# Lab 2: Galileo's Freefall Experiment

General Physics I, Marlboro College, Fall '05

*"You give me frequent occasion to admire the wealth and profusion of nature when, from such common and even trivial phenomena, you derive facts which are not only striking and new but which are often far removed from what we would have imagined."*

- Sagredo (from Galileo's *Dialogue*)

In this lab you will reproduce an elegant experiment first performed by Galileo. The basic idea is to correlate the height of a dropped ball and the length of a pendulum such that the freefall time for the ball and the time for the released pendulum to reach the vertical are equal. In other words, we use a pendulum as a clock to measure how much time it takes a ball to fall from a given height. Combining the results of this correlation with the pendulum period-length relation discovered in Lab 1 permits a quantitative statement of the law of free-fall, i.e., a statment of the amount of time it takes for an object to fall from a given initial height.

## I. INTRODUCTION

It is obvious from everyday observations that heavy objects fall down when released. But why and how do they fall? The ancient Greeks (Aristotle in particular) believed in a geo-centric (earth-centered) model of the universe in which different elements had a "proper" place which they sought. Earth belonged near the center, so heavy earthy objects, when able to do so, would seek their proper place by moving downward toward the center of the universe. Fire and other hot objects, by contrast, belonged in the heavens – as evidenced by the sun and the stars. This was supposed to explain why hot objects like steam and smoke naturally rise.

Of course, this geo-centric model and the associated dynamics was blasted in the 1500's by Copernicus and his followers – including Galileo, one of whose major methodological innovations was to actually observe carefully how things move (rather than leap too quickly to speculations about the causes of their motions). The most important type of motion that Galileo studied was the free-fall motion of heavy objects. There was a long-standing tradition of belief, based on the Aristotelian cosmology, that falling objects fall at a constant speed that is proportional to their mass. Galileo showed not only that objects of different masses fall at the same rate, but also that free-fall motion does not occur with constant speed but, rather, involves acceleration.

In this week's lab, we reproduce the experiment by which Galileo first determined the law of free-fall, that is, the equation for the time needed to fall to the ground from an initial height $H$.[1] Galileo used a pendulum to measure the times in the following clever way: drop a ball from the height $H$ at the same moment that you release a pendulum of length $L$. When the pendulum reaches the vertical, it hits a board and makes an audible sound. For a given $L$, there will be some particular value of $H$ which makes the pendulum strike the vertical at the same moment the ball hits the floor. By systematically varying $L$ and finding, for each value, the value of $H$ such that the times match, one can discover empirically a simple formula relating $H$ to $L$. Doing that is the main empirical component of this week's lab.

But there is also an important analytical component to the lab: after determining the relation between $H$ and $L$, one can determine a relation between $H$ and the free-fall time $t$, by bringing in the results of Lab 1. Given the week 1 relation between the length $L$ and period $T$ of a pendulum, it is simple enough to write down a relation between $L$ and *one quarter of the period*: $t = T/4$. But a quarter period is precisely the amount of time it takes the ball to drop in this week's experiment – so one can get a formula relating $H$ and $t$ by algebraically eliminating the variable $L$ from the two equations ($L$ vs $t$ from week 1, and $H$ vs $L$ from week 2). Getting this $H$ vs $t$ relation is the real goal of this week's lab.

## II. IN-CLASS ACTIVITIES

Two class periods will be spent on this lab. Here, as usual, is a rough suggested schedule.

### A. Day 1

- It's worth spending a few minutes exploring some of the things mentioned in the introduction. For example, drop a ball and watch it fall to the ground. Is it obvious just by looking whether the ball falls with constant speed, or whether the speed increases as it falls? Can you think of any simple way to test this? What about the mass of the ball? Do heavier things fall faster than light things? How can you test this? Maybe you'll want to run over to the non-Leaning Tower of *Risa* (that's, um, Italian-ish for Rice, as in Rice Library) for a quick Galileo-inspired experiment. (Make absolutely sure you don't drop anything on someone's head!) Also, does the mass-independence of free-fall relate to anything you saw in week 1?

- Now onto the real experiment of the day: first, make sure you understand the description of the experiment given above, and how you will use the "pendulum board" apparatus.

- Choose a ball and a pendulum. Try the simultaneous-release operation. The experiment is designed to make it easy to tell (by listening) whether the ball and pendulum motions end at the same moment. But releasing them at the same moment can be tricky. Play around with it for a while until you are confident that you've got a good system. Also, take advantage of the division of labor: you and your partners might want to select a dedicated releaser, a dedicated $H$ and $L$ measurer, and a dedicated note-taker. But remember too that you want to avoid systematic errors. Swapping jobs and reproducing the same data is a good way to test for consistency and hence reliability.

- When you've got a good system going, start taking careful data. Take as many data points as you can over as wide a range of $H$ and $L$ values as possible. And spend some time thinking about how to get the highest quality data you can get.

### B. Day 2

You may want or need to continue taking data on Thursday. If so, by all means do so. When you are done with the data collection, you should go through the following sort of analysis. This can be done in or out of class, but it will be helpful to at least get started as a group in class.

- Make an Excel spreadsheet with your data, one column for $H$ and another for $L$. Perform a curve-fit to find a simple mathematical formula relating the two quantities. Make sure to keep track of the units of any constants that appear in your formula.

- Dig up your formula from week 1 relating the pendulum's period and length, $T$ and $L$. Based on this equation, construct a new equation relating the quarter-period $t = T/4$ to the length $L$. (This involves algebra, but no new data-taking. Ask Travis or Josh if you're confused about this.)

- Algebraically combine your formula involving $H$ and $L$ (the one from week 2) with the just-constructed formula relating $L$ and $t$. That is, algebraically eliminate the variable $L$ from this system of two equations, leaving you with one equation involving only $H$ and $t$ (and some constants). As always, be sensitive to the issue of *units*: if a constant in your formula has units, know what they are.

- Interpret this $H$-$t$ formula. What is it telling you exactly? (Hint: suppose it turns out that $H$ is *proportional* to $t$. This would mean the distance covered ($H$) divided by the time it took to cover that distance ($t$) was a constant... i.e., it would mean the ball was falling with a fixed, constant speed. What can you say along these lines based on your actual formula?)

## III. HOMEWORK

### A. Lab Report

Your main homework assignment for the weekend is to write up a report on your results from this lab. It should include discussions of

- What you did
- How you did it
- Your data (shown as a table and/or a graph)
- The result of your curve-fit
- Your subsequent analysis leading to the $H$-$t$ relation
- Shat this relation means

You should also mention any special problems you encountered, any noteworthy observations you made, any lingering unresolved questions, and anything else that seems important.

### B. Problems

Answer the following using your lab results.

1. A ball is dropped over the edge from the roof of a tall building. It takes 5.0 seconds to reach the ground. How high was the building? (Answer this based on *your* results from the lab!)

2. Measure the height of the balcony above the south-facing entrance to Rice Library. (Specifically: measure the distance from the top of the handrail straight down to the ground below.) Do this by dropping something (appropriate) over the edge and timing (with a digital watch) its fall. Please work with a partner and make sure not to drop anything on anyone's head! (If you live off campus, don't bother making a special trip to do this. Just measure the height of (say) a second-story window in your house instead, by using the same method.

### C. Reading

There is no major reading assignment this week. (I'm aware that it takes quite a bit of time to write up the labs nicely.) But do spend some time reviewing any topics on which you are less than fully up-to-speed. Also, next week we will start studying position, velocity, and acceleration. These topics will bring us significantly closer to the textbook. So you might want to get a head start by reading the relevant chapter from your text (probably called "velocity and acceleration" or "1-D kinematics" or something like that).

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[1] Stillman Drake, *Galileo: Pioneer Scientist*, University of Toronto Press, 1990.