

# High School Phoenix

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## 1 Introduction

Performance of a student in our present system of education is measured by the ability to memorize and not to understand. As a result, most of them are unable to connect what they learn in the classroom to things they encounter in daily life. To some extent this can be corrected by learning based on exploration and experiments. Experiments can be conducted by simple equipment in most of the cases. If the measured physical property is changing very fast, the measurements need to be automated and a computer becomes a useful tool. For example, measuring the time variation of AC mains voltage requires fast measurements, because its value changes almost every millisecond.

Physics with Home-made Equipment and Innovative Experiments, PHOENIX, is a simple computer interface that can be used for doing automated measurements. This document is an attempt to describe how the Phoenix Interface can be utilized for demonstrating the *physics topics covered in the high school syllabus*. We will focus on topics like Electricity and Magnetism where fast measurements are required.

### 1.1 Features of Phoenix

The PHOENIX interface gives you the following facilities through the sockets on its top panel.

- 4 Digital Inputs : You can connect 0V or 5V to them. The software can read the connected voltage level.
- 4 Digital Outputs : The software can set the voltage level on these sockets 0V or 5V.
- 4 Analog Inputs (ADC Ch0 to Ch3) : You can connect any voltage between 0 to 5V to them and the software can measure its value.
- 1 Analog Output (DAC) : The software can set any voltage between 0 to 5V on this socket
- Programmable Waveform Generator (PWG) : Software can set a square wave ranging from 15 Hz to 4 MHz on this socket.

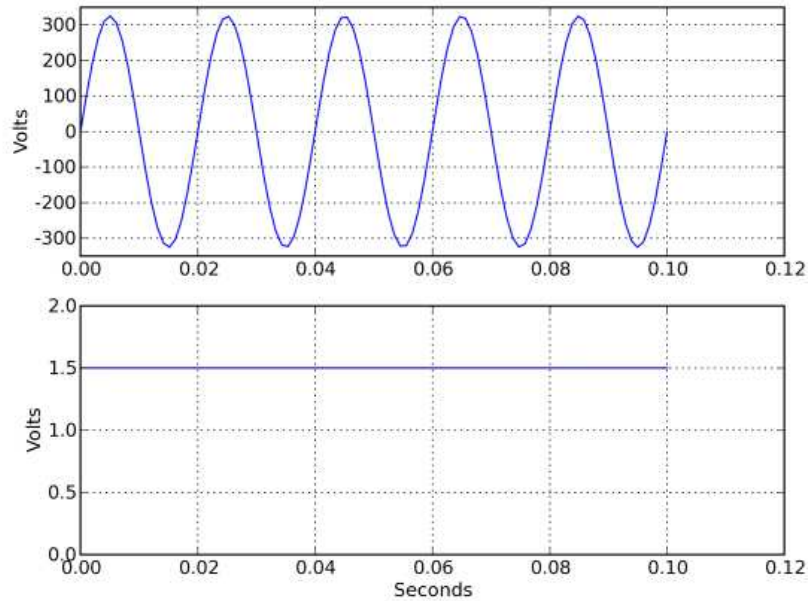


Figure 1: The 50 Hz AC mains voltage and a 1.5 DC voltage waveforms are shown as a function of time.

- Frequency Counter (CNTR) : Software can measure the frequency of a waveform connected to this socket.
- Constant Current Source (CCS) : Gives a constant current of 1 mA for load resistances upto  $4K\Omega$  .
- Two Inverting Amplifiers, with plug-in resistors to set the gain
- One Non-Inverting Amplifier, with plug-in resistors to set the gain
- Two level shifting amplifiers, to convert -5V to 5V voltages to 0 to 5V range.

The voltage levels are restricted to 5 volts for human and equipment safety. You should not feed any voltage larger than 5 volts to any of the sockets. Phoenix is powered by 9V DC and interfaced to the PC using the Serial Port.

## 2 Electricity

While studying electricity we need to measure voltages and currents as a function of time. We will also measure electrical properties like resistance, capacitance of various material objects.

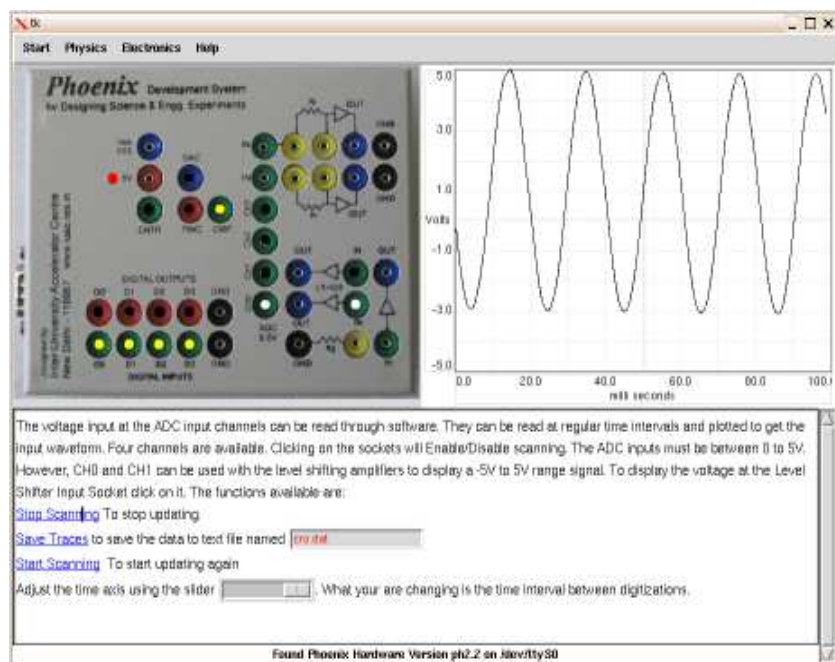


Figure 2: Screen-shot of the power line pickup using Phoenix.

## 2.1 AC and DC Voltages

Text books tell us that the voltage between the two terminals of a dry-cell is 1.5 Volts DC, and the mains supply is 230 Volts AC. It is easy to understand DC, the voltage is constant in time. But how about AC, is the voltage jumping from 0 to 230 V abruptly, is it going to negative values, is the maximum value of the voltage really 230 volts ? All these questions can be answered better by plotting a graph of Voltage and Time, as shown in figure 1 . The instantaneous value of the AC goes smoothly (follows a sine curve) from zero to  $+V_{max}$  and come back to zero in 10 milliseconds, completing one half cycle. Then goes to  $-V_{max}$  and back to zero in the next 10 milliseconds. One full cycle is completed in 20 milliseconds, that means 50 cycles in a second.<sup>1</sup>

## 2.2 Watching AC using Phoenix

Using Phoenix we can view an AC waveform similar to the one shown in figure 1. However playing directly with 230 volts AC is not advisable. We will try to watch the AC waveform without making any direct contact to the mains supply sockets. You need to do the following

<sup>1</sup>The maximum value of the voltage is not 230 but  $230\sqrt{2}$  . 230 is the Root Mean Square (RMS) value of the voltage.

- From the Phoenix menu start *Experiments*.
- Click on socket Ch0 and the level shifter on its right side
- Adjust the *timing axis slider* to make the x-axis 100 milliseconds full scale.
- Connect one end of a wire to the first ADC channel (CH0)

Now you must see a waveform on the window, similar to figure 2. If the waveform amplitude is small try with a longer wire and take the other end of the wire near the power line. From the waveform, you can see that there are roughly five cycles in the 100 milliseconds time span, corresponding to the 50 Hz line frequency. You will also observe that the waveform will change the orientation of the wire or when you touch it.

How do you explain these things. Fifty Hz AC is flowing through the mains lines. You know that there is a magnetic field around a current carrying conductor. When the current changes direction, the magnetic field also changes direction. If you keep a conductor in a changing magnetic field, a voltage will be induced on it. Here we are keeping a piece of wire in the magnetic field generated by the AC mains line and measuring the induced AC voltage as a function of time. You are observing not only the nature of AC voltage waveform but the mutual induction between two conducting wires. Another way to think of it is as a transformer, where the AC line is primary winding and the hanging wire is the secondary. We will learn more about electromagnetic induction in the coming sections.<sup>2</sup>

### 2.2.1 Low Voltage AC using a step down transformer

The previous experiment does not show a stable AC waveform centered at zero. This is due to the very low power level of the pickup, the induced current is in nano-amperes only. To get a clean AC signal, connect the output of a 230V to 3V step down transformer to the input of level shifter, marked (x+5)/2 on the box, and the output of the level shifter to Ch0. The peak value of the voltage from a 3V transformer is  $3\sqrt{2} = 4.2V$ , within the 5V limit of Phoenix.

Another method to get a stable low voltage AC signal is to use an electronic oscillator circuit. That is how the UPS systems generate AC from DC. Once you have a low voltage AC signal, you can study the rectification properties of a diode.<sup>3</sup>

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<sup>2</sup>It is possible to measure the frequency of the induced waveform using curve fitting techniques and you will find it less than 50 Hz at most of the places due to the loading of the generator. Supply frequency will vary as load and generation changes. During overload conditions frequency will decline, and any loss of an interconnection, consuming power, will cause system frequency to rise.

<sup>3</sup>The PWG Socket of Phoenix can generate a square wave whose voltage level changes between 0 and 5V. Connect PWG to CH0 and click on CH0 to view this signal. Click on PWG to vary the frequency of the wave.

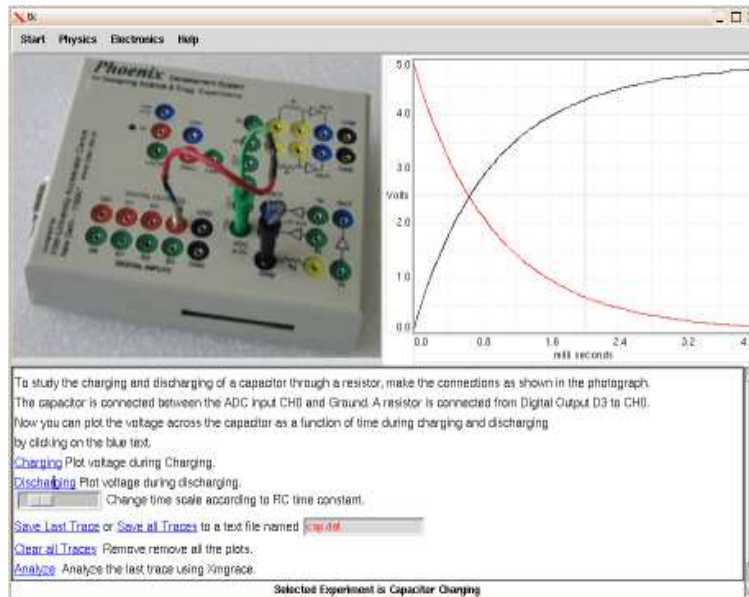


Figure 3: Experimental setup to get the charging and discharging of a capacitor through a resistor.

## 2.3 Study of Capacitor

A capacitor is an electrical device that can store energy in the electric field between a pair of conductors (called "plates"). The process of storing energy in the capacitor is known as "charging", and involves electric charges of equal magnitude, but opposite polarity, building up on each plate. The capacitance is defined by the equation  $C = Q/V$  where  $Q$  is the amount of charge stored and  $V$  is the voltage across the capacitor. Unit of capacitance is Farads, which is big unit, and the once we generally find in circuits are in micro-farads.

Capacitors are often used in electrical circuit and electronic circuits as energy-storage devices. They can also be used to differentiate between high-frequency and low-frequency signals. This property makes them useful in electronic filters.

### 2.3.1 Charging and Discharging of a Capacitor

When we apply a voltage to a capacitor through a resistor, the capacitor will start accumulating charges on the plates and the voltage between the plates will increase gradually. Charging of a 1 microfarad capacitor through a 1  $K\Omega$  resistor will take only few milliseconds. To view this waveform we need to take fast measurements, something Phoenix can do.

Connect the capacitor between CH0 and Ground. Connect the resistor from CH0 to Digital Output D3. Through software we flip the voltage level on D3 and measure the voltage across the capacitor. The experimental setup is shown

in figure 3 . From the discharge curve we can find out the time taken for the voltage to reach half of the initial value and calculate the capacitance.

$$V = V_0 e^{-t/RC} \text{ For } V = V_0/2 \quad RC = t_{1/2}/\ln 2$$

By using a  $1M\Omega$  resistor in series, you can measure capacitors down to few hundred pico farads. One can make a capacitor using paper and aluminium foil and measure it using Phoenix. The same experiment can be extended to measure the dielectric constant of materials.

## 3 Electricity and Magnetism

Electricity and magnetism are two closely related phenomena. An electric current will produce a magnetic field. On the other hand a changing magnetic field generate an electric field. In this section we describe some experiments to demonstrate the relationship between them.

### 3.1 Electric field produced by a changing magnetic field

A voltage will be generated across a conductor kept in a changing magnetic field. We can create a change in the magnetic field by moving a permanent magnet. The magnitude of the voltage is decided by the length of the conductor and the rate of change of magnetic field. That means, to get larger voltage you can

- increase the length of the conductor
- use a stronger magnet
- move the magnet faster

In this experiment we will drop a small magnet into a coil having 5000 turns of insulated copper wire. The coil is connected between ground and the input of the level shifter, and the level shifter output to ADC input Ch0. We need the level shifter since the induced voltage can go to negative values depending upon the direction of motion. From the physics menu select Electromagnetic Induction. A screen as shown in figure will come up. Clicking on the *Scan CH0* tag inside the text will tell the program to scan for the induced voltage, at regular intervals. Now drop the magnet into the coil. If the movement of the magnet through the coil coincides with the scanning, the waveform is captured and a message is displayed. You need to repeat dropping the magnet until this happens. If the waveform similar to the one shown in figure 4 is not obtained, click on *Scan CH0* to repeat the process.

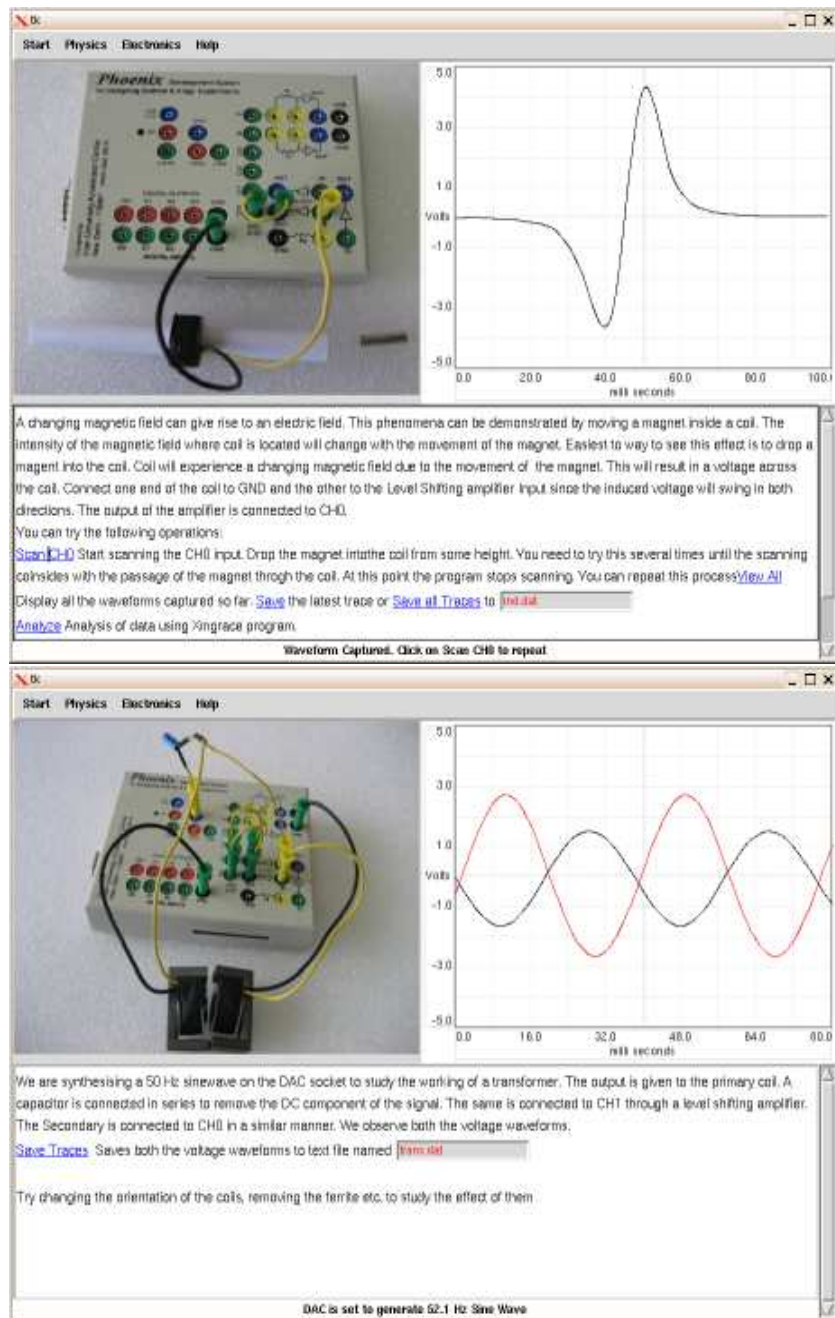


Figure 4: Experiments to demonstrate electromagnetic induction. (a) The wave form induced on a solenoid by moving a magnet through it is captured using Phoenix. (b) Mutual Induction between two coils.

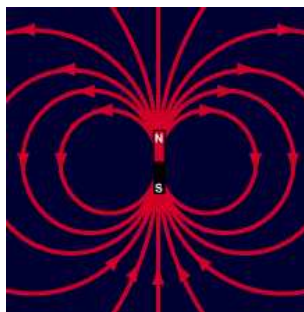


Figure 5: Magnetic field of a cylindrical magnet.

### 3.1.1 Results

The induced voltage first builds up in one direction and then in the opposite direction. How do we explain this waveform. According to Faraday's law, the induced voltage across a coil with  $N$  turns is given by

$$\varepsilon = -N \frac{d\Phi_B}{dt}$$

where  $d\Phi_B/dt$  is the rate of change of magnetic flux intercepted by the coil. From figure 5, it can be seen that the direction of the magnetic field is radially outwards near the north pole. Imagine the magnet entering the coil with the north pole first. The induced voltage goes up due to the effect of the outgoing flux from the north pole. Once the magnet enters inside the coil, one half of the coil will intercept a magnetic field in the outward direction and the other half a field in the inward direction. This results in a zero induced voltage when the magnet is in the middle of the coil. Once the magnet moves out of the coil through the opposite side the contribution from the south pole dominates and we find an induced voltage of opposite polarity.

Since the induced voltage is proportional to the rate of change of magnetic field, the amplitude of the waveform will increase with the velocity of the magnet. This can be verified by dropping the magnet from different heights.

## 3.2 Mutual Induction

In the previous experiment, the changing magnetic field was generated by a moving magnet. We can create a varying magnetic field by changing the current flowing through a coil, by connecting it to an AC source. We can generate a sinusoidal voltage on the DAC socket. For that select *Mutual Induction* from the *physics* menu. The program will display a photograph of the connections to be made. The DAC socket is programmed to generate a 50 Hz sine wave ranging from 0 to 5V. Passing it through a series capacitor will make amplitude ranging



from -2.5 to +2.5V. This is given to the primary coil and also to the level shifter input for monitoring. The secondary coil is connected between ground and the input of the other level shifter. The level shifter outputs are connected to CH0 and CH1.

At this point you should see the sinusoidal primary waveform on the screen. The secondary waveform will be a horizontal line. Now bring the coils closer. Once you make the magnetic circuit using the ferrite core, the secondary output also will be displayed as shown in figure 4. Try reversing the mutual orientation of the coil to see its effect on the phase difference between primary and secondary waveforms.

## 4 Sound and electrical Signals

In the previous experiments, we have seen that a magnet moving inside a coil induces a voltage across the coil. Moving the coil inside a magnetic field also does the same since only the relative motion matters. In a similar manner, *if you allow a current to flow through a conductor kept inside a magnetic field the conductor will experience a force*. This phenomenon is the basis of devices like electric motor, loudspeaker etc. We will take the case of the loudspeaker and explore the conversion of electrical energy into sound energy.

### 4.1 Sound from Electrical signals

A loudspeaker has a movable coil placed inside a magnetic field and a paper cone connected to the coil. When a current is made to flow through the coil, it moves. By applying an AC voltage across the coil we can make the paper cone move back and forth to generate sound waves. We can change the frequency of the waveform to change the frequency of the sound generated.

To study this experimentally using Phoenix, connect a loudspeaker between PGW and Ground sockets along with a  $100\Omega$  resistor to prevent overloading of the PWG output. Now click on the PWG socket and change the frequency, using the slider that pops up. You will observe that at some particular frequency, the intensity of sound shows a maximum. This is due to resonance.

### 4.2 Creating music

The musical notes are produced by certain frequencies, for example a 261.63 Hz frequency represents the note 'Sa'. One can produce some music by programming PWG to generate the notes in some order. From the help screen, clicking on the PWG Socket provides an option to play some tunes.

### 4.3 Convert Sound to Electrical Signals

Using the coil and magnet we have already generated and electrical signal using a moving magnet. In a microphone, there is a moving coil and a permanent

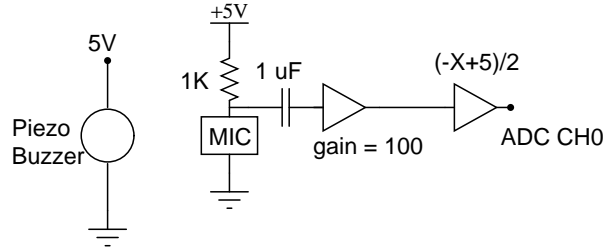


Figure 6: Circuit to digitize sound using Condenser Microphone.

magnet. The coil moves according to the pressure variations created by sound waves and corresponding voltage signals are generated. A loudspeaker also can be used as a microphone for demonstration purpose.

Connect the Speaker between ground and the input of the non-inverting amplifier. Set a gain of 100 and connect the output to CH0 via the level shifter. From the *help menu of the Experiments* select CH0 and the corresponding level shifter. Change the time axis to 100 ms full scale. Tap the speaker or make some loud sound to view the waveform.

#### 4.3.1 Condenser Microphone

The capacitance of a condenser microphone changes with the pressure applied by the sound waves. We connect the microphone between Ground and 5V supply along with a series resistance. When the capacitance changes, the voltage drop across the microphone also changes. This signal is amplified and given to ADC input as shown in figure 6.

A capacitor microphone is available along with Phoenix. Connect

## 5 Study of Pendulum

A body of mass suspended about an axis constitutes a pendulum. For small oscillations, the period of oscillation  $T$  depends on the following factors:

- Moment of inertia of the body about the axis of suspension,  $I_a$
- The distance from point of suspension to the center of mass of the body,  $L_{cm}$
- The value of acceleration due to gravity,  $g$

and is given by the equation

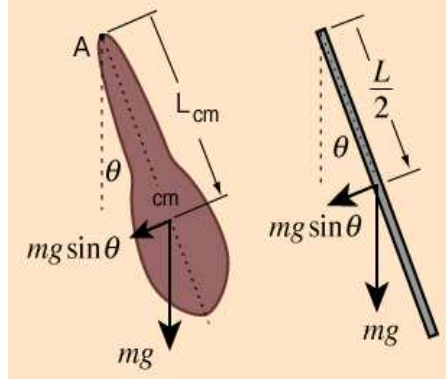


Figure 7: Examples of physical pendula. (1) A body of irregular shape is suspended about the point A. (2) A uniform rod suspended at one end.

$$T = 2\pi \sqrt{\frac{I_a}{mgL}} \quad (1)$$

where  $m$  is the mass of the body, but it will not appear in the calculations since the moment of inertia also depends on mass. For bodies with regular shapes, we get simpler expressions as explained below.

A simple pendulum is a point mass suspended from a string or rod of negligible mass. Substituting  $I_a = mL^2$  in expression 1 gives

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

where  $\ell$  is the length of the pendulum and  $g$  is the value of acceleration due to gravity. For the rod pendulum shown in figure 7, period T is given by

$$T = 2\pi \sqrt{\frac{\frac{1}{3}mL^2}{mg\frac{L}{2}}} = 2\pi \sqrt{\frac{2L}{3g}} \quad (2)$$

## 5.1 Pendulum experiments using Phoenix

Using phoenix we can explore the nature of oscillations of a pendulum, ie. the angular displacement as a function of time. Since it requires expensive angle encoders, we have settled for measuring the angular velocity that can be done using a simple DC motor. A DC motor has an armature rotating inside a magnetic field. If the armature is rotated manually, a voltage proportional to the angular velocity is induced across the armature coil. Using phoenix we can capture this voltage waveform as shown in figure 8. The motor is connected between ground and input of an amplifier, using a gain control resistor of  $100\Omega$ , and the output is connected to CH0 via a level shifting amplifier.

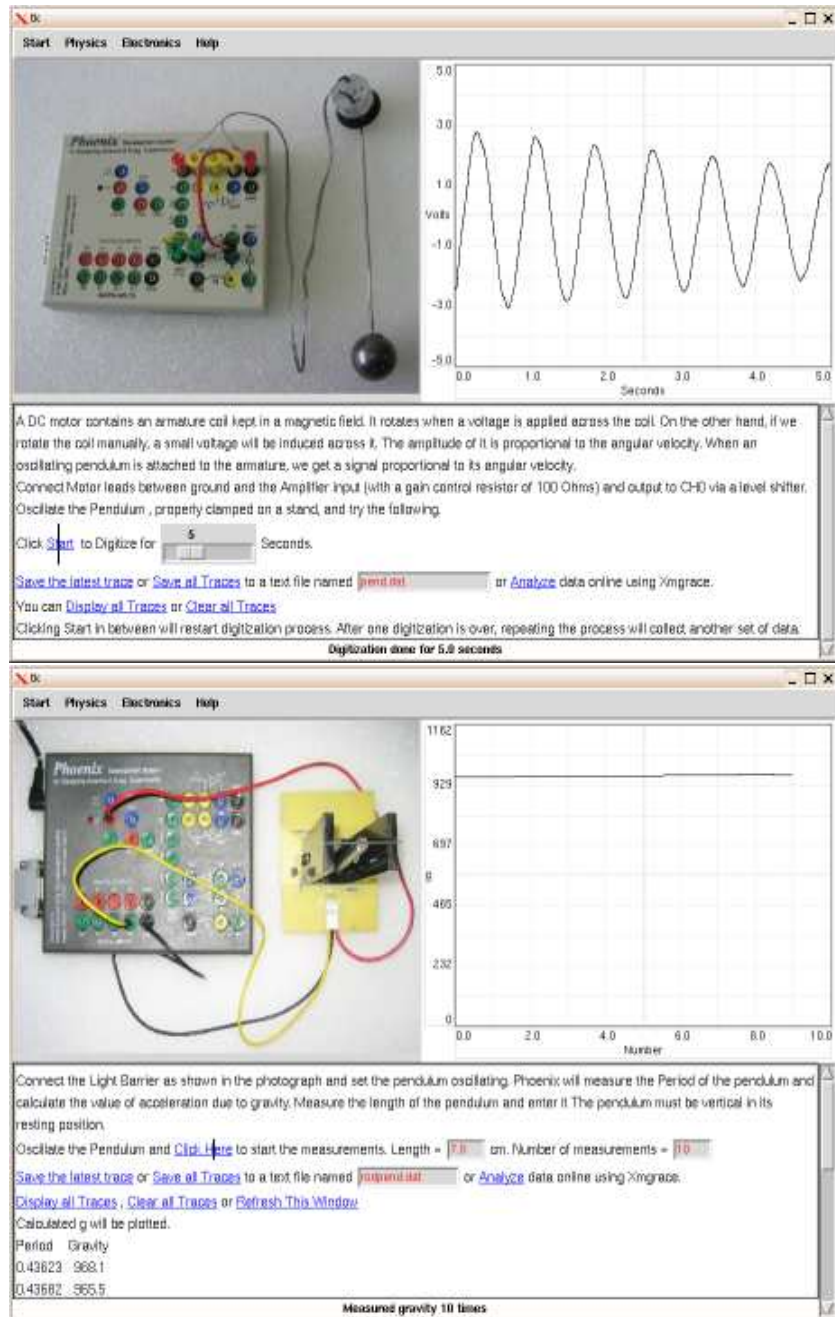


Figure 8: (a) An oscillating pendulum generates an damped sine wave. (b) Time period of a rod pendulum measured using light barrier setup.

### 5.1.1 Measuring 'g' using a rod pendulum

Phoenix can measure time intervals with microsecond accuracy. We can measure the time period of a pendulum by allowing it to intercept a beam of light going from an LED to a photo transistor. The output of the photo transistor is connected to one of the Digital Inputs of Phoenix. The experimental setup to do this using a Rod Pendulum is shown in figure 8. The actual length of the Rod Pendulum must be measured accurately and entered into the program. A 1 mm error in measuring the 7 cm rod will introduce a 1.5% error in the calculated value of 'g'. Care must be taken to make the pendulum vertical in its resting position, if the pendulum makes an angle  $\theta$  with the vertical, you will get  $g \cos \theta$  instead of  $g$ .

### 5.1.2 Large amplitude effects

Period of a pendulum increases with the amplitude of oscillations and for a simple pendulum it is given by the equation

$$T = 2\pi \sqrt{\frac{\ell}{g} \left( 1 + \frac{1}{16}\theta_0^2 + \frac{11}{3072}\theta_0^4 + \dots \right)} \quad (3)$$

where  $\theta_0$  is the amplitude. The correction is about 1% for  $\theta = 23^\circ$ . The accuracy of measurement using the light barrier allows you to see the large amplitude effects. While measuring the time period you will notice the value keeps reducing, along with the reduction in amplitude due to friction.