General Physics Lab 5

Conservation of Energy

Objectives:

- To simultaneously measure both kinetic and potential energies of a projectile to test the hypothesis that the total mechanical energy is conserved under conservative forces

Equipment:

- 1 Racquetball
- Measuring Tape
- Smartphone with Video or Webcam
- Triangular Wood Block
- 2 Rubber Bands
- Tracker Video Analysis software
  available for free download at https://physlets.org/tracker/

Physical Principles:

Kinetic Energy

The energy of motion is called Kinetic Energy. An object with mass, m, moving with speed, v, has a kinetic energy defined by,

$$KE = \frac{1}{2}mv^2 \quad . \tag{1}$$

For 2-D motion, the velocity vector is the vector sum of x and y components, so by the Pythagorean Theorem,

$$v^2 = v_x^2 + v_y^2 \quad . \tag{2}$$

Potential Energy

When a conservative force (such as gravity or a spring) acts on an object, we can define a potential energy based on its position. In a gravitational field, this potential energy takes the form,

$$PE = mgy \ , \tag{3}$$

where y is the height of the object above some reference height.

Conservation of Total Mechanical Energy

In the absence of non-conservative forces (such as frictional or drag forces), the total mechanical energy is conserved.

$$E_{total} = KE + PE = const \tag{4}$$

Procedure:

Mass of the Ball

Use the spring balance to measure the mass of the racquetball in kg. This may be done by sticking a small strip of duct tape to the ball to form a loop. Then, hang the ball from the spring balance (see Fig. 1). Keep the piece of duct tape small so that it doesn't contribute much extra mass to the reading. Don't forget to zero the spring balance if necessary.

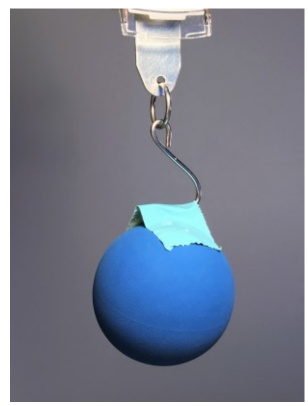


Fig. 1: Rubber ball with duct tape hanging from the spring balance hook.

Video Capture

1. Find a blank, bright wall for a backdrop to provide a nice light contrast with the dark colored projectile (racquetball) when filmed in motion. You will want the background to have a clear, horizontal floor line and a clear vertical line from trim, doorjamb, etc.
2. If you use a smartphone to film the projectile, use the wood block and rubber bands to make a stand as shown (see Fig. 2). Vertical orientation is best for this experiment. Refer to the Smartphone Stand Instructions document for more information.
3. Set the smartphone or webcam on a stable platform facing the wall. The camera lens should be elevated to about the middle of the

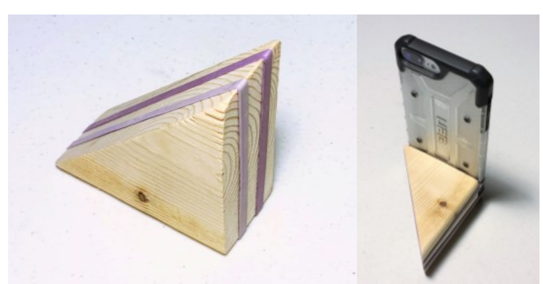
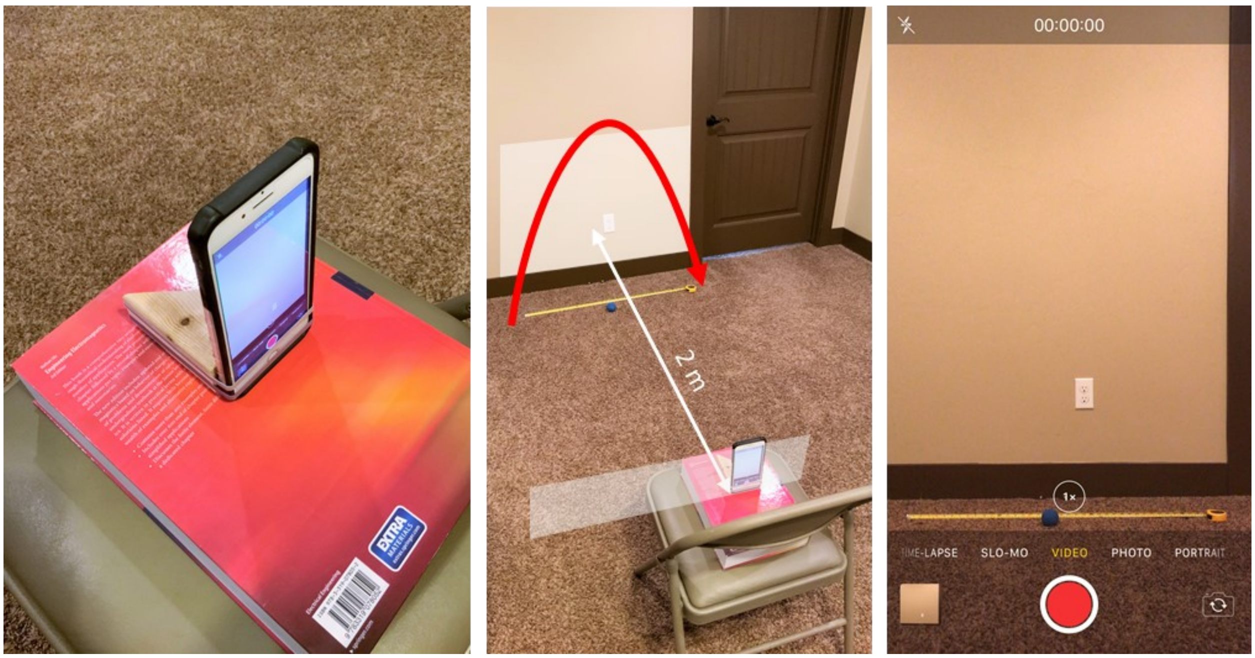


Fig. 2: Simple smartphone stand

projectile's path or about 50-60 cm above the floor (see Fig. 3a & b).

4. Move the camera out about 2 meters away from the wall to make sure you can capture the entire path of the ball. This distance may be different for different camera lenses.
5. Make sure the camera is not angled relative to the wall or the tracking data will be inaccurate. The plane of the wall and the plane of the camera should be parallel to each other (see Fig. 3b).
6. Set the metric measuring tape to precisely 1 meter of length and lay it on the floor parallel to the wall below where you plan to toss the ball. Make sure both ends of the measuring tape are clearly visible to the camera (see Fig. 3c).



(a) (b) (c)

Fig. 3: Smartphone with wood block stand elevated 50-60 cm off the floor and placed 2 meters away from the measuring tape. The camera is pointed straight at the wall, and framed so that both ends of the measuring tape are visible. The right angles of the floor boards and door trim make it easy to align the coordinate axes in Tracker.

7. Start the video recording (ideally 30 fps frame rate) and toss the ball in an arc (from left-to-right as viewed through the camera) directly over the tape measure. The path of the ball should be parallel to the wall as shown by the red arrow in Fig. 3b. Try to get the ball to land in view of the camera if possible. You may need to toss it several times to get a good trajectory, so be patient and keep trying if you don't get it on the first throw. Alternatively, if you are doing this on a hard floor, it works well to bounce the ball across the view of the camera and then track it from when it leaves the floor, bounces up, and then hits the floor again.

8. Review the video to see that the motion of the ball and the measuring tape on the floor are both clearly visible. Make sure you can see the peak of the ball's trajectory and ideally you should be able to see it land as well.
9. If the video is long (more than 30 seconds), you may want to trim it shorter to just the part where the ball is moving across the screen. Tracker does not work well with long videos and the shorter the video, the faster it will load in the program.
10. Transfer the video to your computer via some means (email, Google Drive, iCloud, Dropbox, etc.) for analysis using Tracker Video Analysis software.

Tracking the Motion

Complete the following steps in Tracker.

1. Open the video file in Tracker.
2. Save the Tracker file.
3. If your video was filmed vertically, click Video > Filters > New > Rotate to make the video upright. If you mistakenly tossed the ball from right to left, check the box for Reverse.
4. Using the Calibration Tools, add a new Calibration Stick, align the calibration stick on the tape portion of the tape measure (Shift+Click on the end points), and set the length to 1 meter.
5. Click on the Coordinate Axes and place them on the video. Line up the origin with the intersection of two perpendicular lines in your image (ex. corner of a door) and rotate the axes so that the x and y axes match the angle of the floor and doorframe respectively (see Fig. 6a).
6. Slide through the video to find the frame where the ball hits the floor. Then use the step buttons to step back one frame (this will be our y = 0 reference position). Move the coordinate axes (without changing their rotation) down and left so the x-axis passes through the center of the ball and the y-axis is on the left edge of the video (see Fig. 4b).

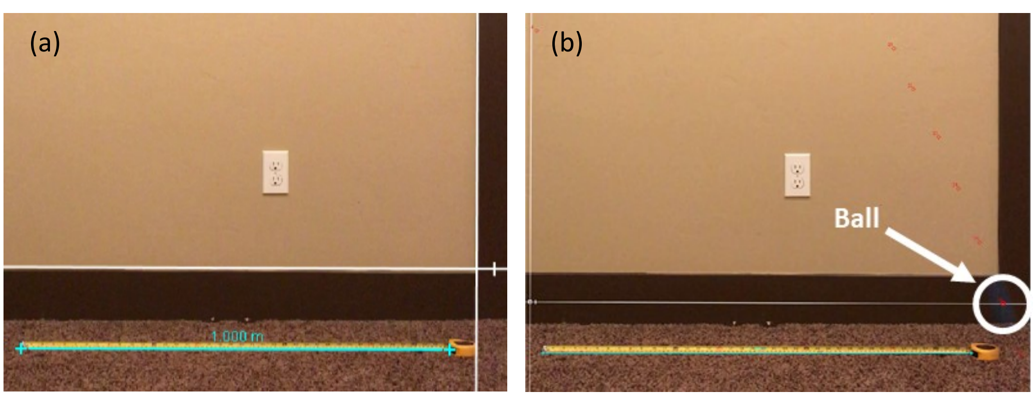


Fig. 4: Tracker calibration stick and coordinate axes added to the video (colors were adjusted for this example to increase visibility). (a) Calibration stick aligned to both ends of the tape portion of the tape measure. Coordinate axes aligned with the baseboard and door trim. (b) Coordinate axes moved to the left edge of the video and down so the x-axis runs through the ball just before it hits the floor.

7. Click Create > Point Mass.
8. Slide through video to the first frame after the ball left your hand or entered the view of the camera and add a point (Shift+Click) on the center of the ball. You will notice that the ball is blurred in front and behind in the direction of motion. Approximate the center of the ball by clicking in the middle of the center dark region of the smear (see Fig. 5a).
9. Continue adding points for each frame at the center of the ball along the trajectory until it hits the floor. Make sure to mark the position at this final point (when it hits the floor) because Tracker will use this point to calculate the velocity for the previous frame.

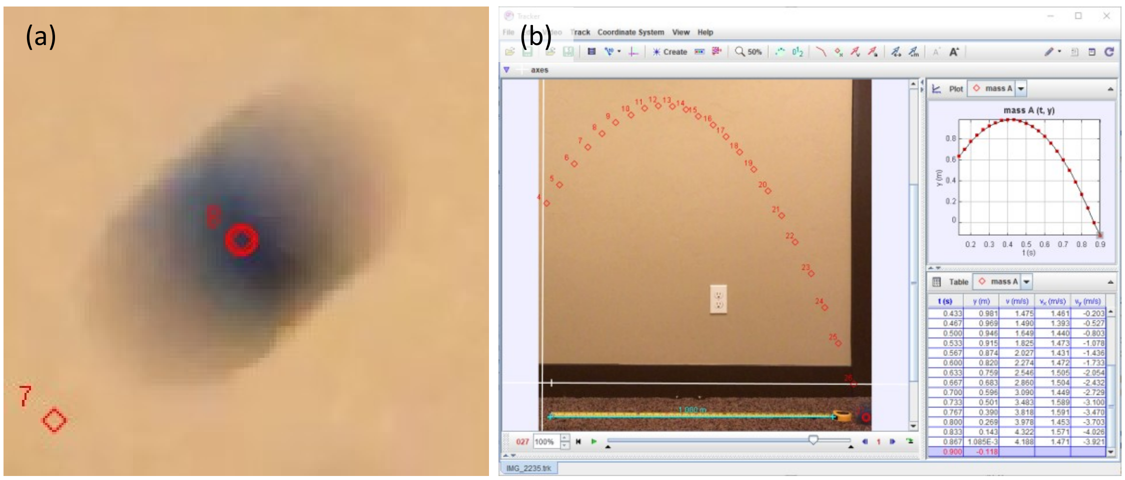


Fig. 5: Add tracking marks to the center of the ball at each frame as it crosses the view of the camera. (a) Place the tracking mark in the center of the dark region of the blurred ball. (b) Track the ball's path all the way across from left to right until it hits the floor. Notice how the plot of y vs t has the same shape as the actual trajectory of the ball.

Export the Data

After you have finished tracking the path of the ball, complete the following steps to export the data:

1. Click Table and select only y and v (total velocity). If you also want to include x, vx, and vy, you can as they may be useful for troubleshooting, but you will not need them for the calculations.
2. Option 1 – Copy and paste the data
    a. Select all the data in the table
    b. Right click > Copy Selected Cells > Full Precision
    c. Paste the data into Google Sheets or Excel

   Option 2 – Export a CSV file with the position and velocity data
    a. Click File > Export > Data File and set the following parameters:
       Cells = All Cells, Number Format = Full Precision, Delimiter = Comma
    b. Click Save As and name the file with the extension ".csv" (ex. "filename.csv").
    c. Using Google Sheets or Excel, import each CSV file.

Analysis:

1. Open a blank Google Sheets or Excel document and import the data from Tracker.
    a. If you copied the data directly from the table in Tracker, you can simply paste it into the blank spreadsheet.
    b. If you exported a CSV file, you will need to import the data from that file into your spreadsheet.
2. Delete the top and bottom rows of data because there is no velocity for those points. Also, remember that when you aligned the coordinate axes, you positioned them so that the x-axis ran through the ball on the frame just before it hit the floor. This was so when you remove the last point, the new last position point is at y = 0.
3. Reformat the cells into Number format and increase the decimal precision to include the full precision you copied from Tracker.
4. Create three new columns for Kinetic Energy, Potential Energy and Total Energy using the following formulas and the mass, m, of your ball.

$$KE = \frac{1}{2}mv^2$$

$$PE = mgy$$

$$E = KE + PE$$

5. Using Google Sheets, Excel, or Graphical Analysis, generate a single scatter plot with KE, PE, and E all on the y-axis and time, t, on the x-axis.

   You will note that neither KE nor PE are constant across the path of the ball, but the total energy, E, is roughly constant. You should also notice that there is a small offset between KE and the x-axis and a corresponding offset between the max of either KE or PE and the total energy, E. This offset in KE is due to the constant velocity in x which always contributes some amount of energy to the ball. Since E is the sum of KE and PE, it also has this vertical offset on the graph.

6. Demonstrate the constancy of E by computing the mean and standard deviation of the total energy data. This can be done in the spreadsheet using these formulas:

   =AVERAGE( )
   =STDEV( )

7. Calculate the relative error by taking the ratio:

$$\%Err = \frac{standard\ deviation}{mean} \times 100\%$$

If you calculate this in a spreadsheet, you can leave off the x 100% and just format the cell as a percent.