

A Penny in Free Fall

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INTRODUCTION

This research is a study of whether a penny would kill a person if it landed on them after falling from the Empire State building (a height of 1,453 feet). For almost 6 years, proving the answer to this question has been puzzling both my partner and I. After developing a stronger math and science background in high school, we decided to tackle this problem. None of the formulae we had seen before was relevant to the practical side of the problem. That is, they did not take into account the fact that a penny will turn in the air and that the changing aerodynamics and surface area will affect its velocity. We finally stumbled onto some formulas that were related to the hyperbolic trigonometric functions and the problem was thought to be much easier. We also looked through several physics books for equations that involve drag. After we found some, the same equations were found on the HP-48 series calculator.

Note that there are two different types of pennies in existence. Pennies made before 1982 are 95% copper and 5% zinc. After 1982, production of that penny stopped and a new penny was introduced. This new penny is 97.5% zinc and 2.5% copper. It weighs only 2.500 grams compared to the old penny weighing 3.110 grams. The difference in mass is 0.61 grams. This is equivalent to 19.61% of the mass of the old penny and 24.4% of the mass of the new penny. Thus, in order to assure accurate results, make sure to experiment with pennies produced after 1983 and before 1981, but obviously not during the same trial. The treasury department has removed the original web page providing numbers, but for the next closest document, see [1].

You and your partner will inevitably want to develop some sort of hand signals so that you will be able to communicate with each other. For example, when over 50 feet separates you and your partner, vocal communication is not very effective. If you are indoors and such a distance separates you, echoes become a major problem. It is possible to use only hand signals for this experiment. One type could mean stop the stopwatch while another means ready. However, if you have 2-way radios, your partner can relay the falling time back to you, you can then both record the times, and compare any discrepancies later. Plus, you can relay information about a perfect drop versus one that was obstructed or tell your partner about problems you had not anticipated and consequently did not develop hand signals for.

The use of a high structure is necessary because it is fun to drop things from great heights. Seriously, though, the height plays a significant role in the accuracy of the measurements. If the distance is too short, the ground partner will have hardly noticed the stopwatch is running and will immediately need to concentrate on stopping it. However, if you use too high of a structure, this can also prove ineffective. The ground partner will become impatient and stop the stopwatch too early in anticipation of the penny colliding with the earth. The structure you decide to use should be *at least* 40' in height.

You should be cautious and aware of both horizontal and vertical wind drafts in the area where you plan to drop the pennies. The reader may recall from classical (or Newtonian) physics that the horizontal motion of a projectile does not affect the falling time. However, in the real world, there is air resistance. As such, any deviation from a purely vertical fall will affect the falling time. If in doubt, refer to Pythagoras who tells us that if the penny's trajectory has a horizontal component from the wind, it will have to fall a greater distance through the air. Thus, there is more resistance in the fall. This resultant motion determines the terminal velocity. If a strong horizontal wind exists, the penny will move too far to the side and it will seem to fall rather slowly toward the earth. The vertical speed is also inevitably linked to the relative speed of the penny with the air. Because this relative speed will *always* be the same, vertical air drafts will change the speed relative to the stationary surroundings.

Be aware of the surroundings, also. Pennies do not fall straight down; they flutter around in the air while they fall. This could potentially be dangerous for observers or objects the penny may hit. Thus, make sure there is a wide enough area for the penny to fall. This way, the penny will reach the ground without its speed or trajectory changed by any external factor.

It is important to use an accurate timing device, but too accurate will not be any better. In other words, a second hand on a wristwatch will not be accurate enough but anything more accurate than hundredths of a second will be too accurate. This is because the falling times of the penny will vary in the hundredths range making more digits useless. The actual terminal velocity of the penny could also be argued over. Since it changes minutely due to its own rotation, it will never achieve a single, terminal speed. However, the speed, averaged over the rotations of the penny, will be close to the same number every time.

PROBLEM: If a penny fell of the Empire State Building and hit a person in the skull, would it kill them?

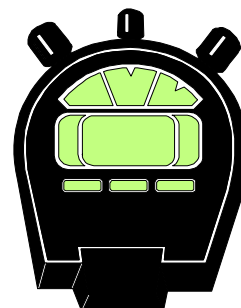
HYPOTHESIS: Depending on where the penny hits, the force of the penny will overcome the protective skull and kill the person.

MATERIALS:

Stopwatch With Start and Pause Buttons	2 Separately Insulated 100'+ Lengths of Wire
50'+ Measuring Tape	100' String
Weight	Soldering Iron
Solder	Large Spool or Dowel (2"+ diameter)
Wire Strippers/Cutters	Electrical Tape
10+ Pre-1982 Pennies	2 Two-way Radios (optional)
10+ Post-1982 Pennies	Momentary Push-button Switch (RS# 275-618A)
10+ 3/8" Ball Bearings	Electric Hand-Held Drill
1/4" Drill Bit	3/8" Drill Bit
Thermometer	Small Pill Container or Experimenter Box

PROCEDURE:

- 1) Take apart the stopwatch (a simple one with well-defined click buttons as shown is preferred). Be careful not to lose any parts, as the watch will be reassembled later. Locate the area where the end of the start/stop button is. You should find two metal plates that connect when the button is pressed. Carefully solder either leads or the ends of the 100' lengths of wire to each metal plate. *Do not bridge the gap with any solder as this will result in a short circuit!*
- 2) Run the wires either through the hole where a neck string was or through the original buttonhole. Test the stopwatch by touching the other ends of the wire together. The stopwatch should start or stop with each contact. If so, place electrical tape over the connections so that nothing else will bridge the circuit. Reassemble the stopwatch. If you soldered leads instead of the actual wires to the plates, solder the wires to the leads and wrap electrical tape around them. For storing the device, wrap the wire around the spool or dowel.
- 3) To make a switch, either take the pill container or the experimenter box and using the 3/8" drill bit, drill a hole in the top. If 3/8" is too big or too small for your switch, use a different size. If you are using a pill container, remove the plastic seal inside the cap before drilling. Insert the push-button switch into the hole and secure it (fasteners are included). On the bottom or side of your container, use the 1/4" drill bit to drill a hole for the wires to come out. If this drill bit is not the correct size for your wires, use the appropriate one. Run the wires through the hole and solder them to the connections on the switch. It is not necessary to tape these connections, as they will be enclosed in the box or pill container. (See the schematic for more information.)
- 4) Find a tall structure from which to drop pennies (30' – 40' at least). Attach the weight to the string and drop the plumb bob. When the bob has reached the bottom and your partner notifies you of its doing so, tighten the string and lower the measuring tape. If the tape does not reach the entire distance, find a spot to stop the tape. Have your partner mark the spot and then measure from that spot. Repeat if necessary. Once the tape has reached the bottom, have your partner hold the tape and tighten the tape. Record your measurement. The accuracy can be a little slack because a difference of 1" or so will hardly be detected by the times. Wind up all measuring devices.
- 5) Measure the temperature. This will be helpful in determining the air density.
- 6) Drop the stopwatch end (that is, keep the switch) to the bottom. When both partners are ready, begin dropping pennies. Push the switch to start the stopwatch the instant you release the penny. When the other partner *sees* the penny hit the ground. Record time of fall. Repeat with different types of pennies and different ways of dropping them (e.g. rolling or flat). Be sure to note which way the penny was dropped and which type of penny it was.
- 7) After several trials involving pennies, switch to the ball bearings. Then, repeat dropping pennies and ball bearings at different heights.



DATA: Eleventh Street Bridge data collected at approximately 77° F while USC data collected at approximately 86° F. Altitude of both trials is approximately 4600 feet above sea level.

11th Street Bridge, 9/12					
<i>Location 1</i>		<i>Location 2</i>		<i>Location 3</i>	
38' 10"		38' 3"		35' 5.5"	
Trial #	Time (s)	Trial #	Time (s)	Trial #	Time (s)
1	1.44	1	1.82	1	1.28
2	1.59	2	1.49	2	1.64
3	1.55	3	1.62	3	1.62
4	1.41	4	1.6	4	1.63
		5	1.54		
		6	1.39		
		7	1.48		
		8	1.48		
Average:	1.4975	Average:	1.5525	Average:	1.5425
Variance:	0.007425	Variance:	0.01705	Variance:	0.030692

USC Stairwell, 9/13			
<i>Location 1</i>		<i>Location 2</i>	
89' 9.5"		63' 11"	
Trial #	Time (s)	Trial #	Time (s)
1	No	1	2.43
2	Data	2	2.40
3	Collected	3	2.49
		4	2.49
		5	2.33
		6	2.46
		7	2.52
		8	2.36
		9	2.33
		10	2.39
		11	2.39
		12	2.33
		Average:	2.41
		Variance:	0.0042

USC Stairwell, 9/20									
89' 9.5" (27.3685m)									
Ball Bearing		Pre 1982 Penny, Rolling		Pre 1982 Penny, Flat		Post 1982 Penny, Rolling		Post 1982 Penny, Flat	
Trial #	Time (s)	Trial #	Time (s)	Trial #	Time (s)	Trial #	Time (s)	Trial #	Time (s)
1	2.55	1	2.33	1	2.96	1	2.74	1	3.11
2	2.49	2	2.64	2	3.05	2	2.77	2	2.90
3	2.54	3	2.70	3	2.77	3	2.68	3	3.21
4	2.58	4	2.58	4	2.98	4	2.68	4	3.15
5	2.58	5	2.67	5	3.12	5	2.73	5	3.11
6	2.55			6	3.12	6	2.55	6	3.08
7	2.55			7	2.90	7	2.46		
8	2.58			8	2.77	8	2.80		
9	2.71								
10	2.55								
11	2.46								
12	2.55								
13	2.61								
14	2.62								
Average:	2.565714	Average:	2.584	Average:	2.95875	Average:	2.67625	Average:	3.09333333
Variance:	0.003473	Variance:	0.02213	Variance:	0.01935536	Variance:	0.01339821	Variance:	0.01098667

USC Stairwell, 9/20									
Location 2									
63' 11" (19.4818 m)									
Ball Bearing		Pre 1982 Penny, Rolling		Pre 1982 Penny, Flat		Post 1982 Penny, Rolling		Post 1982 Penny, Flat	
Trial #	Time (s)	Trial #	Time (s)	Trial #	Time (s)	Trial #	Time (s)	Trial #	Time (s)
1	2.15	1	2.02	1	2.43	1	2.27	1	2.58
2	2.18	2	2.24	2	2.43	2	2.30	2	2.40
3	2.14	3	2.12	3	2.33	3	2.02	3	2.71
4	2.15	4	2.11	4	2.24	4	2.24	4	2.48
5	2.20			5	2.49	5	2.15	5	2.36
				6	2.24			6	2.55
Average:	2.164	Average:	2.1225	Average:	2.36	Average:	2.196	Average:	2.51333333
Variance:	0.00063	Variance:	0.00815833	Variance:	0.01128	Variance:	0.01283	Variance:	0.01638667

CALCULATIONS:

The drag force on an object is given by the equation

$$D = \frac{1}{2} CrAv^2$$

where D is the drag force, C is the drag coefficient usually in the range of 0.5 – 1.0, ρ is the density of air, A is the effective cross-sectional area of the falling body, and v is the speed of the fall. At terminal velocity, the drag force will be equal to the weight of the object, that is,

$$D = mg$$

Thus,

$$v = \sqrt{\frac{2mg}{CrA}}$$

To calculate the air density, use the following table [2],

Density of Air at Standard Atmospheric Pressure

Temperature ° Celsius	Temperature ° Farenheit	Density: dry air mass kg/m ³
-25	-13	1.423
-20	-4	1.395
-15	5	1.368
-10	14	1.342
-5	23	1.317
0	32	1.292
5	41	1.269
10	50	1.247
15	59	1.225
20	68	1.204
25	77	1.184
30	86	1.165
35	95	1.146

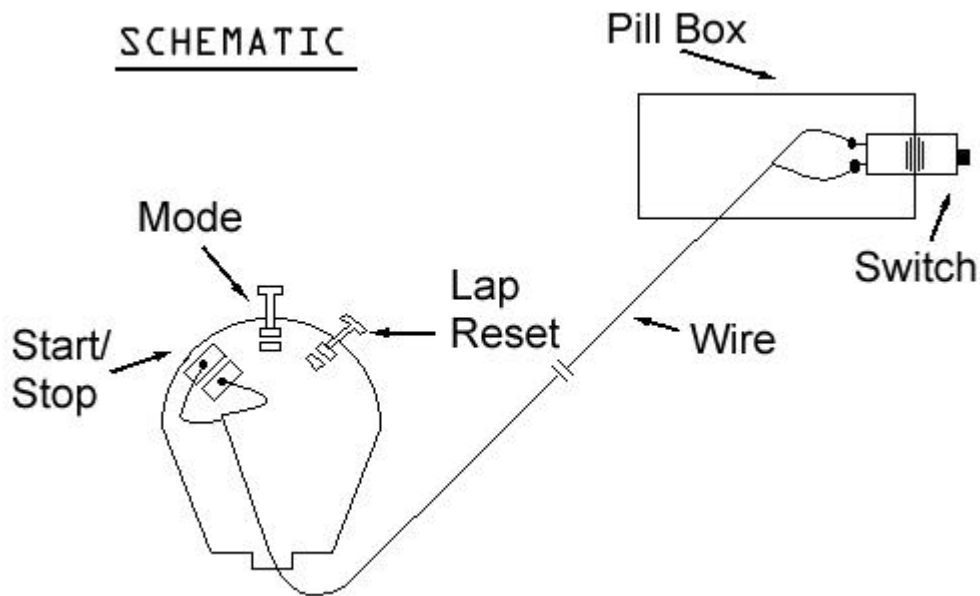
As suggested in the article “Chaotic dynamics of falling disks” [3], the penny will fall in one of four ways depending on how it is dropped. These different paths are steady (falling flat straight down), periodic (oscillating from side to side), chaotic, and tumbling. The flat penny should have fallen either flat or periodic and the rolling penny either chaotic or tumbling. Due to the extreme differences in the path of these falls and the inability to categorize appropriately the fall, actual calculations become very difficult. Consequently, the drag coefficient cannot be accurately determined. Even if it could, it would be a function of time relating to the fall of the penny. The average value of this function would probably be useful for an approximation of the terminal velocity. Hopefully, the falling times and positions (rolling or flat) collected in this experiment will be of assistance to someone in determining an effective cross-sectional area or a drag coefficient. If either of these properties is found, please e-mail macklem@colorado.edu. Until then, comparison with a table [4] of known terminal velocities should be adequate.

<i>Object</i>	<i>Terminal Speed (m/s)</i>
16-lb Shot	145
Sky diver (typical)	60
Baseball	42
Tennis ball	31
Basketball	20
Ping-Pong ball	9
Raindrop (1.5mm radius)	7
Parachutist (typical)	5

CONCLUSION: Reject the hypothesis and instead accept that a penny falling at terminal velocity will not kill a person. After reviewing the table of terminal velocities, a penny may fall faster than a Ping-Pong ball, but certainly not any faster than a basketball. These terminal velocities convert to about 20-45 mph (32-72 kph). This may cause a bit of a sting, but it is not going to kill a person. For further confirmation, Dennis Thompson tells about dropping pennies in a vacuum [5]. He says the pennies simply bounce several feet high, but the impact leaves no visible marks on the penny. Although the fall from the Empire State Building is three times that of the vacuum chamber, a penny certainly will not fall faster in air than in this chamber thus making pennies non-lethal.

DISCUSSION OF ERROR: For the measurements taken in the USC Stairwell on September 13, air conditioners were running in the building. Consequently, air drafts in the stairwell may have skewed the data to represent longer or shorter than actual falling times.

DIAGRAM: Because you will modify the way in which the stopwatch operates, it is important to note how to use the stopwatch. This will cover the operation of a modified stopwatch similar to the one pictured on the first page of the procedure. The two separate wires soldered to the internal components of the stopwatch replace the need of the button. When these two wires are connected, the stopwatch behaves as if the button was pushed. The reason another button is connected to the wires is to ease the operation of the stopwatch. The main unit will be at the bottom of the drop site for the second partner to stop the stopwatch. The first person will have the new button and the wire will be between the partners. When the first partner drops the penny, he will also click the button starting the timer. When the second partner *sees* (not hears) the penny hit the ground, he should hit the pause button (also called lap reset). This is the time it takes for the penny to fall. Of course, the stopwatch is still counting. After assuring the second partner has recorded the time of the fall, the first partner must then click his button again to stop the watch. Then the second partner will need to press the lap reset button once more to revert back to the timing of the stopwatch and finally the clear button.



REFERENCES:

1. <http://www.ustreas.gov/opc/opc0075.html>
2. <http://www.windpower.dk/stat/unitsw.htm#anchor138877>
3. Field, Stuart B., Klaus, M. & Moore, M.G. Chaotic dynamics of falling disks. *Nature*. **388**, 252-254 (1997).
4. Halliday, David & Resnick, Robert. *Fundamentals of physics*. Third Ed. (1988).
Original Source: Adapted from Peter J. Brancazio, *Sport Science*, Simon & Schuster, New York, 1984.
5. http://www.urbanlegends.com/science/penny_falling_impact.html