I. Before you come to lab

- Read through this handout and the supplemental handout.
- In Logger Pro, do the Tutorial named "12 Video Analysis" (in the Tutorials folder under Experiments).
- Complete the pre-lab question as part of HW 2, and turn it in with the rest of your HW by 9:30 am Tuesday.
- Watch the following YouTube video on the Gauss gun (there's also a link from the course website):

http://www.youtube.com/watch?v=zZmCJ5eZlmo

II. Learning objectives

1. Investigate momentum conservation
2. Learn how to determine the combined effects of many different sources of uncertainty in a single calculation

III. Materials

Magnet, 3 steel ball bearings, and some track

- What they are: a magnet, 3 steel ball bearings, and some pieces of track.
- What you can do with them: make a Gauss gun! Check it out! http://youtu.be/ZR_ctC287Gk
- A Gauss gun is an unusual physical system that we can't yet fully describe, because don't yet have a quantitative model for magnetic forces. However, if we take the physical system to be the entire Gauss gun (magnet plus all 3 balls), then we can still describe the *external interactions* of the system.

Carbon paper and typing paper

- What they are: sandwiched sheets of carbon paper and regular white typing paper, taped to the floor.
- What you can do with them: If you drop a ball onto the floor where they're taped, it will leave a mark on the white paper exactly where the ball hit.

2-meter stick

- What it is: like a meter stick, except twice as long.
- What you can do with it: measure lengths up to 2 m.

Digital video camera on tripod

- What it is: pretty sweet.
- What you can do with it: record video of something at 30 frames per second. Then, you can measure the motion of objects in the video using Logger Pro's video analysis capabilities.

Lubricant

- What it is: slippery.
- What you can do with it: reduce sliding friction by applying a small amount of it to the track.

Level

- What it is: a carpenter's level.
- What you can do with it: make sure that a surface is really horizontal. If it's not, you can shim one side or the other with pieces of paper.

Balance

- What it is: a digital balance.
- What you can do with it: measure the mass of small objects.
    - The balance reads to the nearest hundredth of a gram. That means that when you measure a mass using the balance, the reading error on the mass is 0.01 g.
    - If you use the balance to measure the mass of a magnet, you might get an inaccurate reading because of an attractive force between the magnet and the metal inside the balance. To get an accurate measurement, put an inverted plastic cup on top of the balance and re-zero it before putting the magnet on top. That way the magnet will be several inches away from anything metal while it is being weighed.

Computer with Logger Pro installed on it

- What it is: what it sounds like.
- What can you do with it: data collection and analysis.

IV. Warm-up

Before starting the lab, answer the following questions on a piece of paper. You do not have to turn them in, since you will need them later today. You do need to check with your TF before moving on.

1. From the video of the Gauss gun, you can see that after the collision the ball-magnet-ball configuration, which we call 1-M-2, recoils to the left. If 1-M-2 travels a distance Δx in a time $\Delta t = t_r - t_c$ from the moment after the collision until it comes to a stop, and assuming motion with constant acceleration, what was the x-velocity of 1-M-2 at time t_c, in terms of the two quantities Δx and Δt?

2. Refer to figure 2 from the supplemental material. Ball 3 starts out with a horizontal velocity from a height h above the ground, and hits the ground a distance L away from the table. Using the equations for projectile motion, find an expression for the x-component of the velocity of ball 3 as it leaves the table, in terms of h, L, and any relevant physical constants.

V. Procedure

Tell us who you are (picture and names please!)
A:

Taking the data
The goal of today's lab is to observe the Gauss gun system and see whether its momentum is conserved during the brief but violent magnetic interaction. You can read about the definition and setup of the system in the supplemental handout.

Take a few minutes to play around with the setup and plan how you will arrange the various pieces (video camera, balls, magnet, track, carbon paper, box to catch ball 3 after it bounces off the floor). Make sure the entire track is visible in the video camera display. **Do a few test runs before you start taking any data**. You'll only have time to analyze a single run, so you'll want to make sure everything is set up correctly. A very small amount of lubricant (just a drop or two) on the track will help reduce friction.

When you are ready to record, make sure that everything is set (fresh sheet of white paper under the carbon paper, box in place, etc.) before you click Start Capture. Then roll ball 1 slowly towards the magnet, and watch the collision closely.

When the video capture finishes, **make sure all of the following things are true**:

- Ball 1 approaches the magnet smoothly (no bouncing or wobbling as it rolls)
- Collision does not impart any significant y-velocity (vertical motion) to any part of the system (no bouncing)
- Recoiling 1-M-2 system comes to rest *on the track*, and the *entire recoil* (until everything comes to rest) is recorded in the video capture
- You can clearly identify which carbon paper mark was the one left by the ball during your actual run

If any of the above is not true, delete the video capture and repeat the experiment. It doesn't take long to do, but it does take a lot of analysis, and you don't want to waste your time analyzing data from an incomplete run.

Remember, you *don't* need to be able to see ball 3 shoot off in the video capture. We expect that you won't, actually, because it goes too fast. That's why we have the carbon paper setup.

Analyzing the data
Is momentum conserved? You will need to measure the momentum of the system before the collision and after the collision. Measure the relevant quantities, and fill in the table below. The rest of the write up will guide you in doing this.

Momentum before collision			Momentum after collision		
	Value	Uncertainty		Value	Uncertainty
Mass of ball 1			Mass of 1-M-2		
Mass of M-2-3			Mass of ball 3		
Vel. of ball 1			Vel. of 1-M-2		
Vel. of M-2-3			Vel. of ball 3		
Momentum			Momentum		

Before the collision

Measure the relevant masses. See the Materials section for hints on how to use the balance when determining the mass of the magnet.

Use video analysis to find the position of ball 1 before the collision as a function of time. Remember, you'll have to set the scale for the video. Use the length of the track itself to set the scale. Refer to the Tutorial named "12 Video Analysis" if you need a reminder on how to do this.
How long is the track? (Measure it with a ruler.)
A:

You might need to tilt your axes to make sure all the motion is in the *x*-direction. This can happen if your video camera is not aligned perfectly, so that the track is exactly horizontal. See the Logger Pro Help file in the green binder or online if you need help with this. Once you have done this, we are no longer interested in the *y*-motion (there shouldn't even *be* any *y*-motion), so change the settings on the graph so that it *only shows you x vs t*. (We also don't want it to show v_x or v_y. You'll make your own determination of velocity.)

Make sure you include error bars in your *x* vs *t* graph. To get the error bars, you must estimate the uncertainty of the x-values obtained from the video analysis. You can use the same technique you used in the pre-lab question.
Uncertainty in x:

Use a linear fit to an appropriate section of the *x* vs *t* graph to determine the velocity of ball 1 before the collision. **Paste your graph of *x* vs *t*, with the fit, below.**
Insert graph here:

Velocity of ball 1 before collision:

Using the method described in the supplemental materials handout, calculate the uncertainty in the slope that results from error bars of this size. This is the uncertainty in the velocity of ball 1.

Uncertainty in velocity of ball 1:

After the collision

Measure the relevant masses. See the Materials section for hints on how to use the balance when determining the mass of the magnet.

In the same video capture, you can track the motion of the recoiling 1-M-2 trio after the collision. However, unlike the incoming ball 1, we do not expect that 1-M-2 moves at constant velocity after the collision. It has some velocity right after the collision, but later it is observed to come to rest. So there must be a net force acting on it.

Using the video analysis tools, add a new trail and plot the position of the 1-M-2 trio from the first frame after the collision (which we'll call t_c) until it comes to rest (at time t_r).

The best model of the forces acting on the recoiling trio predicts that it will undergo *constant acceleration* from time t_c to t_r. **If the motion really is constant acceleration, what kind of curve will describe the *x* vs *t* graph?**
A:

Try fitting such a curve to the relevant time interval in your video analysis data set. Write the equation so that one of the fit parameters is t_r. This is better than guessing a value of t_r from the video, since t_r will likely occur between successive frames. (t_c, of course, falls exactly on a video frame, by definition.) If you're not sure how to do this, ask your TF. **Does the curve look like a good fit for your data?**
A:

Paste the graph, with fit, here:

Assuming the curve looks like a good fit, we won't even use the values of the parameters it gives us, except for t_r. Instead, we can get the quantity we are interested in (the instantaneous *x*-velocity at time t_c) from the equations for motion with constant acceleration.

The two quantities you can get directly from the video analysis are Δx, the change in *x*-position, and Δt, which is just t_r minus t_c. What are the measured values of these quantities? (NB! Δx should be *negative*, because 1-M-2 moves to the *left* during the recoil.)

Δx =
uncertainty of Δx =
Where did this number come from?

Δt =
uncertainty of Δt =
Where did this number come from?

Plug in your numbers to your solution to the warm-up and calculate a numerical value for the *x*-velocity of 1-M-2 just after collision, which we'll call v_{1fx}:

v_{1fx} =

Use the "worst-case scenario" error propagation method to calculate the uncertainty in v_{1fx}

from the uncertainties in Δx and Δt:

Uncertainty of v_{1fx} =

Using the carbon mark left by ball 3 when it hit the floor, measure the quantities h and L from the figure in the supplemental material. Include an estimate of your reading errors.

h =
Uncertainty of h =

L =
Uncertainty of L =

Plug in your numbers above, and the accepted value of g, to the expression you found in the warm-up, and get the x-velocity of ball 3 just after the collision:

Velocity of ball 3 =

Again, use error propagation to calculate the uncertainty in the velocity of ball 3 based on your estimated uncertainties in h and L. You may neglect any uncertainty in g.

Uncertainty of velocity of ball 3 =

Calculate the x-component of the total initial momentum, with uncertainty, as well as the x-component of the total final momentum, with uncertainty. Write these here and in the table.

p_{ix} =
Uncertainty =

p_{fx} =
uncertainty =

VI. Conclusion

What can you conclude from your data about momentum conservation in the Gauss gun system?
A:

What is the most important thing you learned in lab today?
A:

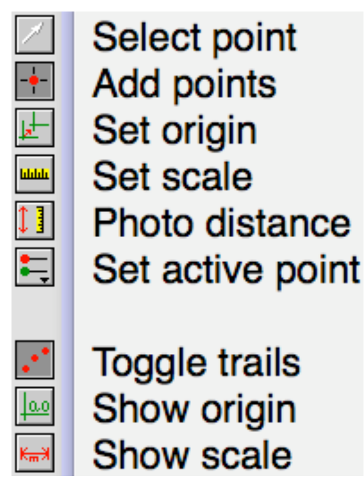
VII. Pre-lab assignment from the Problem Set

A. Let's call t_i the time that Dave releases the basketball, and t_f the time when it reaches the peak of its trajectory. Using your analysis of the ball's position, measure both the time interval and the height change that the ball underwent during that time. *Hint*: if you find it difficult to estimate values off the graph, you can insert a data table with the raw numbers by going to Insert → Table. Alternatively, use the Examine feature from the toolbar, which will show you the numerical coordinates of the nearest data point as you mouse around the graph.

When you perform a measurement using video analysis, it's just like any other measurement: you need to know the uncertainty as well as the value. The uncertainty in the value of Δt is pretty easy to estimate as a reading error: the timing device is just the internal clock of the video. Assuming it's calibrated correctly, the uncertainty in any time measurement made using the video is just the interval between frames. This video was shot at 30 frames per second, so the uncertainty in Δt is about 1/30 of a second, or 33 ms. (It would also not be unreasonable to claim that the reading error was half this much, if you think you can confidently make a statement like, "the ball reached its peak closer to this frame than the next frame.")

However, the uncertainty in Δy is subtler. There is obviously reading error in using the video analysis procedure to measure the position of the ball. Since the measurement is made by using your mouse to click on the ball's position, one reasonable estimate is that the reading error is on the order of one pixel. However, there is also error introduced in the calibration step: we are approximating a length that we call 2 meters, and use that length to calibrate all other distance measurements. We can estimate this calibration error the old-fashioned way: by repeating the "measurement." You can't set the scale for the video multiple times, but you can use the "Photo Distance" tool to simulate repeating the measurement.

B. So let's do it. Here's the procedure: first, uncheck the box for "Show scale" using the bottom button in the video analysis toolbar. (A screenshot of the toolbar buttons and what they do is included at right.) The green line showing your 2-meter scale will disappear.



Next, select the "Photo distance" tool (ruler with a double-headed red arrow). When you click the button, you can then click and drag between two points in the video and Logger Pro will calculate the distance for you, using the scale you've already set. This process is exactly like setting the scale, so we'll use it to "repeat" the measurement.

Use the photo distance tool to "measure" the length of the two-meter stick several times, and report your values. Of course, they will all be approximately 2 meters, but what we are interested in is the *range* of values for the length of the stick. Are they between 1.95 and 2.05 m? 1.99 and 2.01 m? 1.999 and 2.001 m? The spread tells you the reading error when using the video analysis to measure a distance of 2 m. And in fact, since we assume that the reading error in pixels is always about 1 pixel, the value can be used as the absolute reading error in any measurement made from the same video, including Δy. What is this value?

C. According to constant-acceleration kinematics (more on this in the next homework), Δt and Δy should be related by the equation

$$\Delta y = \frac{1}{2}g(\Delta t)^2$$

where g is the acceleration due to gravity. Using your measured values of Δt and Δy, as well as the uncertainties you estimated in part B), calculate a value of g as determined by the basketball measurement, *with uncertainty*. (You will have to do some error propagation—recall the "worst-case" method from Lab 1.) How does it compare to the accepted value of 9.81 m/s^2?