



INTERNATIONAL
TENNIS HALL OF FAME

The Physics of Tennis

Lesson 4: Energy changes when a ball interacts with different surfaces

Unit Overview: In this unit students continue to develop understanding of what can be at first glance a complicated system, the game of tennis. In this activity we have taken two components of the game of tennis, the ball and court, to see if we can model the interactions between them. This activity focuses on the energy interactions between ball and court.

Objectives:

Students will be able to-

- Describe what forces interact when the ball hits a surface.
- Understand what changes occur when potential and kinetic energy conversion is taking place within a system. At the high school level students should include connections to the concept of “work = $F \times D$ ” and calculations of $E_k = \frac{1}{2}mv^2$ and $E_p = mgh$ according to the conservation of energy principal.
- Identify the types of energy used in this system. (restricted to potential & kinetic energy)
- Comparative relative energy losses for typical court compositions.

Lesson Time Required: Four class periods

Next Generation Science/Common Core Standards:

- NGSS: HS-PS3-1.Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.
- [CCSS.Math. Content: 8.F.B.4](#) Use functions to model relationships between quantities.
- Construct a function to model a linear relationship between two quantities. Determine the rate of change and initial value of the function from a description of a relationship or from two (x, y) values, including reading these from a table or from a graph. Interpret the rate of change and initial value of a linear function in terms of the situation it models, and in terms of its graph or a table of values

Possible Sources:

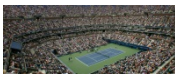
- *Tennis Courts: A construction and maintenance manual* by Carol Shaner (2001)

Materials Needed:

- tennis ball
- diagram of a court
- court surface samples

Vocabulary:

- **Tennis Court Surfaces**- a firm rectangular surface with a low net stretched across the center. The same surface can be used to play both doubles and singles matches. A variety of surfaces can be used to create a tennis court, each with its own characteristics which affect the playing style of the game.
- **Hardcourt**- The US and Australian Opens feature hardcourt surfaces. These are typically constructed from plastic or cement which is considered a "fast" surface. It has effects such as short rallies for players that have hard serves. The amount of sand in the topcoat and the type of base used under the top surface can affect the ball bounce and resulting output speed. (**Serena Williams**)



- **Grass**- Grass courts are used at Wimbledon and other events (including the Dell Technologies Hall of Fame Open). The grass surface tends to move the ball the fastest because it lets the ball slide. Grass surfaces favors players who rush the net following a serve, (Pete Sampras)



- **Clay**- These courts are made of crushed natural materials. The clay court moves the ball the slowest of all surfaces. Players tend to get higher bounces on that type of court. (Rafael Nadal)



- **Indoor Courts** - Most major tournaments are held outdoors, but many players enjoy indoor tennis. Indoor tennis facilities most commonly use carpet type surfaces, such as rubber. These surfaces vary greatly in terms of texture and material. Some indoor courts even use wood. (Martina Navratilova)



Hall of Famer Martina Navratilova

Born in Czechoslovakia in 1956, Martina Navratilova began playing tennis at a young age, and was one of the top female tennis players in the world in the late 1970s and early '80s. At age 9, Navratilova began taking lessons from Czech champion George Parma, who further refined the young player's game. At age 15, she won the Czech national championship. In 1973, at 16, she turned pro and began competing in the United States. With Czechoslovakia squarely under Soviet control, 18-year-old Navratilova defected to the United States at the 1975 U.S. Open. The decision meant she'd be cut off from her family for years, but it also set her career up for an unprecedented level of success. In 1978, she won her first Grand Slam tournament with a victory over American Chris Evert at Wimbledon. By the early 1980s, Navratilova was the most dominant player in women's tennis. In 1982, Navratilova captured both the Wimbledon and the French Open crowns, and would go on to lose only six matches from 1982 to 1984. In all, she won 18 Grand Slam singles titles, 31 Grand Slam women's doubles championships and 10 Grand Slam mixed doubles. Her greatest success came at Wimbledon, where she advanced to 12 singles finals, winning nine titles. Navratilova retired from singles play in 1994, but continued to play in doubles matches. She was inducted into the International Tennis Hall of Fame in 2000.



Hall of Famer Pete Sampras

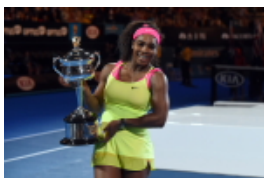
Growing up in California, Pete Sampras started playing tennis at the age of seven. Pete joined the professional tour at age 16 in 1988, won his first pro tournament in 1990, and reached the World No. 1 ranking for the first time in 1993. Pete went on to win 14 major titles (an all-time men's record for 7 years, until it was broken by Roger Federer) and held the year-end World No. 1 ranking for six consecutive years. Pete

won seven Wimbledon titles, including three straight (1993-1995) and four straight (1997-2000). Pete Sampras was inducted into the International Tennis Hall of Fame in 2007.



Rafael Nadal

Rafael Nadal was born in Mallorca, Spain, on June 3, 1986. When he was 3 years old, his uncle, Toni Nadal, a former professional tennis player, started working with him, seeing an aptitude for the sport in young Rafael. Though he is a natural righty, Toni encouraged him to play left-handed, thinking it could give Rafael an edge on the court. At the age of 19, in 2005, Nadal won the French Open the first time he competed in the tournament. His world ranking shot to No. 3, and he was soon dubbed the "King of Clay." Nadal poured it on in 2008, winning the French Open again, in addition to winning Wimbledon, as well as gold at the Beijing Olympics. After Wimbledon, Nadal's winning streak stood at a career-best 32 matches. In 2010, he was triumphant at the French Open and Wimbledon, and his subsequent win at the U.S. Open made him just the second men's player to achieve the career Golden Slam—victories at all four majors, as well as Olympic gold. In June 2014, Nadal won his record-ninth French Open championship by topping Djokovic in four sets. It was his 14th Grand Slam title, tying him with Pete Sampras for second all-time behind the 17 won by Federer. In 2017, Nadal faced off against Roger Federer in the finals at the Australian Open, but was ultimately defeated in five sets.



Serena Williams

Serena Williams embodies style, power, beauty and courage. Currently ranked #1, Serena has overcome insurmountable odds to win 21 career Grand Slams. Not only is she remarkable at tennis, her success with endeavors outside of the sport including film, television, fashion and philanthropy. Her tennis ability combined with her off-court activity makes her one of the most recognizable names and faces in the world—an icon.

Serena was born September 26, 1981 in Saginaw, Michigan, to Richard and Oracene Williams. While still an infant, the family moved to Compton, California where she began playing tennis at the age of four. At nine, Serena and her family moved to West Palm Beach, Florida. Since that time, she has become one of the most dominant figures in tennis.

Martina Navratilova Objects on Display in the Museum



Virginia Slims Singles Championship Trophy, 1974-1978

Tiffany & Co. (American)

This trophy was presented to the winner of the year-end championships. Evonne Goolagong won in 1974 and 1976, Chris Evert won in 1975 and 1977, and Martina Navratilova won in 1978.

Gift of Philip Morris, Inc. 1978

78.20a&b

Location: Area 3, WTA Virginia Slims and Prize Money Case

Virginia Slims Doubles Championship Trophy, 1984-1994

Tiffany & Co. (American)

Presented to the year-end champion doubles team from 1984 through 1994, this trophy has been in the hands of many doubles greats including Martina Navratilova, Pam Shriver, Gigi Fernández, Natasha Zvereva, Arantxa Sánchez-Vicario, Helena Suková, Kathy Jordan, Liz Smylie, Wendy Turnbull and Hana Mandliková.

Gift of Virginia Slims Tennis, 2014

2014.59.2a&b

Location: Area 3, WTA Virginia Slims and Prize Money Case

\$500,000 Virginia Slims Championships Ticket, March 21, 1986

In 1986, Martina Navratilova defeated Hana Mandliková in a best-of-five-sets final (6-2, 6-0, 3-6, 6-1).

Gift of Judy Jolly, 1997

97.52.1

Location: Area 3, WTA Virginia Slims and Prize Money Case



Virginia Slims Legends

Al Hirschfeld (American, 1903-2003)

Pen and ink

1995

Commissioned to commemorate the inaugural year of the Virginia Slims Legends Tour, Al Hirschfeld drew the likenesses of Tracy Austin, Rosie Casals, Françoise (Frankie) Dürr, Chris Evert, Evonne Goolagong, Billie Jean King, Olga Morozova, Martina Navratilova, Betty Stöve, Wendy Turnbull, and Virginia Wade. Hirschfeld is

best known for his caricatures which include his daughter's name (Nina). The number "3" by his signature indicates how many times the word "Nina" appears in the drawing.

Gift of the Virginia Slims Legends, 1996

96.20

Location: Area 3, WTA Virginia Slims and Prize Money Case



Federation Cup Trophy presented to Martina Navratilova, 1986

unknown maker

The World Group Final pitted host Czechoslovakia against the United States. Navratilova, who had defected in 1975, returned to Prague as a member of the American Team. The United States defeated the three-time defending Czechoslovakia 3 rubbers to 0.

Loan courtesy of Martina Navratilova, 2000

L2000.4.34

Location: Area 3, Global Tennis Gallery, Fed Cup Case



Wimbledon Ladies Doubles Championship Trophy, 1984

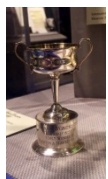
Wakely & Wheeler, Ltd. (British)

Navratilova and Shriver defeated Kathy Jordan and Anne Smith 6-3, 6-4.

Loan courtesy of Martina Navratilova, 2000

L2000.4.76a&b

Location: Area 3, Grand Slam Gallery, Center Case



Australian Open Women's Singles Championship Trophy, 1983

T. County (Australian)

In 1983 and 1984, Martina Navratilova won six consecutive major singles titles to complete a career Grand Slam. At the 1983 Australian Open (held in November), she defeated Kathy Jordan 6-2, 7-6(5) to win her second Australian Championship and her 8th major singles overall.

Loan courtesy of Martina Navratilova, 1997

L97.7.2

Location: Area 3, Grand Slam Gallery, Australian Open Case

French Open Women's Singles Championship Trophy, 1984

Mellerio dits Meller (French)

By defeating rival Chris Evert 6-3, 6-1, Martina Navratilova joined an elite group of players who held all four of the major titles at one time achieving the consecutive career Grand Slam. In 1983 Navratilova won Wimbledon, the US Open and the Australian Open (which was played in December).

Loan courtesy of Martina Navratilova, 2000

L2000.4.72a&b

Location: Area 3, Grand Slam Gallery, French Open Case



Wimbledon Ladies Singles Championship Trophy, 1983

Wakely & Wheeler Ltd. (British)

Navratilova defeated Andrea Jaeger 6-0, 6-3, and with wins at the 1983 US Open and Australian Open (held in November) and the 1984 French Open, Navratilova completed a consecutive career Grand Slam.

Loan courtesy of Martina Navratilova, 2000

L2000.4.46a&b

Location: Area 3, Grand Slam Gallery, Wimbledon Case



"More Control DB 800 MP" Tennis Racquet, 2003

Prince Global Sports LLC (American)

At age 47, Navratilova won her 20th title at Wimbledon, tying Billie Jean King's record for most Wimbledon titles. She partnered with Leander Paes to defeat Anastassia Rodionova and Andy Ram 6-3, 6-3.

Gift of Martina Navratilova, 2004

2004.15

Location: Area 3, Grand Slam Gallery, Wimbledon Case

US Open Women's Singles Championship Trophy, 1983

Fortunoff (American)

In 1983, Martina Navratilova won her first of four US Open titles on her 11th try, defeating rival and defending champion Chris Evert, 6-1, 6-3.

Loan courtesy of Martina Navratilova, 2000

L2000.4.27a&b

Location: Area 3, Grand Slam Gallery, US Open Case

Pete Sampras items on display in the Museum:

Selection of International Series Trade Cards, 2003

The NetPro Trading Card Company (American)

In 2003, NetPro created vibrant colorful trade cards featuring the likes of Jonas Bjorkman and Magnus Norman (Sweden), Richard Gasquet (France), and Pete Sampras and Todd Martin (United States).

Gift of Mr. Bob Perlman, 2010

2010.17.1b, 2010.17.1d, 2010.17.1f, 2010.17.1h, and 2010.17.1i

Location: Area 2, Tennis and Culture, Games, Drawer 2



Davis Cup Trophy awarded to Pete Sampras, 1992

unknown maker

At the 1992 Davis Cup between the United States and Switzerland, Sampras and John McEnroe played doubles, defeating Jakob Hlasek and Marc Rosset 6-7(5), 6-7(7), 7-5, 6-1, 6-2 to help the United States win 3 rubbers to 2.

Loan courtesy of Pete Sampras, 2007

L2007.2.9

Location: Area 3, Global Tennis Gallery, Davis Cup Case



Australian Open Men's Singles Championship Trophy, 1997

T. County (Australian)

Pete Sampras defeated Spain's Carlos Moya 6-2, 6-3, 6-3 to win his second Australian Open Men's Singles title.

Loan courtesy of Pete Sampras, 2007

L2007.2.8

Location: Area 3, Grand Slam Gallery, Australian Open Case



Wimbledon Gentlemen's Singles Challenge Cup, 1993

Wakely & Wheeler Ltd. (British)

In 1993, Pete Sampras bested Jim Courier to win his first of seven titles at the All England Club.

Wimbledon Gentlemen's Singles Challenge Cup, 2000

Wakely & Wheeler Ltd. (British)

In 2000, Pete Sampras won his seventh championship at the All England Club (and 13th overall) by defeating Australia's Patrick Rafter. With this win, Sampras broke Roy Emerson's record for most major singles titles won by a man.

Loan courtesy of Pete Sampras, 2007

L2007.2.5 a&b and L2007.2.6a&b

Location: Area 3, Grand Slam Gallery, Wimbledon Case



US Open Men's Singles Championship Trophy, 2002

Tiffany & Co. (American)

Pete Sampras defeated rival Andre Agassi 6-3, 6-4, 5-7, 6-4 to win his 14th and last major title.

Loan courtesy of Pete Sampras, 2007

L2007.2.4a&b

Location: Area 3, Grand Slam Gallery, US Open Case

Rafael Nadal items on display in the Museum:



Outfit and tennis shoes worn by Rafael Nadal, 2011

Nike, Inc. (American)

In 2010, Rafael Nadal became the 7th player in history to achieve a career Grand Slam in singles when he won the US Open. At the 2011 Australian Open, Nadal had the chance to become the first man since Rod Laver in 1969 to hold all four of the major singles titles at one time, but he fell in the quarterfinals to countryman David Ferrer 4-6, 2-6, 3-6.

Gift of Nike, Inc. on behalf of Rafael Nadal, 2011

2011.26.1, 2011.26.2, and 2011.26.4a&b

Location: Area 3, Grand Slam Gallery, Center Case

Serena Williams items on display in the Museum:



Serena Williams's Catsuit, 2002

Puma (German)

The form-fitting Lycra "catsuit" made headlines and raised eyebrows when Serena Williams wore it as she dominated the 2002 US Open. Although Williams credited

the outfit for the supreme confidence with which she was playing, it was not worn when she completed a “Serena Slam” in Melbourne at the 2003 Australian Open, becoming the fifth woman in history to hold all four major titles at the same time.

Gift of Serena Williams, 2003

2003.22.1

Location: Area 3, WTA Fashion, Players, Year End Champs Case



Serena Williams’s Gold Tennis Shoe, 2002

Puma (Germany)

Williams sported the gilt tennis shoe style during the 2002 French Open Women’s Singles Championships at Stade Roland Garros. She defeated her older sister Venus 7-5, 6-3 to win her first French Open title.

Gift of Serena Williams, 2002

2002.48

Location: Area 3, WTA Fashion, Players, Year End Champs Case



Dress and tennis shoes worn by Serena Williams, 2010

Nike, Inc. (American)

At the 2010 Australian Open, Serena Williams defended her 2009 title by defeating Justine Henin of Belgium 6-4, 3-6, 6-2. This was Serena’s 12th major singles title and an Open Era record 5th at the Australian Open.

Gift of Dianne Hayes on behalf of Nike, Inc. and Serena Williams, 2010

2010.12.1 and 2010.12.2a&b

Location: Area 3, Grand Slam Gallery, Center Case

Lesson & Activity

Students should research the various compositions used in court construction and make predictions as to how a given ball would interact with the surface in terms of energy lost. That energy discussion and analysis will focus on potential and kinetic energy in this simplified modeling of the interaction. The concept of conservation of energy in the system can help students approximate at the high school level resulting velocities of the ball, potential energy at any given time, and kinetic energy of the ball.

Students should be allowed to design their own investigation including variables and constants. Students will drop from a predetermined height (the 3 ft. height at center of the net is a useful starting point and calculate the potential energy lost (input vs output) in the bounce of the ball on several sample court materials or other materials of various compositions. Students can use the conservation of energy principle to examine the resulting velocities after the bounce of the ball. They can also infer how much energy must be added by the player to compensate for the lost energy of the bounce. Students should also be able to infer that if energy is lost in the interaction between ball and court, then the player must, in terms of input energy, drive the ball forward with more initial kinetic energy, to produce the same output of energy as the ball is served or returned. This is an opportunity to also allow students to design procedures; identify controls and variables in an experiment; hypothesize; and particularly formulate claims and provide evidence supporting these claims consistent with NGSS and CCSS for building argumentation. Students at the middle school level can qualitatively describe energy changes during the motion of the ball and analytically analyze the potential energy loss as a ball is dropped from various heights and the resulting height of the “bounced ball.” They calculate the percentage energy lost for each bounce.. First they calculate the input of potential energy and the output of the bounced ball using $E_p = mgh$ where E is the energy in joules, m is the mass in kg and h is the height in meters for the height dropped and the height of the resulting bounce. HS and or MS students can calculate and compare potential and kinetic energy of the ball in various situations by using the conservation of energy principal (i.e. at the instant of the ball hitting the court all potential energy has been converted to kinetic energy. High school students could utilize $E_k = \frac{1}{2} mv^2$ to calculate the impact velocity by a simple vertical drop to a court surface. Rotational energy is not included, but could be treated as an advanced topic for discussion for high school students.

The composition can be of several type materials in official play. Also, high school students can analyze the coefficients of friction of various court type materials depending on deep they want to go in understanding tennis as a system, particularly between tennis shoes/sneakers and the court surface. The bouncing of a tennis ball on a tennis court surface is analyzed by making several simplifying assumptions about the physics of the interaction.

Focus Question: What are the differences in energy lost when a tennis ball interacts with different court surfaces?

Part I.

We know the force of gravity is playing a major role as tennis is played.

- 1) Describe the forces acting on a ball. Use a diagram to help your explanation for each of the following:
 - a) When it is held.
 - b) When it is thrown upward.
 - c) When it is thrown horizontally.
 - d) As it hits the court.
- 2) Describe the energy that the ball has in each of the above situations.
- 3) If the ball is dropped from 3 ft (or .9144 meters), then how much potential energy does the ball have initially?
- 4) As the ball falls what happens to the starting energy?
- 5) Calculate how much energy does the ball have after falling $\frac{1}{2}$ of the distance? (Think about potential and kinetic energies.)

Part II.

Design an experiment to test the interaction in terms of energy lost by a given ball as it interacts with the different court materials samples you have been provided. This can be accomplished by appropriate controls and variables.

Suggested procedure:

- 1) For a given court material sample drop the ball from a height of 1.0 meters (Note: we are rounding off the mid-court net height of 3 ft or .9144m) for ease of calculations. After it bounces measure the maximum height of the bounce.
- 2) Repeat #1 above for two additional trials.
- 3) Determine the average height of bounce.
- 4) Calculate the maximum average potential energy of the ball after it bounces.
- 5) Calculate the percentage of energy lost when the ball bounces off the given surface.
- 6) Repeat the above for a different court material sample.
- 7) Compare your results to other lab partners in other groups.
- 8) **High School Students:** Read the following article - http://www.tennisindustrymag.com/articles/2004/04/follow_the_bouncing_ball.html

In the article the authors compare vertical speeds of the ball before and after the collision. The authors state:

“The ratio of the ball’s vertical speed after the bounce to that before is known as the “coefficient of restitution” (COR). If the vertical speed after the bounce is faster on one court versus another, the ball will bounce higher on that court. The COR is about 0.6 for grass, 0.83 for hard courts, and 0.85 for clay courts. That means that a ball’s vertical bounce will be highest and fastest on clay, lowest and slowest on grass.”

- 9) Calculate the COR for each of two samples of court materials from your experiment.

Hints: You need to calculate the kinetic energy of the ball just before it hits the court, where the initial input of potential energy before it is released is completely converted to kinetic energy. Then you need to calculate the kinetic energy of the ball just after it hits the surface as it begins to bounce upward. That calculation is done by assuming that the kinetic energy just after hitting the court will equal the potential energy at the maximum average height of the bounced ball.

From each of those kinetic energy calculations, before and after the bounce, then solve algebraically for the velocities. Then calculate the COR for each of the two courts.