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## Lab # 2

### Seismic Waves

**Instructions:** Numerical answers require units and appropriate numbers of significant digits. **Remember to show your work!**

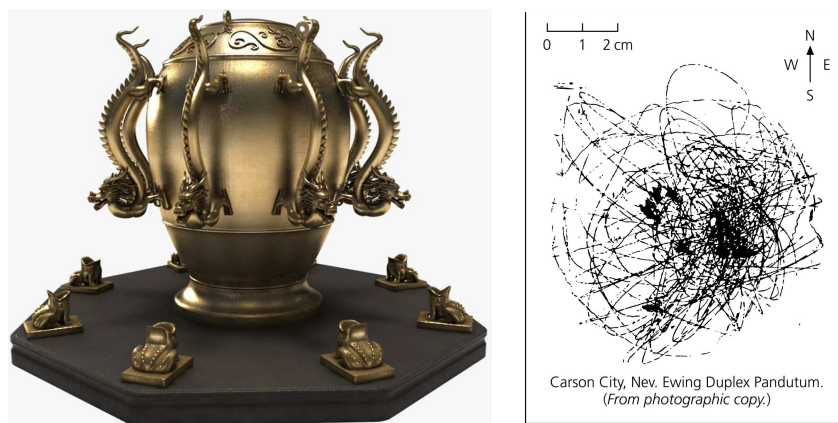
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## PRELAB

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### 1 Seismometers and Seismograms

The earliest attempts to record the motions of earthquakes used *seismoscopes*, which record ground motion without time information. The first known seismoscope, built by the Chinese astronomer Chang Heng in about 132 A.D. (Fig. 1(a)), consisted of a pendulum inside a 6 ft-diameter jar. Eight dragons' heads with metal balls in their mouths were placed around the rim of the jar, so the balls would drop in the direction from which seismic waves arrived. Later seismoscopes included a pendulum marking a path on a surface (Fig. 1(b)).



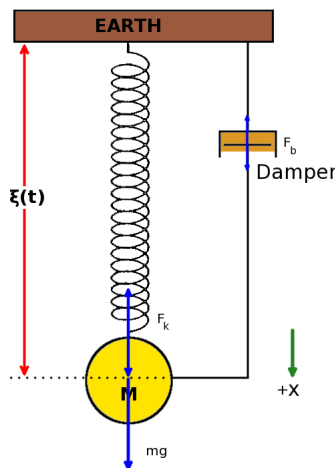
**Figure 1:** *Left:* The first known seismoscope built in China. *Right:* Seismogram of the great 1906 San Francisco earthquake, recorded by the Ewing duplex pendulum seismoscope in Carson City, Nevada.

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Today, seismic waves from earthquakes and other ground movements<sup>1</sup> are recorded using instruments called *seismometers*. In order to do so, nearly all seismometers use an oscillatory system such as mass-spring setups (Figs. 2). Seismometers usually measure movements of ground in three perpendicular directions, i.e. North-South (NS), East-West (EW) and vertical (Z),<sup>2</sup> so we can have a three dimensional understanding of ground movements.

The basic problem of *seismometry* is how to measure the motion of the ground using an instrument that is also on the ground and therefore we will be measuring everything in a non-inertial frame of reference. As we saw in the previous lab, this will result in wrong measurements. The traditional solution is to use an inertial, such as a spring, so that the motion of the pendulum is out of phase with the ground motion. A schematic vertical seismometer is shown in Fig. 2. Also, the motion is damped to avoid infinite, uncontrolled oscillations.



**Figure 2:** Mechanical setup of a simplistic 1-dimensional – vertical – seismometer. Although, this device is rather unrealistic, it is very useful in conveying the main idea of seismometry.

The motion of the pendulum in these systems relative to the frame is measured by moving a coil attached to the mass through the magnetic field produced by a magnet fixed to the seismometer frame (or the other way around). The voltage produced in the coil is proportional to the time rate of change of the magnetic field, and thus to the velocity of the mass relative to the frame (Fig. 3).

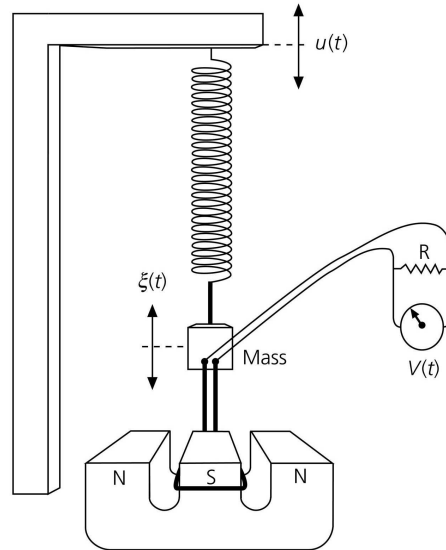
<sup>1</sup> Such *other* motions include but are not limited to the effects of tides, winds, ocean waves, explosions, motion of different objects and people, etc.

<sup>2</sup>An analogy to the Cartesian coordinates ( $X, Y, Z$ ).

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**Figure 3:** Schematic illustration of an electromagnetic seismograph, in which the mass is coupled to an electromagnetic transducer. Motions of the mass move the coil through the magnetic field, generating an electric current. The voltage across the coil is proportional to the relative velocity between the mass and the magnet.

**Questions:**

1. Take a close look at the F-wing Seismometer (the kiosk at the atrium) and make a sketch depicting the parts discussed above. In your sketch, identify the major parts.



**Figure 4:** The exhibit seismometer at the F-Wing of Tech. This is a 1-component seismometer which only records vertical motions of the earth.

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2. Take a picture of the F-wing seismometer and submit the picture file on Canvas.

## 1.1 Recording the Signal

Recording oscillatory signals had become popular by the early 1900s, when Willem Einthoven invented the first reliable EKG<sup>3</sup> device which recorded the electrical activity of the heart through measuring the changes in an external electromagnetic field. Seismology has also benefited from such advancements in technology.

At the dawn of the twentieth century throughout the 60s, the very first seismometers “recorded” the seismic data on rolls of metal or paper (Fig. 5). Although modern seismometers are built using the same principles, the data recording technology applied to them has tremendously improved. Today, seismic data are stored digitally and is accessible instantaneously through online services (Fig. 6).

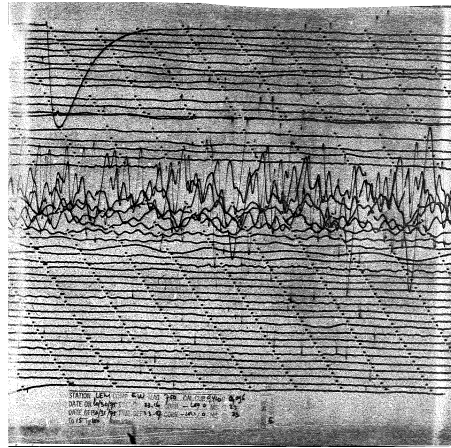
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<sup>3</sup>Electrocardiography

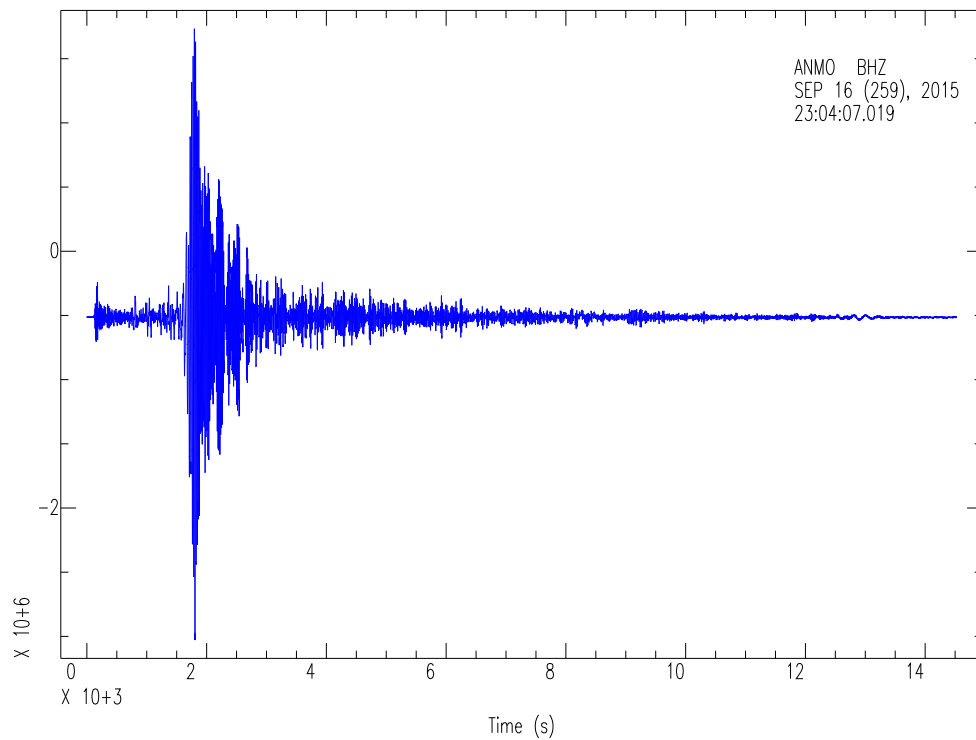
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**Figure 5:** An analog seismogram for an earthquake in the Philippines in 1975 preserved on microfilm and paper.



**Figure 6:** A digitally recorded seismogram for the 2015 Chile earthquake.

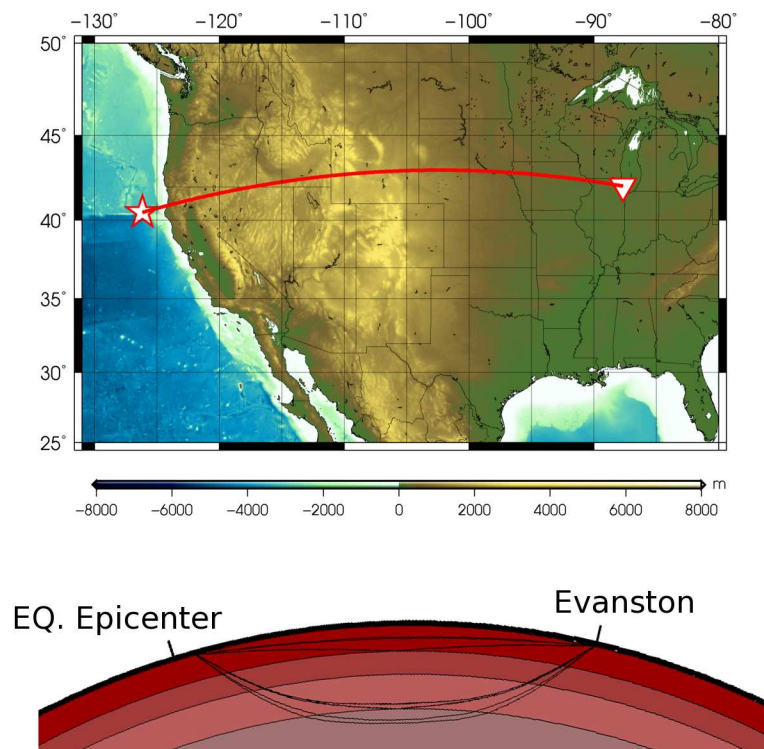
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**Questions:**

On December 8, 2016, at 6:49:46 AM, a magnitude 6.5 earthquake occurred off the coast of California. Although this event was not generally felt by California residents, it was recorded by seismometers all over the world.

1. Download the text file from [www.earth.northwestern.edu/~amir/202/TA.L44A.BHZ.XY](http://www.earth.northwestern.edu/~amir/202/TA.L44A.BHZ.XY). This is a two-column file with time and measured displacement on the first and second columns, respectively.
2. The file you have downloaded is a seismic record of the California earthquake recorded by an NU owned seismometer near Evanston.



**Figure 7:** The California earthquake of 8 December 2016. *Top:* Map view: source (earthquake) and receiver (seismometer) are depicted by a star and an inverted triangle, respectively. *Bottom:* Cross-section: seismic waves travel from the source to the receiver.

Each line of this file is a data point, i.e. a measurement of ground displacement at a moment of time. How many measurements are there in this file?

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3. The “sampling rate”, the rate at which the seismic signal is recorded, for this record is 40 Hz. This means the signal is recorded 40 times per second. How long is this record (in minutes and seconds)?
4. Use EXCEL or your favorite plotting program to plot the seismic signal (Hint: think of the seismogram as a time-series which shows displacement as a function of time.) Submit a HARD COPY along with your labs. Also, submit the spreadsheet or your plotting program on CANVAS.

## 1.2 Accelerometers

Seismometers can be designed in a special way to be sensitive to the acceleration of ground motion instead of velocity or displacement. These instruments are widely used measuring the acceleration due to earthquakes at any surface. The destruction caused by earthquakes is usually quantified through the acceleration they have caused at a given site.

Today, different types of accelerometers are widely used in other aspects of human’s life. Tiny accelerometers in smartphones allow for screen rotations and sometimes switching off the phone when accidentally dropped – yes, your smartphone has a small seismometer!

### Question:

Watch the YouTube video at <https://goo.gl/EBVKjp> and explain how each of the following seismometer parts/processes are done in smartphones.

1. Spring

2. Mass

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### 3. Electric current measurement

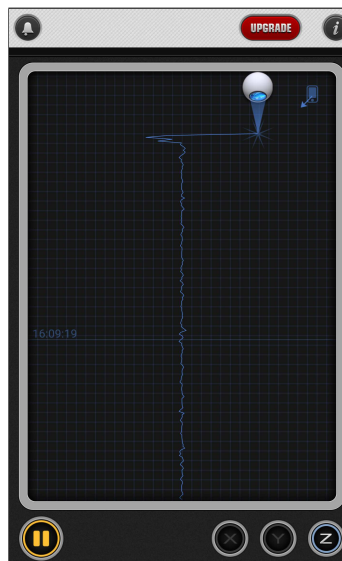
Using the signals from the accelerometer in your smartphone, you can turn your phone into a small seismometer. In order to do this, you will need a piece of software that can read signals from the accelerometer. A good example of such a program is called *Seismometer 6th*. Here, we are going to use this app for a demonstration of motion signals.

*Follow through these steps:*

**A) Installation:** Download and install the Seismometer 6th app from App Store or Google Play.

#### **B) Introduction:**

1. Open the App by tapping its shortcut icon in your phone's screen. A similar screen to Fig. 8 will pop up.




**Figure 8:** First screen of Seismometer 6th.



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2. Using this screen you can see measures of the motions of your phone (= seismometer) on the three axis. Obviously, these axes do not coincide with geographic directions as is customary in scientific seismometers, but rather they represent three perpendicular directions with respect to your phone.
3. Put your phone on a table and try to find out how/why pounding on the table at different locations affects the signal appearing on the three components. You can pause “recording” and freeze the display by tapping the  icon. Try to repeat the “experiment” for 1 minute.
4. Pause the screen and tap anywhere on the record screen and from the pop-up menu choose the option to send the recorded data to your own email account. You will receive an email from yourself with “Seismometer recorded data” in the subject line.<sup>4</sup>
5. There will be a five-column, comma separated text either in the main body of the email or as an attachment. These columns are date, time (“**in whole seconds**”) and the measurements by each of the three components of your seismometer similar to the California earthquake record.

**Questions:**

- (a) What is the sampling rate? How did you calculate it?
  
  
  
  
  
  
  
  
  
  
- (b) In a 6th column, use your calculated sampling rate to write new time values in seconds to the 6th decimal point.
- (c) Using EXCEL or your favorite plotting program, plot the X, Y and Z values against the 6th column values (time). You will turn in these graphs along with your labs AND upload them on Canvas.

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<sup>4</sup>You may need to look into the junk/spam folder of your email account, depending on the settings of your email provider.

## 2 Seismic Wave Velocity

### 2.1 Introduction

In class we learned about different types of seismic waves,  $P$  and  $S$ , and how they travel in *elastic media*. We also learned that the velocity of these waves (and in fact, any other wave) depend on the medium in which they travel.  $P$  and  $S$  waves travel with velocities  $\alpha$  and  $\beta$ , respectively which can be expressed as functions of rigidity,  $\mu$ , and bulk modulus,  $K$ , and density,  $\rho$  of a given material as

$$\alpha = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad , \quad \beta = \sqrt{\frac{\mu}{\rho}} \quad (1)$$

where  $\mu$ ,  $K$ , and  $\rho$  are called *elastic constants*.

#### Questions:

Bulk modulus and rigidity are related using another elastic constant,  $\lambda$ ,

$$\lambda = K - \frac{2}{3}\mu \quad (2)$$

1. Use Eq. (2) to rewrite Eq. (1) in terms of  $\lambda$  and  $\mu$ .
  
  
  
  
  
  
  
  
  
  
2. Derive an equation for a  $P$  to  $S$  wave velocity ratio.

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3. For Earth rocks, generally we can assume  $\lambda \approx \mu$ . Calculate the above ratio for this case.

4. Let's assume that you notice an earthquake being recorded by the F-wing seismometer and the received signal is displayed on the monitor. Since you are not feeling any shaking, you deduce that the earthquake took place at some distance from Evanston. You remember  $\sim 8$  km/s as an approximation for  $P$  wave velocity, but you can't recall a value for  $S$  waves. You can also measure the difference between  $P$  and  $S$  wave arrivals from the monitor. Using this information, calculate how far the earthquake was from the seismometer (show your work!).

5. Using Eqs. (1) and Table 1, answer the following questions.

**Table 1:** Elastic moduli for water and the three major types of rocks in the earth (modified from Lay and Wallace, 1995).

Material	$K$ ( $\times 10^{10}$ dyn/cm <sup>2</sup> )	$\mu$ ( $\times 10^{10}$ dyn/cm <sup>2</sup> )	$\rho$ (g/cm <sup>3</sup> )
water	2.1	0	1.0
sandstone	17	6	1.9
olivine	129	82	3.2
perovskite	266	153	4.1

(a) Calculate the  $P$  and  $S$  wave velocities in the rocks listed in Table 5. *Be careful with the units!*

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- (b) Olivine is the most abundant mineral in Earth's upper mantle (depth:  $\sim 30 - 410$  km) while the lower mantle mainly consists of perovskite (depth:  $660 - 2891$  km). Considering the average densities from Table 5, compare the P and S wave velocities for the upper and lower mantle.

### 3 Seismic Reflection/Refraction

We saw in class that as seismic waves arrive at the boundary of two media *vertically*, the energy they carry (and hence their amplitude) is divided (“partitioned”) into reflected and transmitted (refracted) waves, and “reflection” and “transmission” coefficients for the case of only P-waves are

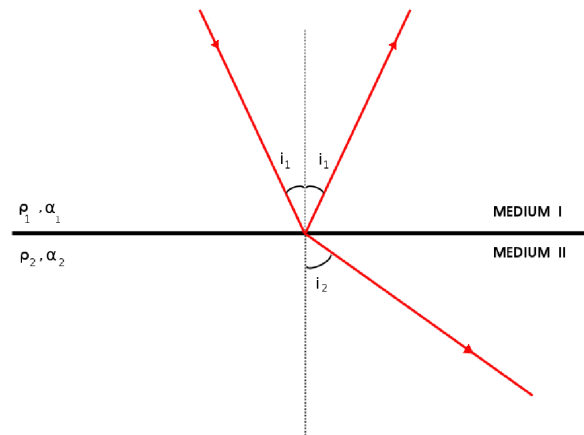
$$R_{12} = \frac{\rho_1 \alpha_1 - \rho_2 \alpha_2}{\rho_1 \alpha_1 + \rho_2 \alpha_2} \quad , \quad T_{12} = \frac{2\rho_1 \alpha_1}{\rho_1 \alpha_1 + \rho_2 \alpha_2} \quad (3)$$

where  $\rho_i$  and  $\alpha_i$  are densities and P-wave velocities for the two media. From Eq. (3) we know that the amplitudes of reflected and transmitted waves depend on velocities and densities of the two media. Note that Eq. (3) is no longer valid for non vertical incidences and the coefficients are more complex. However, for a special case, i.e. when the incident P-wave in Fig. 9 passes through a boundary between two liquid media, where no conversion from P to S waves occurs (why?), the reflection and transmission coefficients are

$$R_{12} = \frac{\rho_1 \alpha_1 \cos i_1 - \rho_2 \alpha_2 \cos i_2}{\rho_1 \alpha_1 \cos i_1 + \rho_2 \alpha_2 \cos i_2} \quad , \quad T_{12} = \frac{2\rho_1 \alpha_1 \cos i_1}{\rho_1 \alpha_1 \cos i_1 + \rho_2 \alpha_2 \cos i_2} \quad (4)$$

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**Figure 9:** Reflected and refracted rays at a non-vertical incidence with an angle  $i_1$ .

### Question

From equation (4) we can see that reflection and refraction are functions of the incidence angle. Using an EXCEL spreadsheet (or your favorite programming language) make a three column file, with incidence angle ( $i_1$ ),  $R_{12}$  and  $T_{12}$  on the three columns while changing the incidence angle from  $0^\circ$  to  $90^\circ$ . In a single graph, plot both  $R_{12}$  and  $T_{12}$  against  $i_1$  using your favorite plotting software for:

- $\alpha_1 = 1.5 \text{ km/s}$ ,  $\rho_1 = 1 \text{ kg/m}^3$ ,  $\alpha_2 = 1.3 \text{ km/s}$ ,  $\rho_2 = 0.8 \text{ kg/m}^3$
- $\alpha_1 = 13.72 \text{ km/s}$ ,  $\rho_1 = 5.57 \text{ kg/m}^3$ ,  $\alpha_2 = 8.06 \text{ km/s}$ ,  $\rho_2 = 9.90 \text{ kg/m}^3$

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## IN LAB

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### 4 Smartphone Experiment

Make an array of your phones, equally spaced, at the long side of the large table in the lab. Make sure to leave 30 cm margins at both ends of the table (Fig. 10). Label the phone position with a Post-It note and include your phone's label in your lab report.

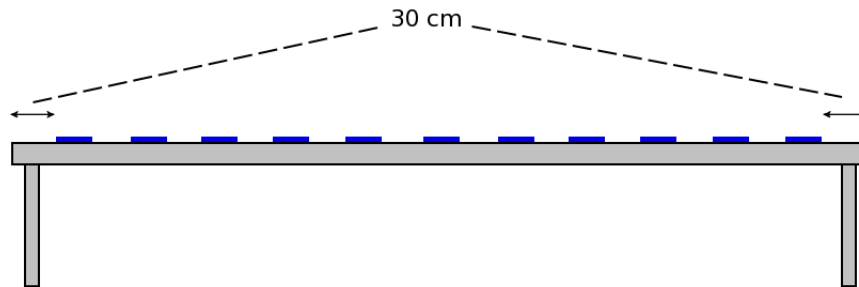


Figure 10: Array of phones on the large table

#### Data Acquisition:

1. Run the Seismometer 6th apps on the phones.
2. Pound “three times” with 5 seconds intervals at one end of the phone array and observe how the corresponding signal shows up on different phones in the array.
3. Stop the recording process.

#### Question

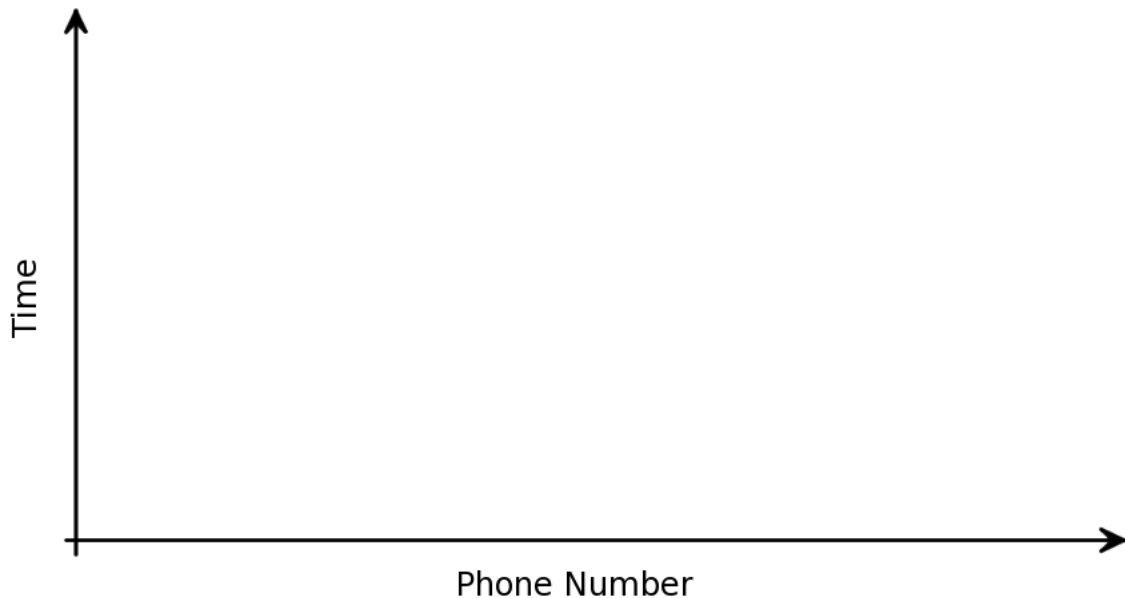
From what you have learned in the lecture and lab, explain how and why the signal changes through phones in the array.

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4. Using EXCEL or your favorite plotting software, plot your recording with measurements and time on the vertical and horizontal axes. Remember to put units and labels on the axes.
5. Upload a copy of your CSV file from the array experiment onto the designated upload space with your label number in the file name (e.g. XX.YOUR\_NAME).
6. Download the all uploaded files into a directory on your computer.
7. In each file, find the time at which the maximum value on the Z-axis had occurred (Hint: Sampling rates and start of the records CAN be different in the phones).
8. Make a 2-column table with phone label and the arrival times of the maximum amplitudes.
9. Plot the file you made with labels on the horizontal and the arrival times of the maximum amplitudes on the vertical axes.



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10. Do you see any pattern? Why or why not? Explain.

## 5 Slinky Experiment

As we learned in the lectures, energy can propagate through elastic material, because they have an intrinsic restoring property for small displacements. While this property causes individual particles to return to their initial equilibrium, it also causes the passing of energy between neighboring particles.

Let's watch the video at [www.earth.northwestern.edu/~amir/202/elastic.mp4](http://www.earth.northwestern.edu/~amir/202/elastic.mp4).

As we saw in the video, we don't get to see the elastic properties of rocks in everyday life. Great example of observable elastic behavior are slinkies. In this section, we will test some basic concepts about seismic waves using slinkies.

### 5.1 Part I:

A. Follow through these steps:

1. Divide into groups of 3 or 4 and pick a slinky from the stack.
2. Stretch it to some length and fix both its ends to a table using scotch tape.
3. Measure the length of your stretched slinky.
  
4. Create a  $P$  wave by pinching *a few* rings.



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5. Measure the time needed for the wave to travel back and forth.

6. Calculate the velocity of the wave.

**B.** Double the length of your slinky by stretching it. Repeat the above steps to measure the velocity.

**C.** How do the velocities from **A** and **B** compare? Explain your answer.

## **5.2 Part II:**

**A.** Follow through these steps:

1. Divide into groups of 3 or 4 and pick a slinky from the stack.

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2. Stretch it to 1.5 m and fix both of its ends to a table using scotch tape.
  3. Firmly fix the slinkies midpoint to the table with scotch tape.
  4. Create a  $P$  wave by pinching *a few* rings in the right-hand side.
  5. Measure the time needed for the wave to travel back and forth in the right-hand side.
  6. Calculate the velocity of the wave. How does it compare with your results from 5.A?
- 
7. Does the wave travel to the left-hand side? Why?

**B.** Follow through these steps:

1. Scotch-tape a slinky to the “rainbow slinky”.
2. Fix the free end of the rainbow slinky on the table using scotch tape.
3. Stretch the slinky series to 2 m.
4. Create a  $P$  wave by moving the free end of the normal slinky back and forth.
5. Measure the velocity of the traveling wave in both slinkies. How do the two values compare?

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6. Create an  $S$  wave by moving the free end of the normal slinky sideways.
7. Using a ruler, measure the amplitude of the traveling wave in both slinkies. How do the two values compare?