**Belmont University Summer Science Camp**

**Friday June 17 – Physics with Phones**

**Dr. Scott Hawley**

## Introduction:

Your phone has many sensors with which you can conduct physics experiments:
- Accelerometer
- Gyroscope
- Magnetometer
- Thermometer
- Microphone
- Camera

We can write our own apps to access these sensors, or we can use a free app such as Sensor Kinetics or the Physics Toolbox series.

For this lab, we will use iOS (Apple) devices. For Android devices, the Physics Toolbox series of apps is quite mature, but their iOS versions still lack many key features. Thus we will use Sensor Kinetics.

In addition to the (noisy) 'raw' data from the Accelerometer & Gyroscope, iOS provides a construct called DeviceMotion which automatically consolidates & refines raw data from multiple sensors to produce values for linear acceleration, attitude and orientation. Often the DeviceMotion information provides superior measurements for use in physics experiments. We will use both raw data and DeviceMotion data in this lab.

## Preparation:

1. Download the following free apps from the iOS App Store:
   - Sensor Kinetics
   - Voice Memo (should be already installed)
   - Polar Pattern Plotter
2. Also review the Physics Concepts & Equations (next page)

## Experiments:

1. Dropping the Phone (Gravity)
2. Bouncing a Ball (Gravity, Cons. of Energy)
3. Swinging the Phone (Pendulum Oscillations)
4. Making the Phone Go Up and Down (Simple Harmonic Motion)

*Extra Experiments, Depending on Available Time:*

5. *Spin the Phone (Acoustics: Polar Pattern)*
6. *Guess the Mass of the Block (Linear Acceleration)*
7. *Bonk Two Phones Together (Newton's 3rd Law)*

**Physics Concepts and Equations**

**Kinematics:**

$$x = x_0 + v_0 t + \frac{1}{2} a t^2$$

**Forces:**

*Newton's 2nd Law*: Sum of forces = mass * acceleration, i.e.

$$\sum F = ma$$

*Weight* is the force due to gravity:

$$w = mg$$

*Contact forces*

*Normal force N* acts "normal" (perpendicular) to surface, usually balances gravity, e.g.

$$N = mg \quad \text{or} \quad N = mg\cos\theta$$

where $\theta$ = angle of incline.

*Friction force f* is equal to the normal force times some coefficient $\mu$. For objects standing still, we call it $\mu_s$ = "coefficient of static friction", and for sliding objects, we call it $\mu_k$ = "coefficient of kinetic friction."

$$f = \mu_{(s\ or\ k)} N$$

*Spring force*

is given by "Hooke's Law",

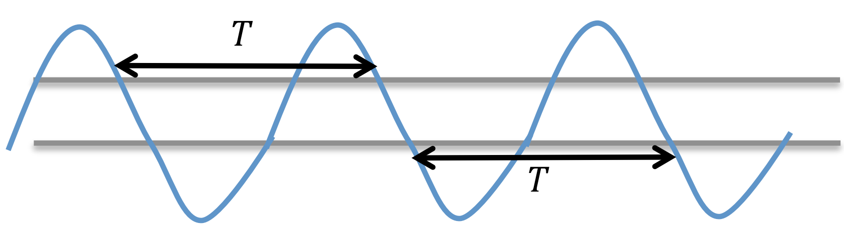
$$F = -kx$$

where $k$ is the "spring constant" in Newtons/meter (N/m) and $x$ is the displacement from equilibrium.

**Oscillations**:

The period $T$ is the time it takes for a signal to repeat itself. (It's inversely related to the frequency in Hertz $f$, i.e. $T = 1/f$.)

*How to measure period:* Count the different in time between places where the graph crosses a horizonal line when "going the same way":




For a mass $m$ oscillating on a spring with spring constant $k$, the period is given by

$$T = 2\pi\sqrt{\frac{m}{k}}$$

whereas for a pendulum of length $\ell$ in a gravitational field of strength $g$, it's

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$

**Experiment 1:** Dropping the Phone: Gravitational Acceleration & the Equivalence Principle

**Materials:**

- Smartphone with Sensor Kinetics installed
- Distance-measuring device, e.g. 2-meter stick
- Padding/foam on which to drop the phone.

We're going to drop your phone! Don't worry, we'll let it land on something soft.

*The Equivalence Principle:*
At the moment you let go of your phone, the accelerometer shows a *drop* in acceleration – in fact it goes to *zero!* How can this be? This is because of the *Equivalence Principle* introduced by Albert Einstein. Einstein said that, when an object is freely falling in a gravitational field, it is *equivalent* to being in an "inertial" (unaccelerated) frame of reference. In other words, when you are freely falling, you are weightless! The phone experiences weightlessness as it falls; the moment you let go, the "weight" registered by the phone changes from registering the force of your hand opposing gravity, to *no force*, in the freely-falling reference frame of the phone. In Einstein's version of gravity known General Relativity, gravity is not a force but rather a "warpage" of the space in which objects move.

*Kinematic Equation:*
Relative to us in the laboratory, the phone will be we accelerating downward at a constant rate which we call $g$. Using the phone, we can measure $g$ if we know the height $h$ that the phone drops from, and the time $t$ it takes to fall. A classic equation of mechanical physics, known as *kinematic* equations, says that displacement $x$ can vary like

$$x = x_0 + v_0 t + \frac{1}{2} a t^2$$

,

were $x_0$ is an initial position, $v_0$ is an initial speed, and $a$ is the acceleration. For us, this equation takes the form

$$h = \frac{1}{2} g t^2$$

,

where we set $x=h$, $x_0=0$, $a=g$, and we let $v_0=0$ because we'll be dropping our phones from rest.

Solving for $g$, we get

$$g = 2h/t^2. \qquad (1.1)$$

Equation (1.1) is what we will use, in concert with the phone, to measure gravitational acceleration of the phone relative to us (in the "lab frame").

*Using the App to do the Experiment*:

Step 1: Place something soft padding material (e.g. foam) below where you intend to drop the phone. Be mindful to cover a sufficient area in case the phone bounces.

Step 2: Measure the height *h* from which you intend to drop the phone; we suggest 1.5 meters. Measure from the “top” of the padding material, not the floor.

Step 3: In the Sensor Kinetics app, find “Accelerometer” near the top, then set the “Rate” as high as it will go, e.g. 100Hz, as shown in Figure 1a.

Step 4: Then press the “arrow-graph” pointing to the right, as shown in Figure 1b below. You should then see a graph setup like in Figure 1c.

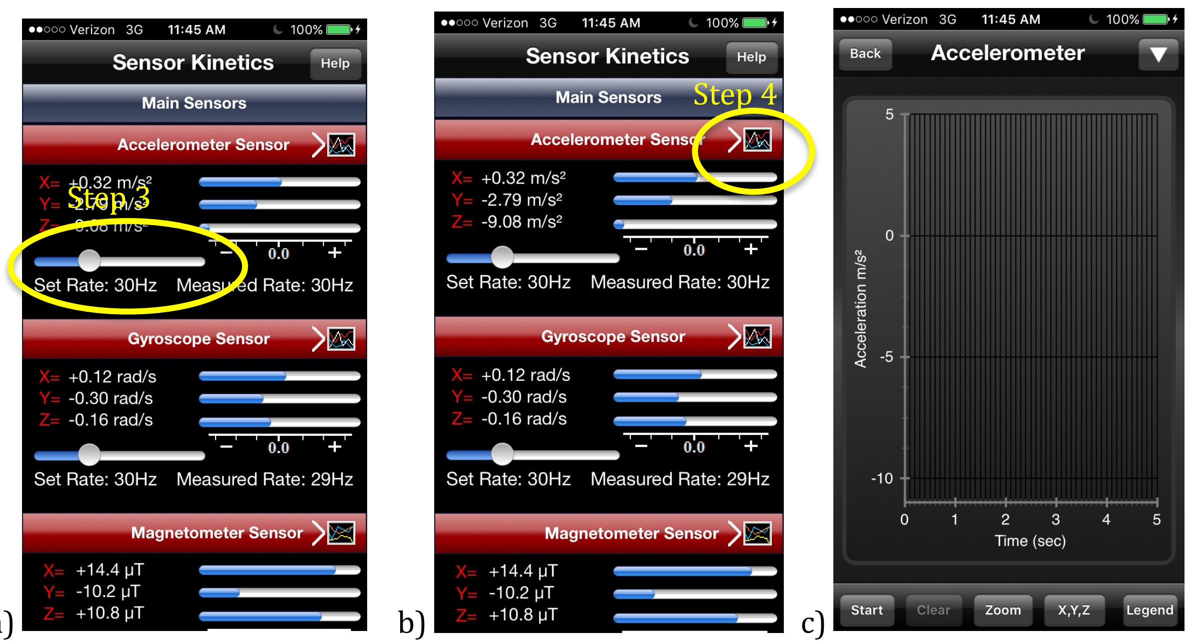
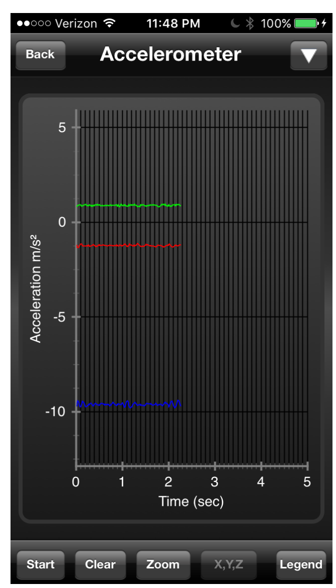



Figure 1: a) Set the sample rate as high as it will go, then b) press graph-arrow for the Accelerometer Doing so will bring up the screen shown in c).

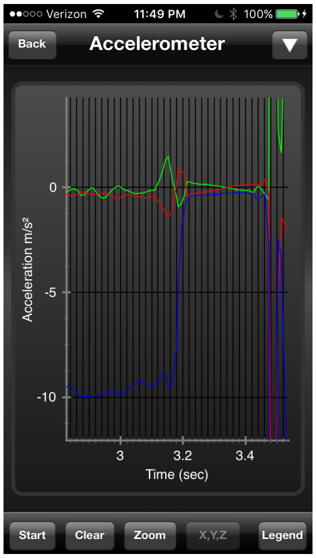
Step 4: Hold the phone “horizontally” (flat) at your desired starting height *h*. Write that height here:

$h =$ ________________ m.




Step 5: Now press the “Start” button in the app. It will begin graphing acceleration. (Notice the blue line which is around -10 m/s$^2$. This is “already” a measure of $g$.)

Step 6: Drop the phone. Then reach down and press the “Stop” button in the app.




Step 7: Notice how there's a period during which the blue line drops to zero? That's the time during which the phone was in free-fall! You've just demonstrated the Equivalence Principle! Now, by reading the graph, find out how long the phone was in free fall. Call this time $t$, and write it in the following blank:

$t$ = ____________________ s.

Step 8: Using Equation (1.1) from earlier in the lab (i.e., "$g = 2h/t^2$"), write in $g$:

$g$ = ____________________ m/s$^2$.

Congratulations! You have measured the acceleration due to gravity in two different reference frames, using only your phone and a meter stick!

**Experiment 2:** Bouncing a Ball (to Measure Gravity)

Source: "Acoustic measurements of bouncing balls and the determination of gravitational acceleration" by Oliver Schwartz, Patrik Vogt and Jochen Kuhn, *The Physics Teacher* **51**, 312 (2013).

**Materials:**
- Smartphone with Voice Memos (or other recording app) installed on it
- Ball (plastic or rubber)
- Meter stick

**Introduction:**
We're going to measure gravity a different way now, this time using a bouncing ball. Each time the ball bounces, it loses a little bit of energy and so both the height it bounces and time between bounces get shorter and shorter as it goes. If we take the initial height $h_0$ and the time $\Delta t$ between the first "hit" and the second, the acceleration due to gravity $g$ is given by

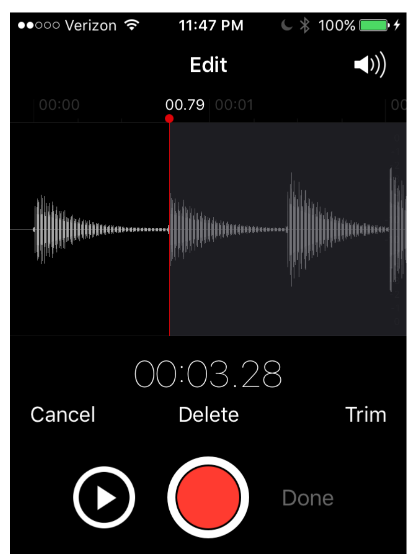
$$g = \frac{8\,\varepsilon\, h_0}{\Delta t^2} \tag{2.1}$$

where $\varepsilon$ is called the *coefficient of elasticity*, which describes how resilient the ball (and tabletop) are when bounces occur. The coefficient $\varepsilon$ is defined in terms of how the energy changes from one bounce to the next, e.g. $E_2 = \varepsilon E_1$. Since the potential energy $mgh$ is proportional to $h$, and $h$ is proportional to time squared, one can show that $\varepsilon$ can be found from the "flight times" of two successive bounces $\Delta t_1$ & $\Delta t_2$:

$$\varepsilon = (\Delta t_2 / \Delta t_1)^2.$$

**Procedure:**
1. Open the Voice Memos app
2. Place the phone on the tabletop.
3. In one hand, hold the meter stick vertically so it extends upwards from the tabletop *and in the same hand*, hold the ball at the desired starting height $h_0$ over the tabletop.

   $h_0$ = _____________ m.
4. Using your free hand, press the Record button on the app.
5. Drop the ball, and let it bounce 4 or 5 times.
6. Grab the ball and press the stop button.
7. Press the "Edit" button in the app, and then the "Trim" tool.
8. By sliding the selector around, measure the time *differences* $\Delta t_1$, $\Delta t_2$, between successive hits on the tabletop.




$\Delta t_1$ = _____________ s

$\Delta t_2$ = _____________ s

9. Find the coefficient of elasticity $\varepsilon$:

$$\varepsilon = (\Delta t_2 / \Delta t_1)^2 = \_\_\_\_\_\_\_\_\_\_\_\_\_\_.$$

10. Find the acceleration due to gravity $g$:

$$g = 8\,\varepsilon\, h_0 / (\Delta t_1)^2 = \_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ m/s}^2.$$

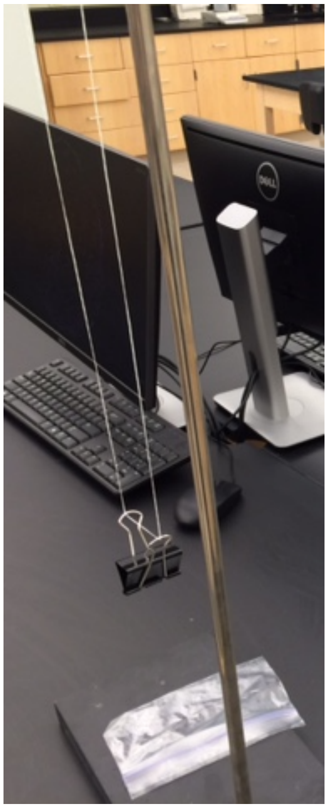
11. You can even use successive time differences $\Delta t_3$, $\Delta t_4$, etc., and get multiple values of $k$ and $g$. Do this and get three more values of $g$ and average them. (Hint: It may be helpful to enter your data into Excel and create a formula that will repeat the calculations for you.)

$\Delta t_3$ = ______________ s , $\Delta t_4$ = ______________ s, $\Delta t_5$ = ______________ s

Average $g$ = ____________________ m/s$^2$

You now have quite a precise measure of $g$! Let's use that in another experiment...

**Experiment 3:** Swinging the Phone (Period of a Pendulum)



**Materials:**

- Smartphone with Sensor Kinetics installed on it
- Large binder clip
- Plastic sandwich bag (to keep the phone from getting scratched)
- Horizontal rod
- String

**Introduction:**

We expect the period $T$ of a pendulum's oscillation to follow the equation

$$T = 2\pi\sqrt{\frac{\ell}{g}} \qquad (3.1)$$

where $\ell$ is the length of the pendulum (i.e., the distance from the axis of rotation to the center of mass) and $g$ is the acceleration due to gravity. In this experiment we're going to use the smartphone to measure $T$, and given a value of $g$, we'll compare the $\ell$ we measure with the one we calculate by inverting Equation 1:

$$\ell = g\left(\frac{T}{2\pi}\right)^2 \qquad (3.2)$$

**Procedure:**

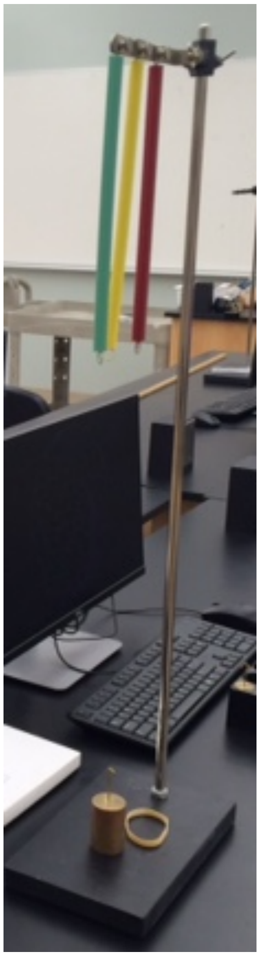
1. Start up the Sensor Kinetics App, and under Device Motion, find Gravity Sensor.
2. Press the graph icon for the Gravity Sensor
3. Place the phone in the plastic bag, to prevent it from getting scratched. (You can still operate the phone through the bag!)
4. Clip the binder clip around the phone. You now have a pendulum, consisting of the phone, binder clip and string.
5. Pull the pendulum back – but not too far, no more than an angle of about $30^o$.
6. Press the "Start" button and let go of the pendulum!
7. Let the pendulum swing as many times as you like, then grab it and press the "Stop" button.
8. By zooming in on the graph, measure the period $T$ of oscillation of the pendulum, e.g. using the green line.

   $T$ = ________________ s
9. Use this and the value of $g$ to compute $\ell$ using Equation (3.2) above:

   $\ell$ = ________________ m
10. Use the meter stick and measure down from the axis of rotation by the amount $\ell$ which you just calculated. Where does that fall on the phone/clip system?

    ____________________________________________.
11. Celebrate!

**Experiment 4:** Making the Phone Go Up and Down (Simple Harmonic Motion)



**Materials:**

- Smartphone with Sensor Kinetics installed
- Springs with various spring constants
- Mass, e.g. 500g
- Strong rubber band

**Introduction:**
This is very similar to Experiment 3, except instead of swinging the phone we'll be making it oscillate up and down. In this case, the period $T$ depends on the mass $m$ and spring constant $k$ by

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{4.1}$$

With a little algebra, we can get an expression for $m$:

$$m = k\left(\frac{T}{2\pi}\right)^2 \tag{4.2}$$

**Procedure:**

1. Hang the spring from a horizontal bar.
2. In Sensor Kinetics, under Device Motion, enable the graph for the Linear Acceleration sensor.
3. Strap the phone to the mass using the rubber band.
4. Go and put the phone+mass+rubberband system on the scale. Write the mass in grams of the whole system here:

$m$ (in grams) = ____________________ g.

5. Convert this to kilograms by dividing by 1000:

$m$ = __________________ kg.

*This is the value we'll use below, not the one in grams.*

6. Pick one of the available springs. By reading the color code on the top of the box of springs, determine the value of the spring constant $k$ corresponding to the spring you chose, and write it here:

$k$ = __________________ N/m

7. Hang the mass+phone system on the spring.
8. Raise the mass so the spring is just barely touching its coils together.
9. Press the "Start" button in the app
10. Let go of the phone/mass system, and let it oscillate for many periods.
11. Grab it and press the stop button.
12. By reading the graph and zooming in as necessary, read off the period $T$ of the oscillation. (Same as you did in Experiment 3.) Write that here:

$T$ = ____________________ s.

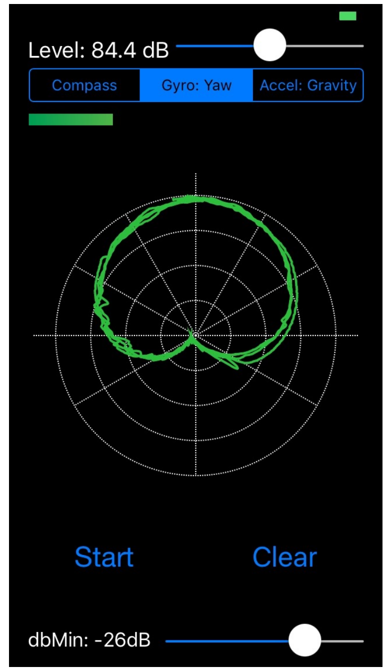
13. Try computing the quantity in Equation (4.2), namely $k(T/2\pi)^2$:

$$k(T/2\pi)^2 = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

    How does that compare with the value of $m$ you computed above?

14. Using other springs, measure the period again, and compute $k(T/2\pi)^2$ for those sytems. Does these agree with your $m$?

**Experiment 5:** Spining the Phone (Polar Pattern Measurement)




**Materials:**

- Smartphone with Polar Pattern Plotter app installed
- Loudspeaker
- Microphone
- TRRS adaptor (to connect mic to phone input jack)

**Introduction:**

Dr. Hawley just had his very own app come out on the App Store yesterday! It makes a graph of the intensity of sound, as a function of the direction the sound is coming from. In the audio engineering industry, this is referred to as a "polar pattern." Since the new app plots a graph of the sound directivity, the app is called "Polar Pattern Plotter"!

**Procedure:**

Instructions to be given verbally.

**Experiment 6:** Guess the Mass of the Block (Linear Acceleration)

Instructions to be given verbally.

**Experiment 7:** Bonking Two Phones Together (Action/Reaction Forces)

Instructions to be given verbally.