**Air Resistance Simulation**

# Notes:

1. ***This is a three-week lab. This assignment can be done at home, or from any other computer with Microsoft Excel and a word processor***
2. We recommend doing the lab early in each week rather than waiting until it is almost due. If you have computer trouble, or need to ask questions, you will want to have plenty of time before the deadline. No excuses!
3. Turning in your report:
   1. This lab has separate parts due separate days! Please be sure to check the course calendar
   2. If you work in a group, turn in only one report, but be sure it lists all group members as authors.
   3. Lab reports should be uploaded to Canvas in .pdf format by the deadline in the course calendar.
4. Getting help:
   1. Your lab TA can answer questions by email or during their office hours listed in the syllabus.
   2. You can also ask advice from lab partner(s) and/or other students.

# Objectives of this lab:

These are things you will address in your report

1. You will learn to use a spreadsheet to simulate a physical process. (Simulations are major skill in many industries)
2. Use your simulation to find the time it takes an object to fall to the ground from a given height with a given initial velocity.
3. Assure that your simulation gives correct results by comparing it with the analytical result (the “paper and pencil math” solution).
4. Incorporate air resistance into your simulation and use it to find the time for a fall, the terminal velocity, and other aspects of this more complex situation.
5. Assure that your simulation *still* gives correct results by comparing it with the analytical result (the “paper and pencil math” solution).
6. Use your simulation as an experiment to investigate the effects of air resistance on a falling object.
7. Design and run at least one experiment of your own in your simulation.

# What you will learn:

Please review the learning goals for the semester in lab in the handout from the first week. In addition, this lab has several specific goals:

1. You will practice keeping lab notes in a paper notebook, computer file, or other format.
2. You will enhance the spreadsheet skills you learned previously.
3. You will learn to use numerical integration, a method that allows you to see how variable changes by using a computer to add up many small changes according to a formula, say, finding the change in velocity by using for many .
4. You will learn to test a complex spreadsheet with lots of formulas, to gain confidence that it is giving reliable results
5. You will learn to use such a spreadsheet as a way to do “simulated experiments” that help you understand how a complex system behaves.

# Equipment:

* A computer equipped with *Microsoft Excel* and *Word* (or their equivalents)

# Dos & Don’ts:

* + ***Do*** remember the goals: you are learning a skill (creating and testing a spreadsheet that does complex calculations) and gaining a deeper understanding of physics (how do the laws of motion work out in real life).
  + ***Do***work on this steadily over the next few weeks. If you get behind, it will be difficult to do a good job and get full credit).
  + ***Don’t*** worry about breaking anything or doing anything dangerous. This is a simulation lab!
  + ***Don’t*** forget that you can get help with this from the TAs.
  + ***Do*** use your imagination and have fun.

# ACTIVITY 1: Simulating an object falling without air resistance

### Note: Your report on this activity is due after the first week of lab! Submit your spreadsheet and a first draft of your report through Canvas.

We want to use Newton’s 2nd law and to see how the velocity changes. The difficulty is that is only true if the acceleration is a constant. What if it isn’t? What if it is really *a(t)*? Numerical integration is a way of dealing with this. What we do is make the (usually good) approximation that *a(t)* is constant as long as we only consider very short time periods. Then, we can say that Similarly,

(Note: If you’ve taken a calculus class, you can understand this using regular integration. Specifically, and ). We will use this, to “simulate” a ball of mass *m* that starts at height *H*, is thrown upwards with velocity *v*0, then drops to the ground in free fall. We will put in cells that hold the constants we use: *t, m*, *H*, *g*, and *v*0. We will make columns for time, force, acceleration, velocity, and position.

The key will be getting from one row to the next. To do this, we use a simple version of the “Euler Method” there are more complex versions than we use here, and you are welcome to look those up online. In this version, we take *v* in each row to equal *v* in the previous row plus *a* in the previous row times our *t*. As an equation, that is *vn*+1 = *vn* + *an**t*. We will do the same to get *x* from *v*, that is,   
*xn*+1 = *xn* + *vn**t*. The figure below shows the beginning of the sheet, for the case of a 5 kg ball thrown upwards at 10 m/s from a height of 20 m (Row 2 in the spreadsheet image below). The “regular view” is on the left. The view on the right shows all the formulas.

Application, table, Excel

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Have a close look at each formula in rows 5 and 6. Column by column, you should see that

1. Our time step, *t*, is set to 0.05 s. That is, we calculate values every 50 milliseconds.
2. Row 1 has labels for all the constants, row 2 has the values of the constants, and row 5 has the initial values.
3. *F = mg* and *a = F/m* in every row
4. *tn*+1 = *tn* + *t*, where *n* is the number of the row, starting with *n* = 5
5. *vn*+1 = *vn* + *an**t* and *xn*+1 = *xn* + *xn**t*

### Your job

1. Build this spreadsheet yourself and fill down at least 100 rows.
2. Scroll down and look for where *y* becomes negative. That is the time you have calculated for the ball to be “below the ground”; you can use it as an approximation for when the ball hits. (The graph below illustrates this). For the values given, it should be between 3.3 and 3.35 s. Is it? If not, you need to fix your calculation.
3. Solve the problem the way we did in chapter 2, that is, using *y* = *y*0 + *v*0*y*t – ½*gt*2 . Does your answer agree? It should!
4. Use your spreadsheet and the mathematical formula to calculate the time for 5 different initial velocities. If you pick a high-speed going up, you may need to add rows to your spreadsheet to give your ball time to hit the ground. In your report, compare the times calculated with a formula to the times computed in Excel. They should agree to within 0.1 seconds or so.

**Note: This process of checking against an analytical solution is an important skill in creating simulations.** Always start simple and try to reproduce a value you can calculate with pencil and paper. If you can, you have confidence your computation is working, and can move on to more complex calculations. Each time you finish coding a part, test it. Move on once you are confident it is working.

# What goes in my lab notes, and what about my report?

The purpose of lab notes is to enable you or a colleague to reconstruct what was done and why.

* They don’t have to be neat, in complete sentences, etc., but they do have to be useful.
* They should be quick notes of what you did, and what you learned. It is perfectly OK to include screen images from your spreadsheets. Examples:
  1. What constants did you use, and where did you put them in your spreadsheet?
  2. Where there any tricks you figured out to get the spreadsheet working?
  3. How close was your simulated final time to the analytical version? Did you do anything to get closer?
  4. What values of initial velocity did you try, and what were the simulated and analytical times for those? Tables are useful for this sort of thing!
* If you store multiple versions of your spreadsheet, recording what the different filenames correspond to is a good idea.

The purpose of a report is to explain what you learned and how you learned it. The sorts of things that belong here are

* A description of each thing you did as part of the activity. That includes your analytical solution to the problem of how long it takes a ball to hit the ground, given an initial height and velocity.
* At least one example graph of height vs. time.
* Your data from your investigation of simulated fall time vs. analytically calculated fall time, including percent errors.
* A discussion of the data. Any surprises? Do you think any changes to your spreadsheet are needed? Did you choose initial velocities well? Anything else?
* You can also test your spreadsheet by assuring that it gives close to the analytical result for the ball’s velocity when it hits. Include that data too!

# ACTIVITY 2: Including air resistance

### Note: Your report on this activity is due after the first week of lab! Submit your spreadsheet and a second draft of your report (including any updates to the first part) through Canvas.

Now that we know our calculation is working, we can put in air resistance. I recommend copying everything you have done so far to a new tab in Excel, so you can modify it without losing what you did.

You may have wondered why we bothered to put in *F = –mg* and *a = F/m*. Why not just put in *a* = –*g*? Now, that choice will pay off. We want to include air resistance, so we can add that as a second term to the force formula.

A simple model of air resistance on a sphere, which is pretty good for this problem, is

.

In this expression,  is the density of air (about 1.25 kg/m3), *A* is the cross-sectional area of the sphere, r2, *Cd* is the “drag coefficient,” and *v* is the speed of the ball. *Cd* is a value that depends on the shape of the object and is determined experimentally. For a sphere, it is a reasonable approximation to put in *Cd* ≈ 0.5. *Like friction, the drag force is always opposite to the direction of motion.*

In my version of the spreadsheet, I find it convenient to set *b* = *(1/2)Cd**A.* With this, substitution, my total force is *F = mg –* sign(*v*)*bv*2. In Excel, the function sign(*x*) (not sin!) gives –1 for any negative value of *x* and +1 for any positive *x*. That lets me make sure the drag force is negative when *v* is up (positive) and positive when *v* is down. Drag is like friction, always opposite the motion!

Also, to be consistent, I put in the density and radius of the ball and calculate the mass and cross-sectional area. That way, the comparison of ball area and mass stay “sensible.” The result looks like the figure below. I used yellow to highlight the cells you might put in an input. The density I started off with, 2700 kg/m3, is about right for aluminum.

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Almost done! Once you have this working, you can test your results. Try “dropping” the ball from 100 meters with zero initial velocity. Without air resistance, it should take about 4.52 seconds to fall to the ground. With the densities of aluminum and air above, and *Cd* = 0.5, the same drop should take just a bit longer, about 4.66 seconds. Use these values to be sure your spreadsheet is still working. If it isn’t, keep working until you get it fixed!

Find some additional ways to test your spreadsheet, to make sure that it is working correctly.

Now, you can do a simple experiment: use the spreadsheet you have built to simulate the time for a fall with air resistance from five different heights: choose a spread of values that correspond to building heights from regular houses to big skyscrapers (you can look those up online). Keep using the values above for density of 2700 kg/m3 and radius = 0.05 m. Note: for very tall buildings, you might need to add rows. Include and discuss your results in your report.

## What goes in my lab notes, and what about my report?

The purpose of lab notes is to enable you or a colleague to reconstruct what was done and why. By this time, you can think for yourself what should be included.

The purpose of a report is to explain what you learned and how you learned it. Here are a few things, but again, you can figure out others for yourself.

* Any adjustments you needed to make to your spreadsheet to get the activity done.
* The methods you used to be sure your spreadsheet is giving reliable results.
* Data tables for your experiments.
* Any analytical calculations you did.
* One or more graphs showing your results.

# ACTIVITY 3: Studying the physics of air resistance with your simulation.

### Note: Your report on this activity is due after the third week of lab! Submit your spreadsheet and a final report (including any updates to the first two parts) through Canvas.

**Now that you have verified that your spreadsheet works, you can start doing experiments.**

Experiment 1. The density of the material your sphere is made of makes a big difference. Find the time it takes to drop some fixed distance (up to you, but it should be high enough to see significant differences due to air resistance) vs. density for 10 widely spaced values. You can look up densities of elements and more exotic materials online, but you don’t need to stay strictly within that range. Make sure you use a broad enough range to really show the effects of air resistance.

Experiment 2. Same as Experiment 1, but now look at the “terminal velocity,” the speed at which air resistance is equal and opposite to weight. You can calculate this analytically as well as using your spreadsheet to find an approximate value (say, when the speed stops changing by more than 0.1% in successive rows).

Experiment 3. Your choice. Study the behavior of air resistance (as it affects time, velocity, or some other variable) vs. the input of your choice. You can work with air density, drag coefficient, ball diameter, etc. For more information, you can look at the resources below.

<https://www.grc.nasa.gov/www/k-12/airplane/falling.html>

<https://www.wired.com/2015/01/air-resistance-force-make-difference/>

## What goes in my lab notes, and what about my report?

No more hints! You know the purpose of the notebook and lab report. Show what you have learned!