Air Resistance Simulation

At-Home | Two Weeks | Draft & Report Submissions

Introduction

This experiment explores the use of simulations to solve complex problems using relatively simple physics. In this case, a simulation will be developed based on the kinematic equations for 1D projectile motion. Having verified the accuracy of the simulation by comparing its output to a known solution without air resistance, air resistance effects will be incorporated. The simulation can then be used in experiments which highlight air resistance, its dependence on environmental factors, and its impact on kinematic results. In this way, relationships can be clarified which are difficult to determine using hand calculations alone. Students will also get practice identifying the limitations of simulations and reasonably stating the error associated with them.

Theory

Kinematic Equations:

Systems involving an object undergoing *constant acceleration* in one dimension are characterized by these equations, which you should recognize as *kinematic equations*.

$$y_f = y_0 + v_0 t + \frac{1}{2} a t^2$$

$$v_f = v_o + at$$

If an object experiences no acceleration at all, implying a constant velocity, the following simplification of the first equation is applicable.

$$y_f = y_o + vt$$

Also, the acceleration of an object is directly related to the net force acting on it via Newton's second law, stated below.

$$F_{net} = F_1 + F_2 + \cdots = ma$$

The Euler Method:

These equations are powerful, but what if an object's acceleration is non-constant? To precisely solve such a problem, calculus is required, which is beyond the scope of this analysis.

One way of approximating an answer to this problem without using calculus is to divide the larger kinematics problem (the continuous motion of the object at all moments over a long time) into a series of very small kinematics problems (the motion of the object calculated only every 0.01 seconds, for example). The benefit of this approach is that, though the acceleration may be changing over a long period of time, the "time step" used can be made so small that acceleration doesn't have enough time to change much between any two individual steps – so in that tiny amount of time it's nearly constant. With that in mind, a kinematic equation based on constant acceleration ($v_f = v_0 + a\Delta t$) can give us a reasonable approximation of the velocity of the object a very short time later (v_f) by starting with the velocity and acceleration at the previous time (v_o, a). This method of solving only a tiny bit into the future then repeats over many steps. This approach, which also works for approximating position due to a non-constant velocity, is called the Euler method. It's mathematically represented by taking kinematic equations and formatting them in this way, where n is the "step" you're on and Δt is the tiny amount of time between steps:

$$v_n = v_{n-1} + a_{n-1}\,\Delta t$$

Obviously, performing this calculation over and over for each step until longer times are reached would be a tedious process – but that's what spreadsheets are for!

Air Resistance:

In this experiment, we'll use a simple model for the force due to air resistance represented by the equation below, where ρ_{air} is the density of air, v is the velocity of the object, A is the cross-sectional area of the object, and C_d is a constant called the drag coefficient that depends on the object's shape.

$$F_{air} = \frac{1}{2} C_d \rho_{air} v^2 A$$

The fact that this force depends on the velocity of the object means that it will change in time as the object moves, leading to a non-constant acceleration. It's also important to note that the force due to air resistance is always in the opposite direction of the object's velocity – it's resisting further motion, trying to slow it down.

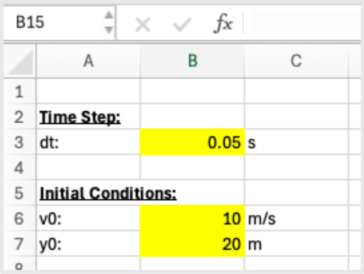
Procedure

For this lab, we will utilize the following equipment:

- A computer with Microsoft Excel and Microsoft Word (or equivalent software)

Activity 1: Simulating Motion

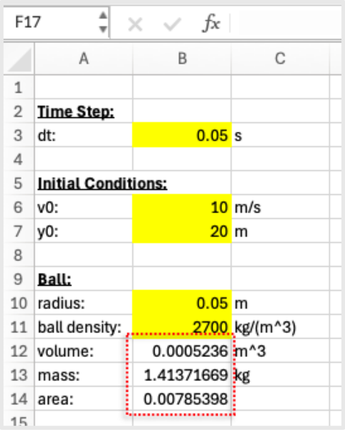
1. On one side of your spreadsheet, label cells for the initial position y_0 and initial velocity v_0. Similarly label a cell for time step Δt. Make sure to label with units too! It's also good practice to distinguish cells you'll use for inputs from those with labels or formulas, so use a color to highlight those cells as shown and do the same for all future inputs.



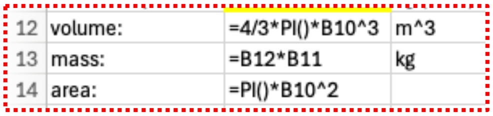
	A	B	C
1			
2	**Time Step:**		
3	dt:	0.05	s
4			
5	**Initial Conditions:**		
6	v0:	10	m/s
7	y0:	20	m

2. The ball's mass can be calculated from information about its size and material. Below the other constants, label cells for the ball's density ρ_{ball} and radius r. For now, use the density of aluminum (2700 kg / m^3) and 0.05 m, respectively. Then label two more cells below those for the ball's volume and mass m and use formulas to first calculate volume from the radius, then mass from the density and volume.

   Calculating air resistance later will require the cross-sectional area of the ball, so label another cell for the cross-sectional area of the ball A. Type a formula into the cell which calculates it from the radius.

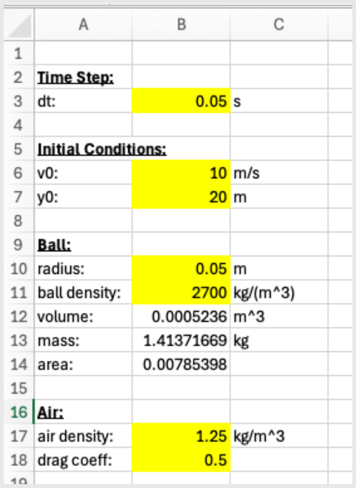


	A	B	C
1			
2	**Time Step:**		
3	dt:	0.05	s
4			
5	**Initial Conditions:**		
6	v0:	10	m/s
7	y0:	20	m
8			
9	**Ball:**		
10	radius:	0.05	m
11	ball density:	2700	kg/(m^3)
12	volume:	0.0005236	m^3
13	mass:	1.41371669	kg
14	area:	0.00785398	



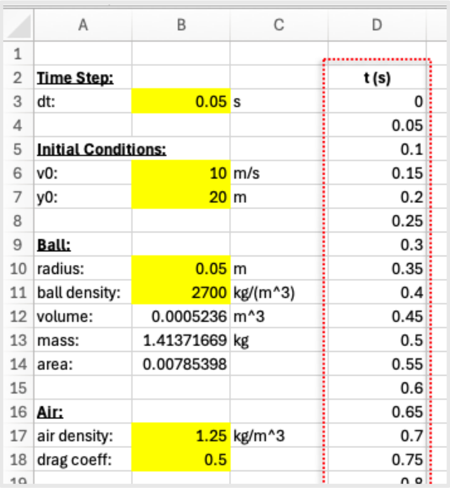
12	volume:	=4/3*PI()*B10^3	m^3
13	mass:	=B12*B11	kg
14	area:	=PI()*B10^2	

3. The remaining constants are all related to air. Below the other constants, label input cells for the density of air ρ_{air} (we'll start with an air density of 1.25 kg/m^3) and the drag coefficient C_d. The drag coefficient depends on the shape of the object, and its value is about 0.5 for a sphere.

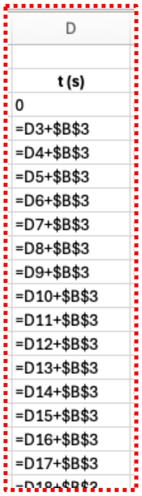


	A	B	C
1			
2	**Time Step:**		
3	dt:	0.05	s
4			
5	**Initial Conditions:**		
6	v0:	10	m/s
7	y0:	20	m
8			
9	**Ball:**		
10	radius:	0.05	m
11	ball density:	2700	kg/(m^3)
12	volume:	0.0005236	m^3
13	mass:	1.41371669	kg
14	area:	0.00785398	
15			
16	**Air:**		
17	air density:	1.25	kg/m^3
18	drag coeff:	0.5	

4. Now you have all the constants you need to start simulating the ball's motion! In the open part of your spreadsheet, label a column for time t and set the first row in that column to zero. For the rest of the rows, apply a formula that refers to your time step Δt cell to fill in at least 100 more rows, each of which is one time step larger than the last (mathematically, that's $t_n = t_{n-1} + \Delta t$ where n is the row).



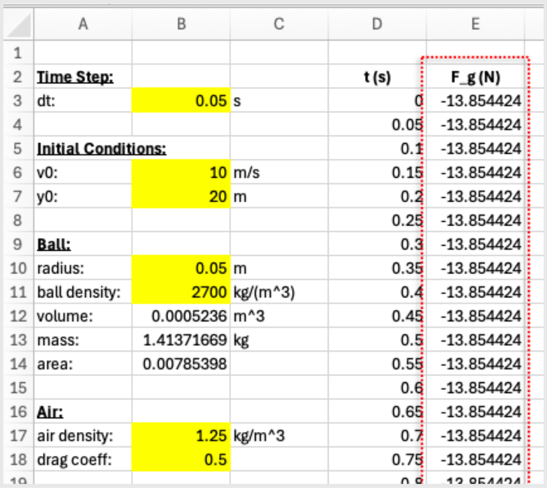
	A	B	C	D
1				
2	**Time Step:**			**t (s)**
3	dt:	0.05	s	0
4				0.05
5	**Initial Conditions:**			0.1
6	v0:	10	m/s	0.15
7	y0:	20	m	0.2
8				0.25
9	**Ball:**			0.3
10	radius:	0.05	m	0.35
11	ball density:	2700	kg/(m^3)	0.4
12	volume:	0.0005236	m^3	0.45
13	mass:	1.41371669	kg	0.5
14	area:	0.00785398		0.55
15				0.6
16	**Air:**			0.65
17	air density:	1.25	kg/m^3	0.7
18	drag coeff:	0.5		0.75



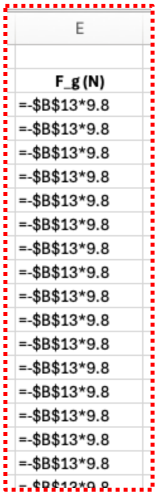
D
t (s)
0
=D3+$B$3
=D4+$B$3
=D5+$B$3
=D6+$B$3
=D7+$B$3
=D8+$B$3
=D9+$B$3
=D10+$B$3
=D11+$B$3
=D12+$B$3
=D13+$B$3
=D14+$B$3
=D15+$B$3
=D16+$B$3
=D17+$B$3

5. At each time step, we need to know the two forces acting on the ball (gravity and, soon, air resistance). First, label a column next to the time column for the force of gravity F_g and use a formula to calculate it for all rows (as you know, $F_g = mg$ where $g = 9.8\ m/s^2$). You'll notice

this value doesn't depend on time, so it's value in every row will be the same. That makes sense – gravity is acting on the ball with a constant force!



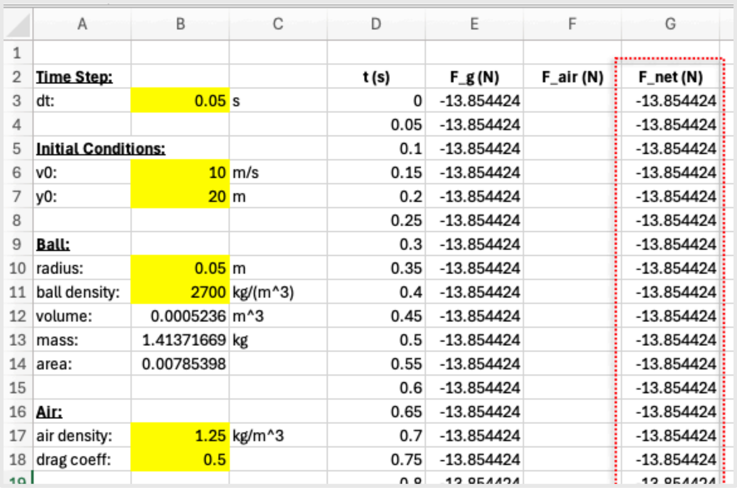
	A	B	C	D	E
1					
2	**Time Step:**			**t (s)**	**F_g (N)**
3	dt:	0.05	s	0	-13.854424
4				0.05	-13.854424
5	**Initial Conditions:**			0.1	-13.854424
6	v0:	10	m/s	0.15	-13.854424
7	y0:	20	m	0.2	-13.854424
8				0.25	-13.854424
9	**Ball:**			0.3	-13.854424
10	radius:	0.05	m	0.35	-13.854424
11	ball density:	2700	kg/(m^3)	0.4	-13.854424
12	volume:	0.0005236	m^3	0.45	-13.854424
13	mass:	1.41371669	kg	0.5	-13.854424
14	area:	0.00785398		0.55	-13.854424
15				0.6	-13.854424
16	**Air:**			0.65	-13.854424
17	air density:	1.25	kg/m^3	0.7	-13.854424
18	drag coeff:	0.5		0.75	-13.854424



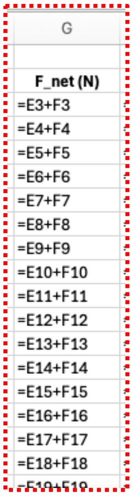
E
F_g (N)
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8
=-$B$13*9.8

6. Label the next column as the force due to air resistance F_{air}! If you tried writing a formula for this right now, you'd run into an issue: we haven't set up the ball's velocity v yet, which is part of the air resistance equation! You'll come back and fill this in later after setting up velocity. Leave it empty for now, which is like saying air resistance isn't a present yet.

7. Regardless of which individual forces are involved; to calculate the acceleration of the ball at a certain time, we need to know the total force on it. Label a column for net force F_{net} and use a formula so that, in each row, its value is the sum of the gravity and air resistance forces. For now, this result will just match the force due to gravity since we haven't yet filled in air resistance.



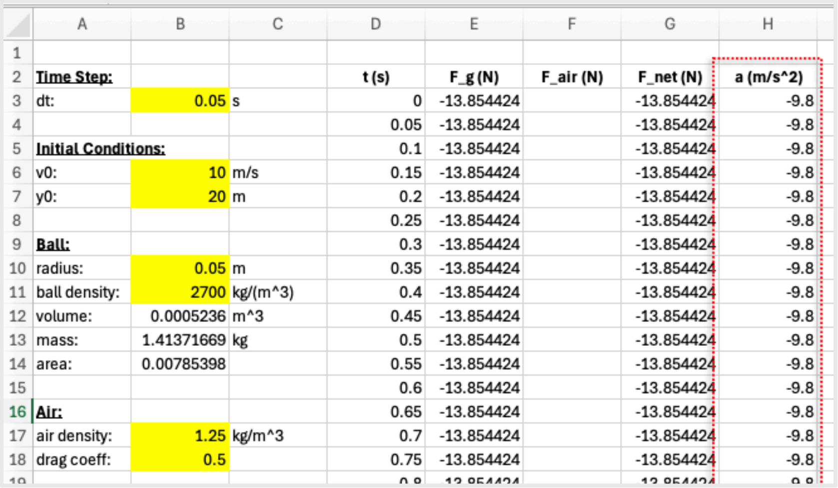
	A	B	C	D	E	F	G
1							
2	**Time Step:**			**t (s)**	**F_g (N)**	**F_air (N)**	**F_net (N)**
3	dt:	0.05	s	0	-13.854424		-13.854424
4				0.05	-13.854424		-13.854424
5	**Initial Conditions:**			0.1	-13.854424		-13.854424
6	v0:	10	m/s	0.15	-13.854424		-13.854424
7	y0:	20	m	0.2	-13.854424		-13.854424
8				0.25	-13.854424		-13.854424
9	**Ball:**			0.3	-13.854424		-13.854424
10	radius:	0.05	m	0.35	-13.854424		-13.854424
11	ball density:	2700	kg/(m^3)	0.4	-13.854424		-13.854424
12	volume:	0.0005236	m^3	0.45	-13.854424		-13.854424
13	mass:	1.41371669	kg	0.5	-13.854424		-13.854424
14	area:	0.00785398		0.55	-13.854424		-13.854424
15				0.6	-13.854424		-13.854424
16	**Air:**			0.65	-13.854424		-13.854424
17	air density:	1.25	kg/m^3	0.7	-13.854424		-13.854424
18	drag coeff:	0.5		0.75	-13.854424		-13.854424



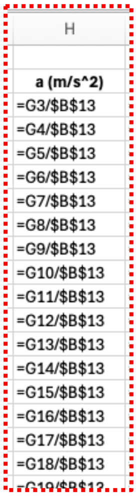
G
F_net (N)
=E3+F3
=E4+F4
=E5+F5
=E6+F6
=E7+F7
=E8+F8
=E9+F9
=E10+F10
=E11+F11
=E12+F12
=E13+F13
=E14+F14
=E15+F15
=E16+F16
=E17+F17
=E18+F18

8. Label a new column for <u>acceleration a</u> and use a rearranged version of Newton's second law ($a = F_{net}/m$) as a formula to calculate the acceleration in each row by referring to cells for the net force in that row and the ball's mass.

   For now, these values will all be -9.8 m/s^2. That's because we don't have air resistance yet, so the only force right now is gravity, which causes a constant acceleration of g!



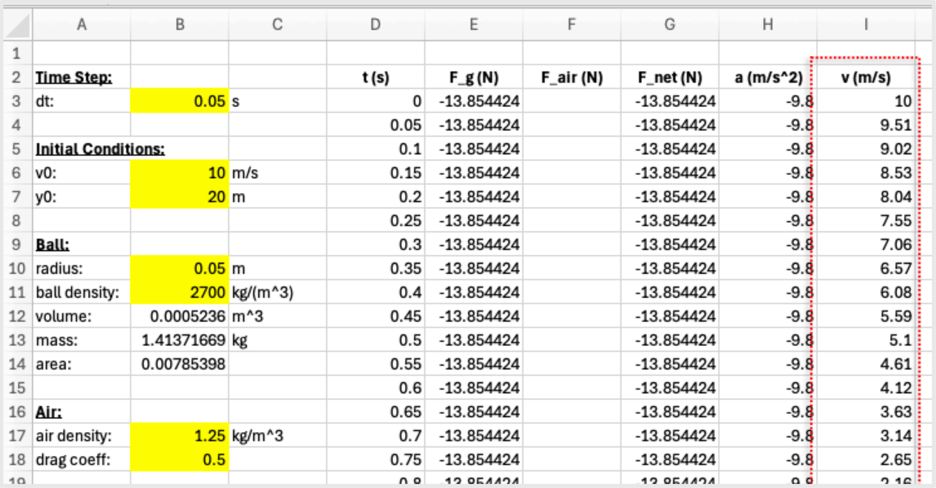
	A	B	C	D	E	F	G	H
1								
2	**<u>Time Step:</u>**			**t (s)**	**F_g (N)**	**F_air (N)**	**F_net (N)**	**a (m/s^2)**
3	dt:	0.05	s	0	-13.854424		-13.854424	-9.8
4				0.05	-13.854424		-13.854424	-9.8
5	**<u>Initial Conditions:</u>**			0.1	-13.854424		-13.854424	-9.8
6	v0:	10	m/s	0.15	-13.854424		-13.854424	-9.8
7	y0:	20	m	0.2	-13.854424		-13.854424	-9.8
8				0.25	-13.854424		-13.854424	-9.8
9	**<u>Ball:</u>**			0.3	-13.854424		-13.854424	-9.8
10	radius:	0.05	m	0.35	-13.854424		-13.854424	-9.8
11	ball density:	2700	kg/(m^3)	0.4	-13.854424		-13.854424	-9.8
12	volume:	0.0005236	m^3	0.45	-13.854424		-13.854424	-9.8
13	mass:	1.41371669	kg	0.5	-13.854424		-13.854424	-9.8
14	area:	0.00785398		0.55	-13.854424		-13.854424	-9.8
15				0.6	-13.854424		-13.854424	-9.8
16	**<u>Air:</u>**			0.65	-13.854424		-13.854424	-9.8
17	air density:	1.25	kg/m^3	0.7	-13.854424		-13.854424	-9.8
18	drag coeff:	0.5		0.75	-13.854424		-13.854424	-9.8
19				0.8	-13.854424		-13.854424	-9.8



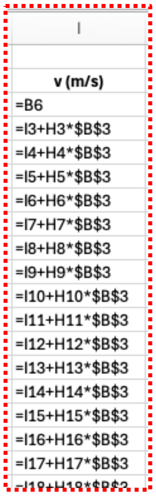
H
a (m/s^2)
=G3/$B$13
=G4/$B$13
=G5/$B$13
=G6/$B$13
=G7/$B$13
=G8/$B$13
=G9/$B$13
=G10/$B$13
=G11/$B$13
=G12/$B$13
=G13/$B$13
=G14/$B$13
=G15/$B$13
=G16/$B$13
=G17/$B$13
=G18/$B$13
=G19/$B$13

9. Label two final columns, one for velocity v and one for position y. The first row in each are those values at zero seconds: the defined <u>initial velocity v_0</u> and <u>initial position y_0</u>. Use formulas to set the first cells in the velocity and position columns to refer directly to those two inputs.

10. The final piece is calculating how the velocity changes from one row to the next. This is where the Euler method comes in: use the kinematic equation for velocity due to constant acceleration ($v_f = v_o + at$) to create and apply a formula for the <u>velocity v</u> column. In each row, you'll treat the initial velocity as the velocity of the previous row, the constant acceleration is the acceleration of the previous row, and the change in time is always Δt. Mathematically, this is $v_n = v_{n-1} + a_{n-1}\Delta t$ where n represents the row.

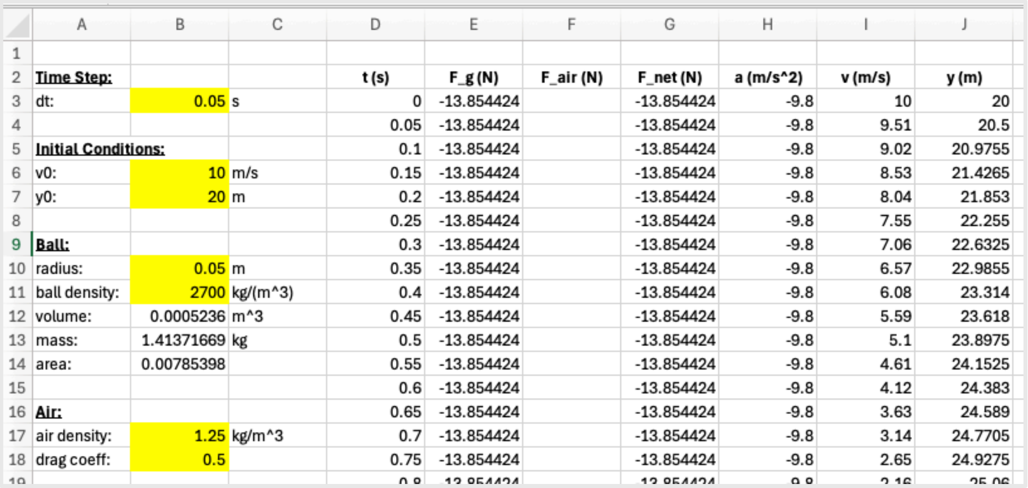


	A	B	C	D	E	F	G	H	I
1									
2	**Time Step:**			t (s)	F_g (N)	F_air (N)	F_net (N)	a (m/s^2)	v (m/s)
3	dt:	0.05	s	0	-13.854424		-13.854424	-9.8	10
4				0.05	-13.854424		-13.854424	-9.8	9.51
5	**Initial Conditions:**			0.1	-13.854424		-13.854424	-9.8	9.02
6	v0:	10	m/s	0.15	-13.854424		-13.854424	-9.8	8.53
7	y0:	20	m	0.2	-13.854424		-13.854424	-9.8	8.04
8				0.25	-13.854424		-13.854424	-9.8	7.55
9	**Ball:**			0.3	-13.854424		-13.854424	-9.8	7.06
10	radius:	0.05	m	0.35	-13.854424		-13.854424	-9.8	6.57
11	ball density:	2700	kg/(m^3)	0.4	-13.854424		-13.854424	-9.8	6.08
12	volume:	0.0005236	m^3	0.45	-13.854424		-13.854424	-9.8	5.59
13	mass:	1.41371669	kg	0.5	-13.854424		-13.854424	-9.8	5.1
14	area:	0.00785398		0.55	-13.854424		-13.854424	-9.8	4.61
15				0.6	-13.854424		-13.854424	-9.8	4.12
16	**Air:**			0.65	-13.854424		-13.854424	-9.8	3.63
17	air density:	1.25	kg/m^3	0.7	-13.854424		-13.854424	-9.8	3.14
18	drag coeff:	0.5		0.75	-13.854424		-13.854424	-9.8	2.65
19				0.8	-13.854424		-13.854424	-9.8	2.16



I
v (m/s)
=B6
=I3+H3*$B$3
=I4+H4*$B$3
=I5+H5*$B$3
=I6+H6*$B$3
=I7+H7*$B$3
=I8+H8*$B$3
=I9+H9*$B$3
=I10+H10*$B$3
=I11+H11*$B$3
=I12+H12*$B$3
=I13+H13*$B$3
=I14+H14*$B$3
=I15+H15*$B$3
=I16+H16*$B$3
=I17+H17*$B$3
=I18+H18*$B$3

11. Use the same Euler method outlined above to develop a formula for the <u>position y</u> column. Base your formula on the kinematic equation for position due to a constant velocity ($y_f = y_0 + v\Delta t$).



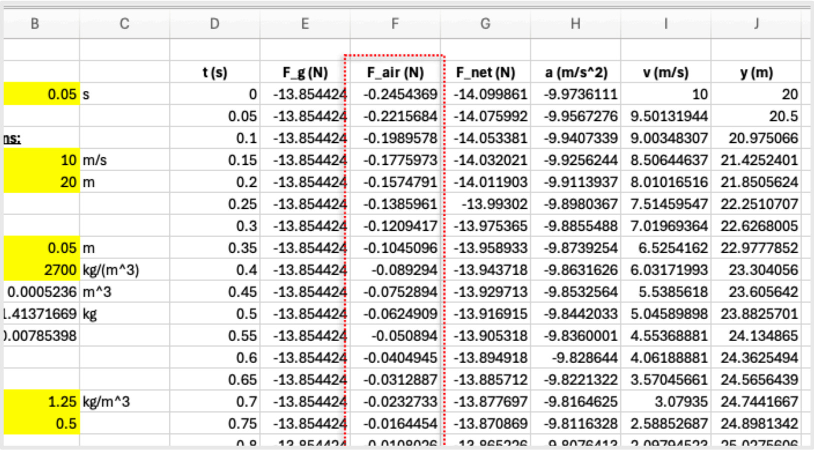
	A	B	C	D	E	F	G	H	I	J
1										
2	**Time Step:**			t (s)	F_g (N)	F_air (N)	F_net (N)	a (m/s^2)	v (m/s)	y (m)
3	dt:	0.05	s	0	-13.854424		-13.854424	-9.8	10	20
4				0.05	-13.854424		-13.854424	-9.8	9.51	20.5
5	**Initial Conditions:**			0.1	-13.854424		-13.854424	-9.8	9.02	20.9755
6	v0:	10	m/s	0.15	-13.854424		-13.854424	-9.8	8.53	21.4265
7	y0:	20	m	0.2	-13.854424		-13.854424	-9.8	8.04	21.853
8				0.25	-13.854424		-13.854424	-9.8	7.55	22.255
9	**Ball:**			0.3	-13.854424		-13.854424	-9.8	7.06	22.6325
10	radius:	0.05	m	0.35	-13.854424		-13.854424	-9.8	6.57	22.9855
11	ball density:	2700	kg/(m^3)	0.4	-13.854424		-13.854424	-9.8	6.08	23.314
12	volume:	0.0005236	m^3	0.45	-13.854424		-13.854424	-9.8	5.59	23.618
13	mass:	1.41371669	kg	0.5	-13.854424		-13.854424	-9.8	5.1	23.8975
14	area:	0.00785398		0.55	-13.854424		-13.854424	-9.8	4.61	24.1525
15				0.6	-13.854424		-13.854424	-9.8	4.12	24.383
16	**Air:**			0.65	-13.854424		-13.854424	-9.8	3.63	24.589
17	air density:	1.25	kg/m^3	0.7	-13.854424		-13.854424	-9.8	3.14	24.7705
18	drag coeff:	0.5		0.75	-13.854424		-13.854424	-9.8	2.65	24.9275
19				0.8	-13.854424		-13.854424	-9.8	2.16	25.06

At this point, your simulation is set up to solve a problem *without* air resistance! Now that we've defined a velocity column, we can revisit the air resistance force column so that your simulation takes that into account too!

12. In the empty <u>air resistance F_{air}</u> column, type a formula that uses constants (C_d, ρ_{air}, and A) and the ball velocity in each row to determine the resistive force in that row according to $F_{air} = \frac{1}{2}C_d\rho_{air}v^2A$.

    One important thing: air resistance always acts *against* the ball's motion, so you want to make sure that when the velocity of the ball is positive (it's rising) this force is in the negative direction (it's pushing the ball down) and vice versa. To make the sign of this force in a given row opposite the sign on the velocity, take advantage of an excel tool called SIGN( ) in your formula like this: $F_{air} = -\text{sign}(v)\frac{1}{2}C_d\rho_{air}v^2A$. This way, the sign of F_{air} will always be opposite v.

This will cause the net force, acceleration, velocity, and position columns to change. That makes sense! Adding air resistance affects the ball's acceleration, which affects every aspect of its motion.



B	C	D	E	F	G	H	I	J
		t (s)	F_g (N)	F_air (N)	F_net (N)	a (m/s^2)	v (m/s)	y (m)
0.05	s	0	-13.854424	-0.2454369	-14.099861	-9.9736111	10	20
		0.05	-13.854424	-0.2215684	-14.075992	-9.9567276	9.50131944	20.5
ns:		0.1	-13.854424	-0.1989578	-14.053381	-9.9407339	9.00348307	20.975066
10	m/s	0.15	-13.854424	-0.1775973	-14.032021	-9.9256244	8.50644637	21.4252401
20	m	0.2	-13.854424	-0.1574791	-14.011903	-9.9113937	8.01016516	21.8505624
		0.25	-13.854424	-0.1385961	-13.99302	-9.8980367	7.51459547	22.2510707
		0.3	-13.854424	-0.1209417	-13.975365	-9.8855488	7.01969364	22.6268005
0.05	m	0.35	-13.854424	-0.1045096	-13.958933	-9.8739254	6.5254162	22.9777852
2700	kg/(m^3)	0.4	-13.854424	-0.089294	-13.943718	-9.8631626	6.03171993	23.304056
0.0005236	m^3	0.45	-13.854424	-0.0752894	-13.929713	-9.8532564	5.5385618	23.605642
.41371669	kg	0.5	-13.854424	-0.0624909	-13.916915	-9.8442033	5.04589898	23.8825701
.00785398		0.55	-13.854424	-0.050894	-13.905318	-9.8360001	4.55368881	24.134865
		0.6	-13.854424	-0.0404945	-13.894918	-9.828644	4.06188881	24.3625494
		0.65	-13.854424	-0.0312887	-13.885712	-9.8221322	3.57045661	24.5656439
1.25	kg/m^3	0.7	-13.854424	-0.0232733	-13.877697	-9.8164625	3.07935	24.7441667
0.5		0.75	-13.854424	-0.0164454	-13.870869	-9.8116328	2.58852687	24.8981342

F
F_air (N)
=-SIGN(I3)*0.5*$B$18*$B$17*I3^2*$B$14
=-SIGN(I4)*0.5*$B$18*$B$17*I4^2*$B$14
=-SIGN(I5)*0.5*$B$18*$B$17*I5^2*$B$14
=-SIGN(I6)*0.5*$B$18*$B$17*I6^2*$B$14
=-SIGN(I7)*0.5*$B$18*$B$17*I7^2*$B$14
=-SIGN(I8)*0.5*$B$18*$B$17*I8^2*$B$14
=-SIGN(I9)*0.5*$B$18*$B$17*I9^2*$B$14
=-SIGN(I10)*0.5*$B$18*$B$17*I10^2*$B$14
=-SIGN(I11)*0.5*$B$18*$B$17*I11^2*$B$14
=-SIGN(I12)*0.5*$B$18*$B$17*I12^2*$B$14
=-SIGN(I13)*0.5*$B$18*$B$17*I13^2*$B$14
=-SIGN(I14)*0.5*$B$18*$B$17*I14^2*$B$14
=-SIGN(I15)*0.5*$B$18*$B$17*I15^2*$B$14
=-SIGN(I16)*0.5*$B$18*$B$17*I16^2*$B$14
=-SIGN(I17)*0.5*$B$18*$B$17*I17^2*$B$14
=-SIGN(I18)*0.5*$B$18*$B$17*I18^2*$B$14

Now, your simulation works for a system with air resistance, which involves a force that depends on velocity! This is a problem that would be very challenging to solve by hand.

You need to validate your simulation by using it to solve a problem you already know the answer to and making sure it matches that answer. You don't know how to solve a kinematics problem with air resistance, so that won't work, but you *do* know how to solve one *without* air resistance!

13. Verify your simulation by solving the following projectile motion problem in two ways: by hand using the appropriate kinematic equation ($y_f = y_0 + v_0t - \frac{1}{2}gt^2$), and by using your spreadsheet to find the answer when $\rho_{air} = 0$. This implies the air isn't present – so if your spreadsheet works it should produce the same result as your hand calculation, which also doesn't include the effects of air!

    A ball made of aluminum (density 2700 kg/m^3) with a radius of 0.05 m is thrown directly upward with a velocity of 12 m/s from a point 8 m above the ground. Assume air resistance is negligible ($\rho_{air} = 0$). How long does it take the ball to hit the ground?

    Carefully consider how you would use your spreadsheet to identify when the ball hits the ground and how to find the uncertainty of that landing time, then keep that in mind when reporting all the result from this activity and the next. If your two answers do not agree, make sure to fix your spreadsheet before moving on.

Activity 2: Exploring Air Resistance

Now that you've built a simulator and validated its output, you're able to study the effects of air resistance based on key parameters!

1. Input five different initial velocities and find two landing times for each, one without air resistance ($\rho_{air} = 0$) and one with air resistance ($\rho_{air} = 1.25\ \mathrm{kg/m^3}$).

2. Input five different ball densities (use densities of real materials) and find the "terminal velocity" for each with air resistance ($\rho_{air} = 1.25\ \mathrm{kg/m^3}$). This is the maximum *constant* velocity of the ball, meaning after reaching it the ball's velocity will stop changing. Keep in mind you may have to extend the number of rows in your spreadsheet to get to it!

3. Design and perform a novel experiment which studies the effect of some other parameter (air density, ball size, drag coefficient) on some kinematic result (landing time, maximum height, terminal velocity, etc.) using your simulation with air resistance ($\rho_{air} = 1.25\ \mathrm{kg/m^3}$). The number and range of inputs is up to you, but the results *must* demonstrate a clear trend.

Analysis

Please report the following results from your data and analysis:

Activity 1:

- Two solutions to the verification problem provided: one found by hand and one using your simulation when $\rho_{air} = 0$. Compare these two results by finding the percent difference.

Activity 2:

- Plot or table showing the two landing times for each of the five initial velocities tested, one without air resistance and one with air resistance.

- Plot or table showing the terminal velocity for each of the five initial velocities tested.

- Plot or table with the kinematic result for each of your inputs.

Discussion

As *parts* of your discussion, please make sure to include:

Activity 1:

- How did you identify the landing time from the data in your simulation?

- Is your simulation validated by your two solutions to the verification problem (one analytical, one simulated)? Explain any difference between the results.

Activity 2:

- Based on your experiment, what is the relationship between initial velocity and landing time? What effect does air resistance have on this relationship? Explain both trends by applying physics concepts to the motion of the ball.

- Explain why the phenomenon of "terminal velocity" occurs using what you know about the physics of air resistance. How did you identify the terminal velocity from the data in your simulation?

- Based on your experiment, what is the relationship between ball density and terminal velocity? Explain this trend by applying physics concepts to the motion of the ball.

- How is air resistance related to the parameter of your choosing? Explain this relationship using what you know about the physics of air resistance.

Please discuss potential sources of error in your simulation. Consider the limitations of a spreadsheet which uses time steps like is one. With how much precision can the landing time, terminal velocity, or any other parameter be determined based on your simulation? How could that precision be improved, and what effect would that improvement have on the simulation's size?

FAQ’s & Recommendations

How should I prepare for lab time?

You only have so much time in lab each week, so proper preparation makes a huge difference in what you’re able to accomplish! Read the handout ahead of time so that you can ask clarifying questions immediately and get started as soon as you arrive!

What goes in my lab notes?

The purpose of lab notes is to enable your or a colleague to reconstruct what was done and why after you’ve left the lab and are performing analysis or writing a submission.

- You can use any form you like to record experiment information: notebook, spreadsheet, etc.
- They don’t have to be neat, in complete sentences, etc., but they do have to be useful!
- Make sure to take detailed notes about your setup, how to use the equipment, what results you found, measurements related to the environment you may need, etc. You may not be able to get back into the lab later in the week if you miss something, so record as much detail as possible!
- When storing multiple data files while in lab, make sure to name the files clearly so they’re easy to find later.

When should I work on the experiment and analysis?

We strongly recommend doing the lab as early in the week as possible, rather than waiting until it is almost due. This is just so that, if you run into trouble and need help, you’ll have plenty of time to talk to your TA and get issues resolved before the deadline.

How do I turn in my results?

After leaving lab, performing your analysis, and completing your submission, you’re ready to turn in your work!

- Every lab session requires submission of either an assignment, summary, draft report, or report.
- Collaborate with your partners on data collection, analysis, and writing.
- Turn in a single group submission and make sure the names of all group members are included.
- Upload your submission to Canvas/Brightspace as a .pdf by the deadline in the course calendar.
- Other than the spreadsheet assignment, you will not upload any spreadsheets. Just copy and paste figures and other elements from your spreadsheet into your formal submission as needed.

Where can I get help?

Your lab TA can answer questions during the lab, by email, or by setting up a time to meet. You can also ask advice from lab partners and/or other students.

General DO’s and DON’T’s

- *DON’T* break the equipment – always be careful when using lab supplies!
- *DO* consult with your lab TA before leaving a lab session about your experimental method, the validity of your results, and any confusion you have about the analysis process.
- *DON’T* forget to record all the parameters and measurements for your experiment, including saving files.
- *DO* be creative in your experimental design and enjoy!