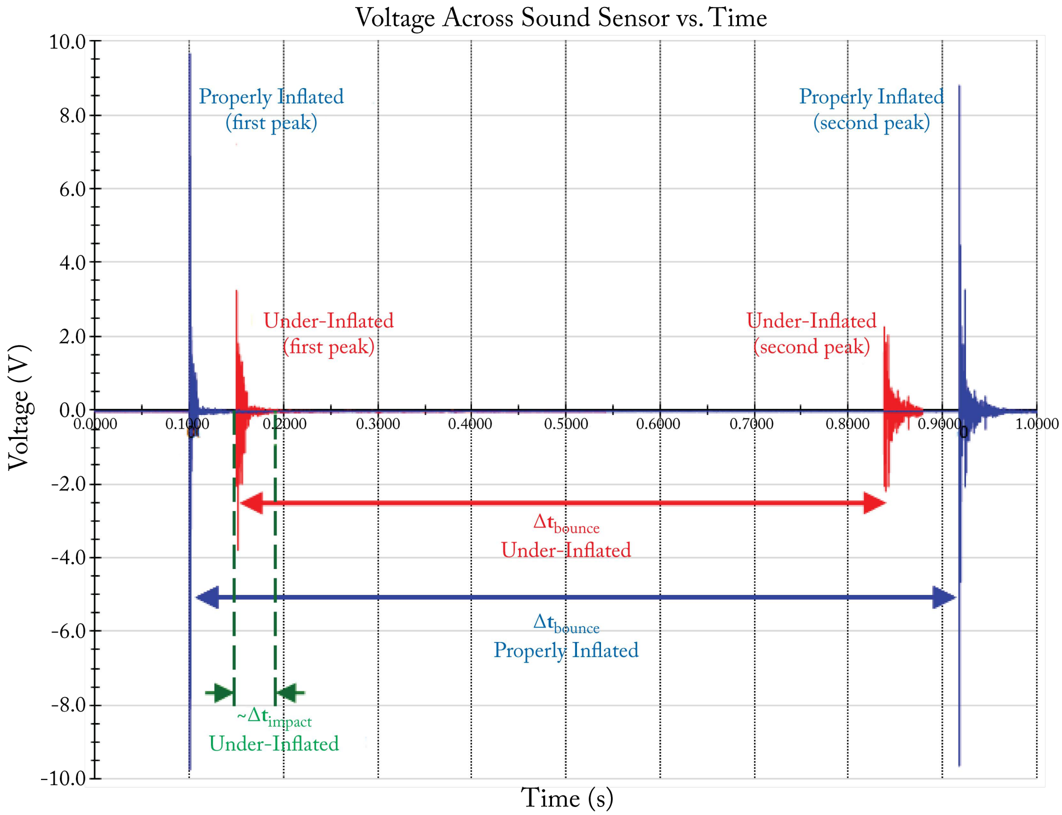

Figure 1.5: Typical plot of ***Voltage*** across the sound sensor vs. ***Time*** for a single bounce of a properly-inflated football and an under-inflated football. The determination of Δt_{bounce} for both footballs is shown.

two values were determined and tabulated: (1) Δt_{bounce}, the time between the initial impact of the ball with the ground and the time until its next subsequent impact with the ground. This value is easily determined as the time interval between initial spikes in the recorded sound levels at each impact; and (2) Δt_{impact}, the duration of the initial impact of the ball with the ground. This value is determined by estimating the width of the waveforms occurring each time the ball strikes the ground. Typical recordings are shown in Figures 1.5 and 1.6 to indicate how Δt_{bounce} and Δt_{impact} were determined for the rebound of a properly inflated football. The data for the under-inflated football (5 PSI below its average recommended gauge pressure) is shown in comparison.

From these measured quantities, the following values were then calculated: the value of the rebound-height, h_5 as: $h_5 = 1/2 * g\,(\Delta t_{\text{bounce}}/2)^2$, the coefficient of restitution e as: $e =$

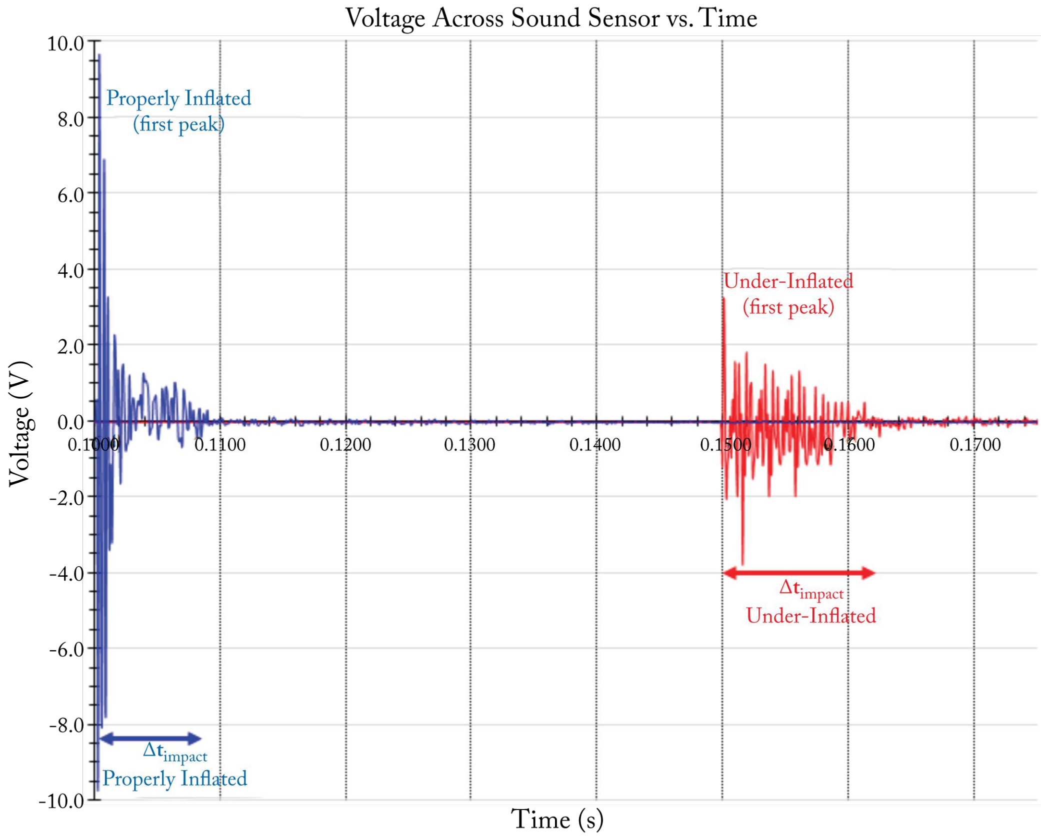

Figure 1.6: Typical plot of ***Voltage*** across the sound sensor vs. ***Time*** for the initial impact of a properly-inflated football and an under-inflated football. The determination of Δt_{impact} for both footballs is shown.

$\sqrt{h_5/h_1}$; and the percentage of energy lost due to the impact as: $U_{lost} = (h_1 - h_5)/h_1$. Table 1.1 shows our data for the professional-grade men's basketball, football, and soccer ball.

Figures 1.7, 1.8, 1.9, and 1.10 were used to discuss results with students. First, all data depicting inflation pressure was plotted using "reduced gauge pressure," $P_{\text{reduced}} = P - P_{\text{regulation average}}$, over the range $[-5, +5]$ PSI, (i.e., in increments of 1 PSI, the pressure of each ball was inflated from 5 PSI below to 5 PSI above its average recommended gauge pressure). For example, the recommended inflation pressure of a professional-grade football is between 12.5 and 13.5 PSI. Using the average recommended pressure of 13 PSI, the ball was first inflated to 8 PSI and tested. For each trial, the pressure was then increased by 1 PSI until a final pressure of 18 PSI was tested.

Table 1.1: Data gathered for three professional-grade sports-balls

		Data Table: "Deflategate and the Physics of a Bouncing Ball" Drop-Height, h_1 = 48"														
		Basketball					Football					Soccer				
		Range of Regulation Pressures:		7.5–8.5 PSI			Range of Regulation Pressures:		12.5–13.5 PSI			Range of Regulation Pressures:		8.5–15.6 PSI		
		$P_{regulation\ average}$:		8.0	PSI		$P_{regulation\ average}$:		13.0	PSI		$P_{regulation\ average}$:		12.0	PSI	
	Set	Measure		Calculate			Measure		Calculate			Measure		Calculate		
	$P_{reduced}$	Δt_{bounce}	Δt_{impact}	h_5	COR, e	U_{lost}	Δt_{bounce}	Δt_{impact}	h_5	COR, e	U_{lost}	Δt_{bounce}	Δt_{impact}	h_5	COR, e	U_{lost}
	PSI	s	s	in			s	s	in			s	s	in		
Under-Inflation	-5	0.816	0.013	32.1	0.82	33%	0.688	0.013	22.8	0.69	52%	0.670	0.014	21.65	0.67	55%
	-4	0.829	0.012	33.1	0.83	31%	0.733	0.012	25.9	0.73	46%	0.720	0.013	25.00	0.72	48%
	-3	0.834	0.012	33.5	0.84	30%	0.764	0.012	28.2	0.77	41%	0.750	0.013	27.13	0.75	43%
	-2	0.839	0.012	33.9	0.84	29%	0.794	0.012	30.4	0.80	37%	0.780	0.013	29.34	0.78	39%
	-1	0.849	0.010	34.8	0.85	28%	0.810	0.010	31.6	0.81	34%	0.790	0.012	30.10	0.79	37%
	0	0.859	0.009	35.6	0.86	26%	0.818	0.009	32.3	0.82	33%	0.800	0.012	30.87	0.80	36%
Over-Inflation	1	0.869	0.009	36.4	0.87	24%	0.832	0.009	33.4	0.83	30%	0.810	0.12	31.64	0.81	34%
	2	0.879	0.009	37.3	0.88	22%	0.839	0.009	33.9	0.84	29%	0.820	0.011	32.43	0.82	32%
	3	0.889	0.009	38.1	0.89	21%	0.855	0.009	35.3	0.86	27%	0.830	0.011	33.22	0.83	31%
	4	0.899	0.008	39.0	0.90	19%	0.866	0.008	36.2	0.87	25%	0.840	0.010	34.03	0.84	29%
	5	0.909	0.008	39.9	0.91	17%	0.871	0.008	36.6	0.87	24%	0.850	0.010	34.84	0.85	27%

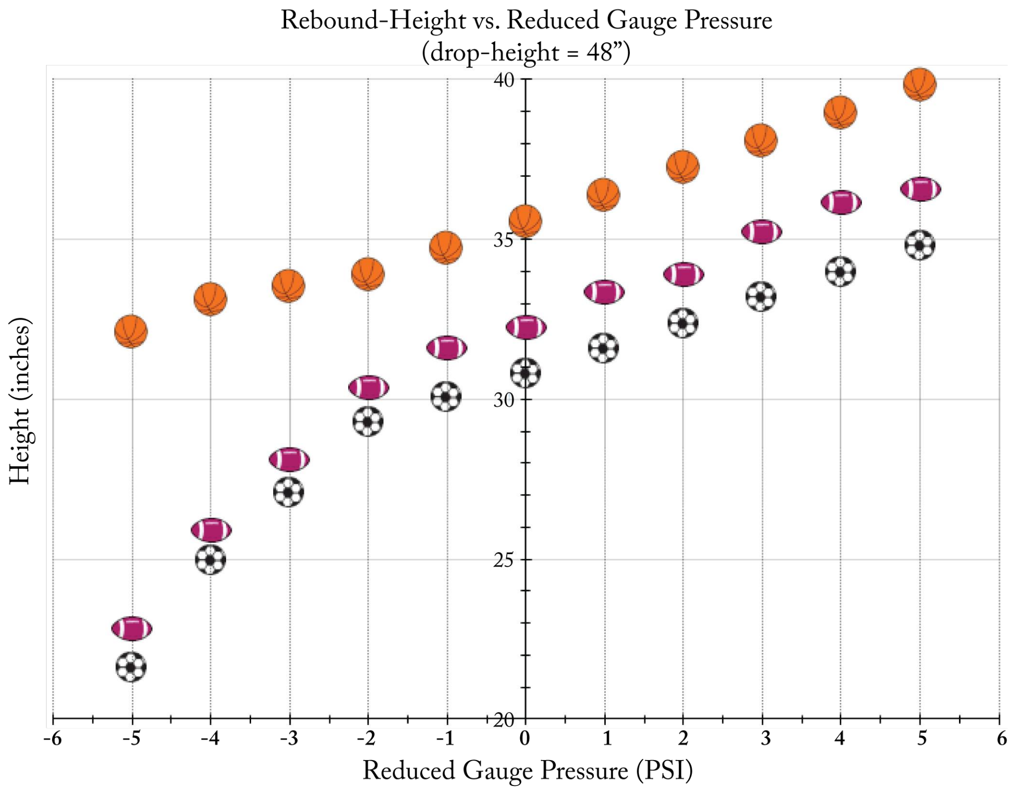

Figure 1.7: ***Rebound-Height*** vs. ***Reduced Gauge Pressure*** for three types of sports-balls.

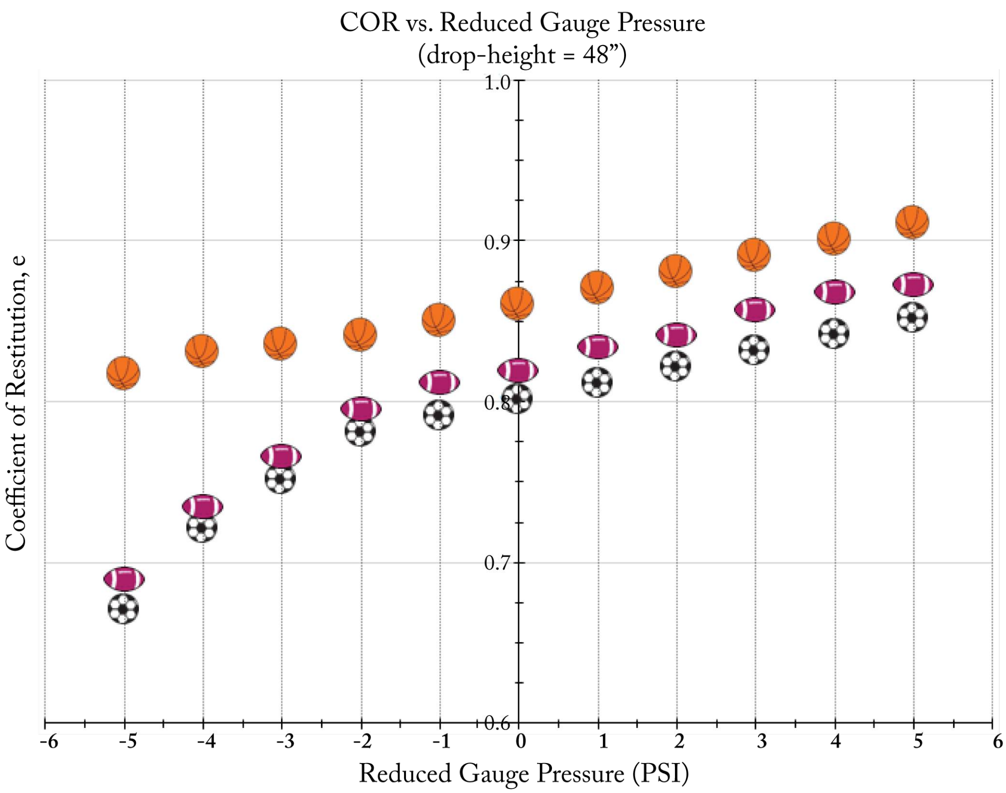

Figure 1.8: ***COR*** vs. ***Reduced Gauge Pressure*** for three types of sports-balls.

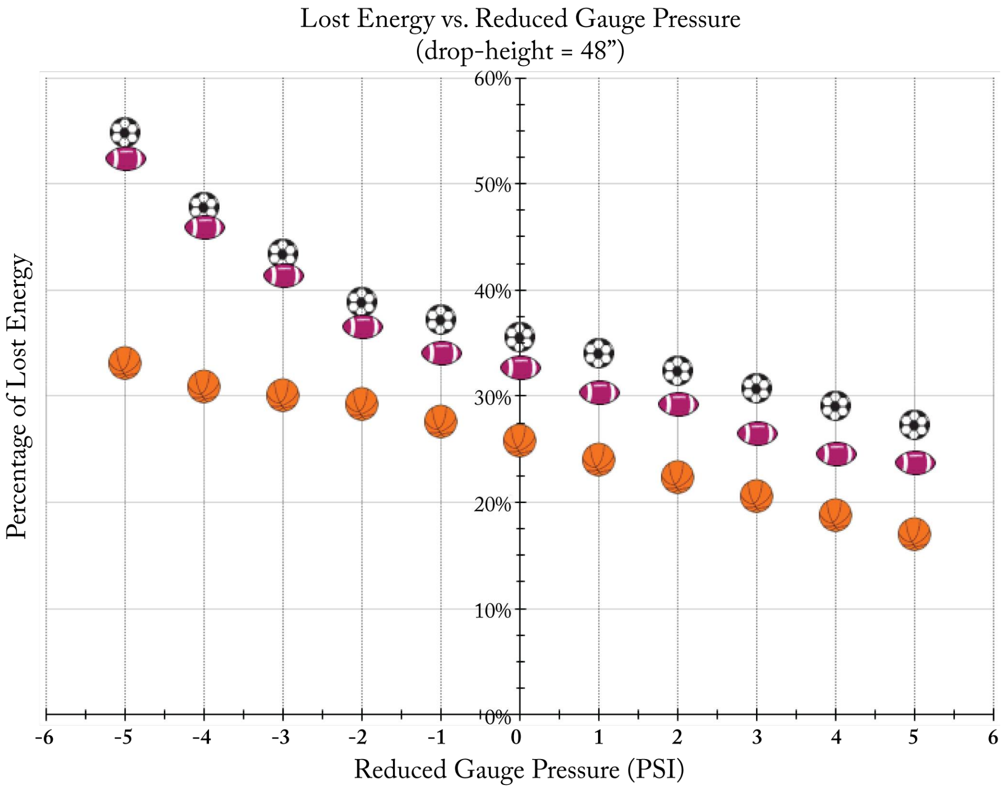

Figure 1.9: ***Percentage of Lost Energy*** vs. ***Reduced Gauge Pressure*** for three types of sports-balls.

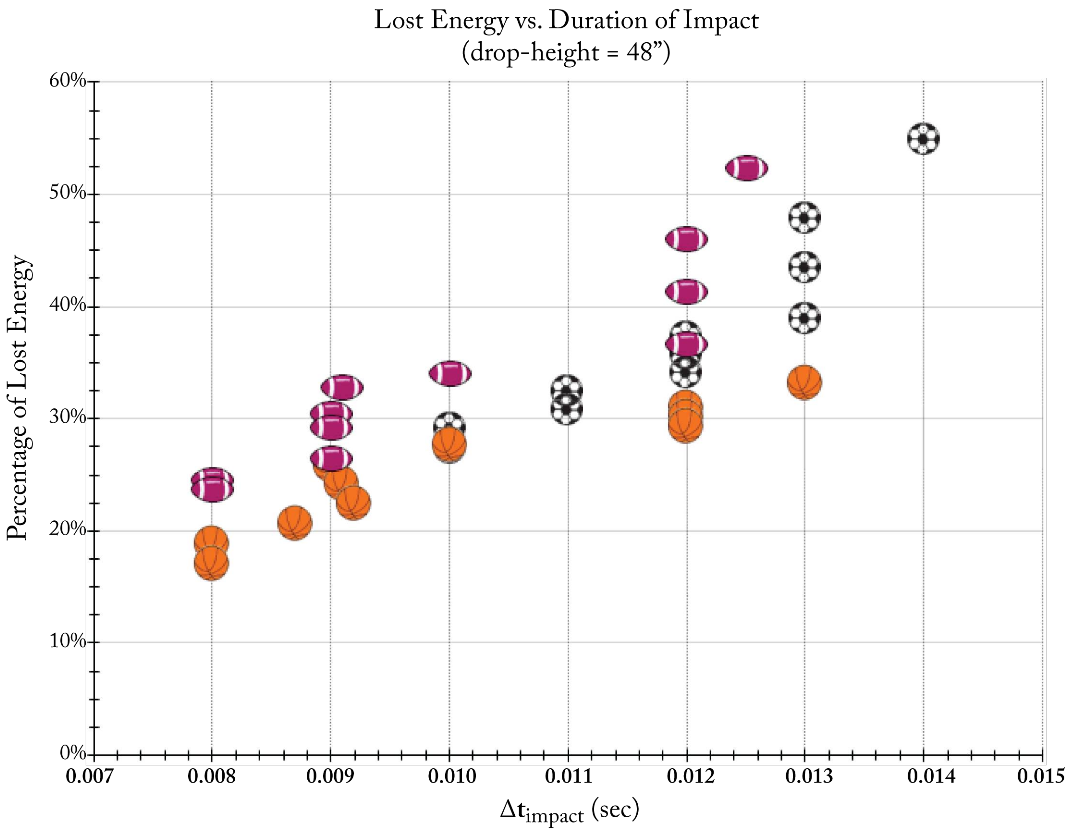

Figure 1.10: ***Percentage of Lost Energy*** vs. Δt_{impact}, or ***Duration of Impact***, for three types of sports-balls.

Figure 1.7 shows the rebound-height of each ball vs. reduced pressure when released from a drop-height of 4 feet. As expected, the rebound-height of each ball decreases with decreasing reduced pressure. At the proper inflation pressure, the men's basketball rebounds to a height of 35.6 inches; the football rebounds to a height of 32.6 inches; and the soccer ball rebounds to a height of 30.9 inches. As a function of reduced pressure, the rebound-height of the men's basketball exhibits a linear relationship. Interestingly, the football and soccer ball do not exhibit similar linear relationships. Instead, at or near 2 PSI below the average recommended gauge pressure, the rebound-height of the football exhibits a sharp decline with respect to decreasing reduced pressure. In other words, our experimental results demonstrate that if the Patriots indeed wanted to under-inflate their game-supply of footballs in such a way as to significantly change the rebounding performance of these balls, the culprit should have under-inflated each ball by at least 2 PSI. As noted before, news reports indicated that the Patriots' game-supply of balls were indeed under-inflated in the 1.4–2 PSI range—the approximate pressure-range suggested by our experimental results at which the footballs first begin to display drastic changes in performance. After seeing this result, one student jokingly commented: "Perhaps Belichick was more versed in physics than his press conference lend us to believe?" Figure 1.8 shows the coefficient of restitution of each ball vs. reduced gauge pressure when released from a drop-height of 4 feet. Figure 1.8 supports our previous statement that each ball is designed to perform optimally in the range of heights that commonly occur in the sport for which it is intended. At the proper-inflation pressure, each ball has a coefficient of restitution in the 0.8–0.9 range: the basketball performs best with a coefficient of restitution of 0.86; the football is next with a value of 0.82; and the soccer ball last with a value of 0.80. Again, the football and soccer ball exhibit a drastic decrease in performance at or near the reduced pressure of 2 PSI, causing students to increasingly suspect intentionality behind the under-inflation of the Patriots game-supply of footballs. Figure 1.9 illustrates the percentage of lost energy, relative to the initial gravitational potential energy supplied to the ball at a height of 4 feet, as a function of reduced gauge pressure. The trend is clear: that as a ball is increasingly under-inflated, it loses increasing amounts of energy upon impact with the ground due to the increased duration of the impact. Finally, though its data is scattered, Figure 1.10 illustrates to students the expected result that increasing the duration of an impact increases the percentage of energy lost. In our trials, the over-inflated basketball and over-inflated football were in contact with the ground for the smallest duration of time, 0.008 seconds, corresponding to a loss of energy of only 17–24%, while the under-inflated soccer ball remained in contact with the ground for the longest duration of time, 0.014 seconds, corresponding to a loss of energy of 55%. Students can readily see the trend suggested by Figure 1.10 that increasing the duration of impact increases the percentage of loss of energy at impact.

1.2 CONCLUSIONS

On May 11, 2015, the NFL announced that Patriots' quarterback Tom Brady was suspended for four games, without pay, for the following season for his involvement in "Deflategate," based on "substantial and credible evidence," that he knew Patriots' employees were deflating footballs and that he failed to cooperate with the investigation. Because Brady had taken a pay cut for the 2016 season (agreeing to a $1 million salary, down from his $8 million salary in 2016), the suspension only (yes, I had difficulty using the word "only" in this sentence) cost Brady $235,000. Had Brady been suspended immediately after the controversy, his suspension would have cost him $1.9 million.

Some of life's greatest mysteries have stymied physicists for decades: "How many licks does it take to get to the center of a Tootsie Pop?" "What truly is at the center of a golf ball?" and "Why do Disney characters only have 3 fingers?" The controversy known as "Deflategate," surrounding the 2015 AFC Championship Game between the New England Patriots and Indianapolis Colts, can now be added to this list of unsolved mysteries. The purpose of this article is to add to the methods of deciphering the events of "Deflategate" using the equations and equipment of introductory physics courses. First, we provide some information on the actual events and media circus surrounding the game. Next, we provide a context for connecting "Deflategate" to the physics of a bouncing (or rebounding) ball. The analysis of a bouncing ball is ideal for the introductory physics sequence since it poses an opportunity to unite **Projectile Motion**, **Conservation of Energy**, and **Linear Impulse/Momentum** in one problem. Finally, an experimental design is constructed that allows for a simple but informative series of experiments using equipment already found in most high school or undergraduate laboratories. The key to the design is the release-mechanism that is allows students to drop various sport-related balls with no rotational motion and with the appropriate angle and orientation relative to the ground. Results can be used to illustrate a number of physical principles to students.

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