Name_______________________________ Date ________________ Section ____________

# LAB 9: MAGNETIC INDUCTION

## Purpose

The purpose of this lab is to observe and use Faraday's law of induction and Lenz's law to study mutual and self inductances.

## Theory

Michael Faraday (1791-1867), an English chemist, set out to determine whether magnetic field can produce an electric field. A simplified version of his experiment is shown in Figure 1.

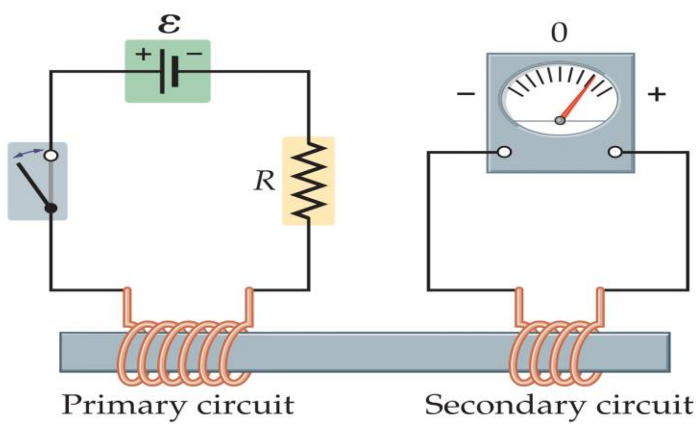



**Figure 1:** Basic setup of Faraday's experiment on magnetic induction. It consists of a primary circuit and secondary circuit connected by an iron bar.

Here, a primary circuit consists of a battery, a switch, a resistor to control current, and a coil of several turns. A secondary circuit consists of a coil wrapped around an iron bar. This coil is connected to an ammeter to detect any current in the circuit. Note that there is no battery in the circuit and the two circuits are only linked by the bar.

When the switch is closed, the magnetic field in the bar changes (increases) and the ammeter in the secondary circuit deflects to one side briefly. When the switch is opened, the ammeter deflects in the opposite direction. Nothing occurs while the current (and, therefore, the magnetic field) in the primary circuit remains constant. The secondary current that is generated is called an **induced current**. The changing magnetic field creates an induced electromotive force (emf) in the secondary circuit. This drives a current.

The term magnetic flux, $\Phi_{B,}$ is used to describe a quantity related to the magnetic field. It may be defined as a measure of the number of field lines that cross a given area. If a magnetic field, **B,** crosses a surface area, A, at right angles, the magnetic flux is defined as:

$$\Phi = BA. \qquad \mathbf{1}$$

Faraday found that if this magnetic flux through a particular portion of a circuit *changes* with time, then this change induces a voltage, ε, across that circuit element:

$$\varepsilon = -N\frac{d\Phi_B}{dt}. \qquad \textbf{2}$$

Equation (2) is known as Faraday's law of induction. This principle underlies the operation of an electrical generator, which converts mechanical energy to electrical energy. The minus sign on the right-hand side of Equation (2) is Lenz's Law, which states that the circuit reacts in such a way as to oppose the change in $\Phi_B$.

Because the magnetic field is proportional to the current producting it, Faradays' law can be rewritten as

$$\varepsilon = -M\frac{dI}{dt}, \qquad \textbf{3}$$

where the proportionality constant is called the "inductance." There are two kinds of inductance: mutual inductance and self inductance.

Consider two circuits which are not electrically connected, as described earlier. If a current $I_1$ flows trough the primary circuit, then it generates a magnetic field **B** which creates a flux $\Phi_2$ through the secondary circuit that is proportional to the primary current: $N\Phi_2 = MI_1$, where M is the mutual inductance.

This principle underlies the operation of a transformer, which takes AC power having a particular voltage and current from a primary circuit and transforms it into AC power at a different voltage and current in a secondary circuit.

The current I through any individual element in a circuit generates a magnetic field **B.** This magnetic field creates a flux, $\Phi_B$, through this same circuit element that is proportional to the current: $\Phi_B = LI$, where L is the self inductance. The self inductance is small (and usually can be ignored) for all circuit elements except for "inductors." If I varies with time, then Faraday's law states that the voltage $V_L$ induced across the inductor is proportional to the rate of change of the current I flowing through the inductor:

$$V_L = -L\frac{dI_1}{dt}. \qquad \textbf{4}$$

The minus sign in this expression Lenz's law: An inductor is resistant to having its current changed.

**Part I: Equipment Usage**

The first part of this lab is done while working "in sync" with the rest of the students, as the instructor applies voltage signals to the odd-numbered lab power network.

**Equipment needed:** Digital oscilloscope, digital multimeter (including narrow test leads), function generator, one BNC-to-BNC cable, one BNC-to-alligator cable, 270-Ω resistor, even- and odd-numbered binding posts.

**Procedure**

## 1. DC

Here you will confirm that your scope measures the same voltage as your digital voltmeter.

1. Turn on your oscilloscope. Note the BNC connector on the two inputs and also on one or more end(s) of most of your cables. This connector is used for both the scope and the function generator. Take a BNC-to-alligator-clip cable and attach one end to Channel "1" (or "X") of your scope. Shorten together the two alligator-clip leads ($\rightarrow \Delta V=0$) on the other end of this cable. Note the horizontal trace and the "ground" location, which can be moved up and down with the "Position" knob located under the lit-up "1" button.

   Disconnect the alligator-clips from each other and connect them instead to the D-cell battery

2. By changing the Volts-per-division (located over the lit-up "1" button) and Position knobs, accurately determine the voltage. Note the voltage per division in the upper left corner. Record your value of the voltage: ____________________

## 2. AC

Now you will use your oscilloscope to determine the type (sine, square, or triangle), amplitude A, period T, and frequency f ($\equiv 1/T$) of the voltage signal being broadcast.

1. Replace the D-cell with the function generator. Use these steps to produce a 40 Hz sine-wave as your signal:
   a. On the bottom menu, select "Sine."
   b. Select "Frequency," type "40" and press "Hz."
   c. Select "Amplitude," type "1.5" and press "$V_{rms}$"
   d. Press the "Channel" button (over the BNC output) and toggle "Output" to "On."

You should see a "sine wave" instead of a horizontal trace. The voltage can be expressed as:

$$V(t) = V_o \sin 2\pi f t = V_0 \sin(2\pi t / \tau).$$

Note the time in the upper portion of the screen.
What is the period, $\tau$, of the signal? __________________

What is the frequency, $f$, of this signal? __________________

What its the amplitude, A, ($V_0$)? __________________

2. Take a moment to change the settings of the function generator and oscilloscope in order to get acquainted with the usage of the both devices.

Get your instructor's initials before proceeding.

**Part II: Time Domain Measurement**

**1. Mutual Inductance**

**Equipment needed:** Oscilloscope, function generator, primary coil, secondary coil, three BNC-to-alligator cables, and 10-Ω resistor.

**Procedure**

1. Construct the following pair of circuits (See **Figure 2.**): (1) Primary circuit – It consists of a series combination of the function generator, the primary coil (tape-covered coil of wire with a rod sticking out of one end), and 10-Ω resistor (the voltage across which is being monitored by Channel 1 of the oscilloscope). Note that the black alligator clips on the wire running to the function generator and on the wire running to the scope must be located at the same spot on the primary circuit owing to the fact that both the generator and the scope are "grounded" ; otherwise, you circuit will not work. Note also that the voltage across the resistor will numerically equal ten (10) times the current flowing through this, owing to the value which we have chosen for R. (2) Secondary Circuit – It consists solely of the secondary (copper) coil, the voltage across which is being monitored by Channel 2 of the oscilloscope.

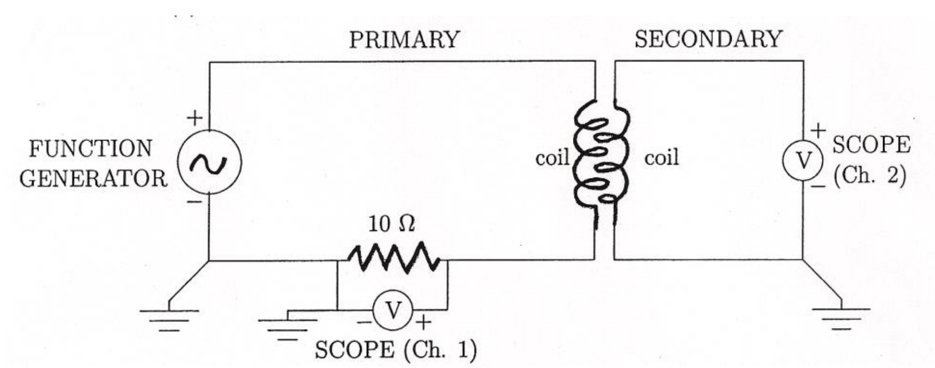



**Figure 2: Schematic of the setup of the primary and secondary circuits.**

2. Set the function generator to 40 Hz triangle wave form (you will need to select "Ramp" for the waveform and a "Symmetry" of 50%) with an amplitude of 5 $V_{pp}$.

3. Insert the rod of the primary coil as far as possible through the secondary coil. On the oscilloscope, display the primary current on Channel 1 (somewhat triangular wave form) and the secondary voltage (square wave form) on Channel 2.

Note that the slope of the Channel-1 signal is proportional to the value the Channel-2 signal. (If the slope of your Channel-1 seems to be proportional to the negative of the value of the Channel-2 signal, simply switch the leads attached to the secondary coil.)

4. Make a fairly accurate sketch of the oscilloscope display, including the time for the horizontal axis and each channel's waveform, ground level, and voltage (each label as either primary or secondary). Use large-grid graph paper, which is located at the end of the write up.

5. Choose a particular time (horizontal position on the scope screen) when the value of the secondary voltage is fairly constant.

6. Record the value of this voltage on the graph paper page.

7. Determine the slope of the (primary coil) current at the time when the secondary voltage has reached the voltage you recorded in **Step 5** by measuring the rise and run of this portion of the signal <u>and dividing the result by 10 Ω.</u> Be sure to record your values on the graph page. The ratio of the secondary voltage to the primary slope is your measured value for the mutual inductance M.

8. Change the wave shape from **triangular to square** and repeat **Steps 4--7**.

9. Change the wave shape from **square to sine** and repeat **Steps 4--7** again.

10. Calculate the percent differences of your values for "M" between:
    a. Triangle and Square
    b. Square and Sine
    c. Sine and Triangle

## 2. Self Inductance

**Equipment needed:** Computer, printer, Science Workshop Interface with voltage sensor in Channel A and current sensor in Channel B, function generator, 10-mH (nominal) inductor (labeled "103J"), one BNC-to-alligator cable.

### Procedure

1. Your inductor should be considered as an ideal inductor (with self inductance L) in series with an internal resistor R, as diagramed in **Figure 3**. This quantity is sometimes called the "parasitic" resistance of an inductor. Use an ohmmeter to determine R for your inductor. (Note that its nonzero value of L may require you to wait a few moments before its displayed value for R equilibrates to a single value.)

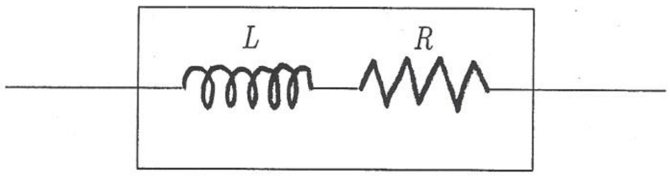



**Figure 3:** Schematic of inductor in series with resistor.

2. Construct the following circuit (See **Figure 4**) which consists of a function generator, your inductor, and DS monitoring the current through the circuit and the voltage drop across the inductor.

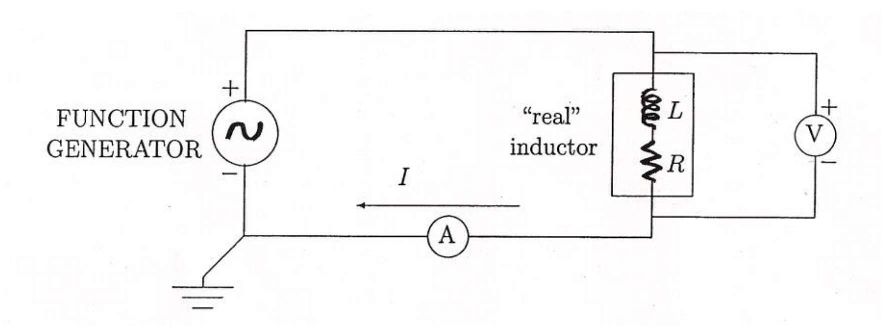



**Figure 4:** Schematic of circuit with function generator, inductor, ammeter, and voltmeter.

3. Start Data Studio and open the "inductor.ds" activity. Create graphs of I and V vs. t.

4. Turn on the function generator and set the signal to be a 200 Hz triangle wave (again, a "Ramp" waveform with 50% "Symmetry") with an amplitude of 4 $V_{pp.}$ Click *Start* to begin taking data. (The data taking will stop automatically after a fraction of a second.)

5. The DS Graph will display the Voltage across the inductor and the Current which flows through it (you will need to zoom in to see this). The current should resemble a simple triangle wave while the voltage signal will be a bit more complicated, owing to the fact that it is measuring the voltage drop ($V_{tot}$) across the series combination of the inductor ($V_L$) and internal resistor ($V_R$).

In the next step, the quantity $V_R$ (=IR) will be subtracted from $V_{tot}$, leaving the difference $V_L$. (Kirchhoff's loop rule)

6. Click on the *"Inductor Voltage"* tab in the *Data Summary* window to open up the calculator window. Change the resistance, *R*, to be the resistance that you measured. Click *Accept* in the window.

7. Drag inductor voltage from the *Data Summary* list into your graph so that it is plotted with the total Voltage. This should fairly be a "square" wave. If not, you may need to invert the wires leading to the current sensor or you entered the value of *R* incorrectly.

8. Drag the *Calculator* function derivative of current from the *Data Summary* into your graph. Note that this function should be approximately the same shape as the inductor voltage graph, owing to the fact that $V_L$ = L x dI/dt. Hence, the proportionality constant in this relationship between $V_L$ and dI/dt is the self inductance L. Rename your graph as *Graph 1* for (your last names). **Print and make sure every group member signs.**

9. Create a graph of inductor voltage vs. derivate of current.

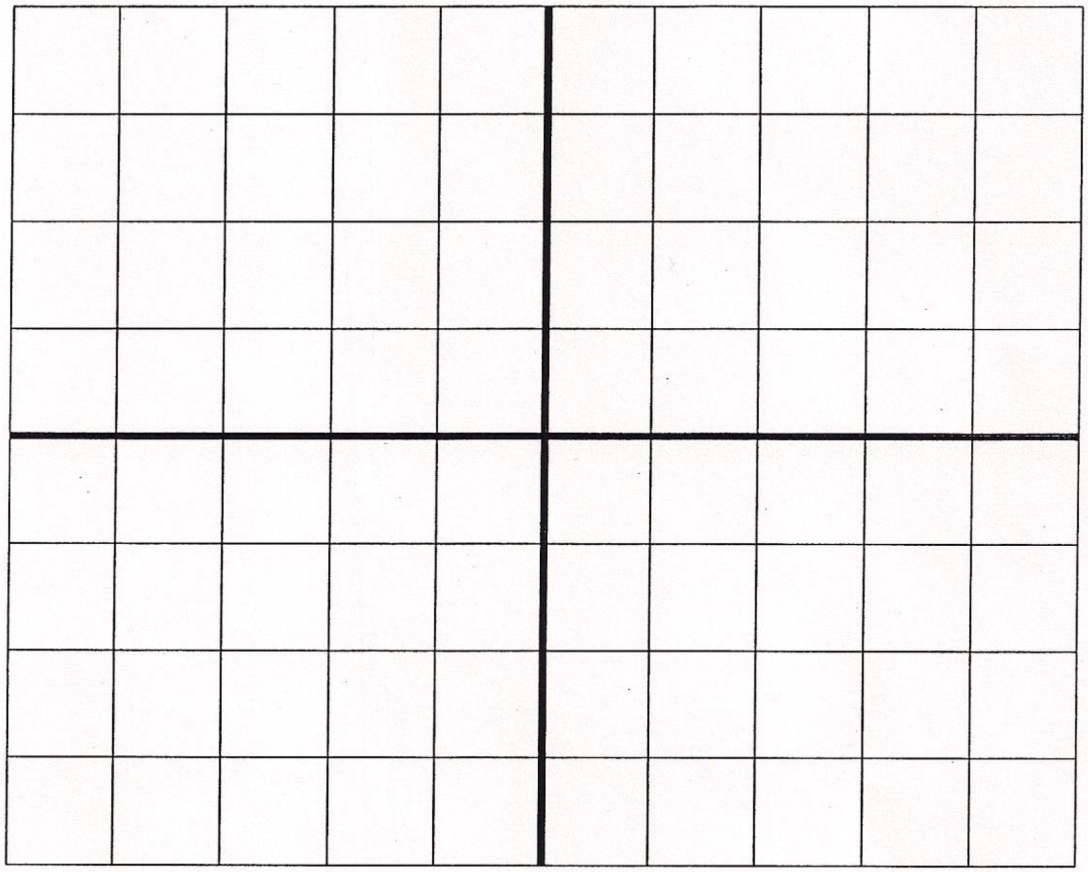
10. Note that this graph should be a straight line passing through the origin. Use DS to perform a *proportional Fit* to your data and record this (experimentally determined) value for L. Name this Fit as *Proportional Fit-Triangle*. Do so by double-clicking the Proportional Fit box and editing the upper region containing the phrase *Proportional Fit*. Change the data set's name from *Run #* to something appropriate.

11. Change the function generator wave shape from triangular to sine and record another set of data. (Recheck your graph of Voltage to ensure that its absolute value is less than one volt.) Repeat **Step 10** for the determination of L and rename the fit as *Proportional Fit-Sine*.

12. Change the wave shape from sine to square and record another set of data. Repeat **Step 10** and rename this graph as *Graph 2* for (your last names). **Print and make sure every group member signs.**

13. Using the three values you obtained for L, compare using the percent error formula for each of these values and the nominal value for the inductor.

# Grid for Sketching Oscilloscope Waveforms



voltage per division on Channel #1 =

voltage per division on Channel #2 =

time per division on horizontal axis =

shape of generator waveform:

Remember to indicate (along the right side) the positions of the grounds for Channel #1 and #2.

**Secondary Voltage ____________ at time t = ________________**

**Slope of Primary <u>current</u> at that time: ______________________**

**Ratio, M, of secondary voltage to slope of primary current:**

# Grid for Sketching Oscilloscope Waveforms

voltage per division on Channel #1 =

voltage per division on Channel #2 =

time per division on horizontal axis =

shape of generator waveform:

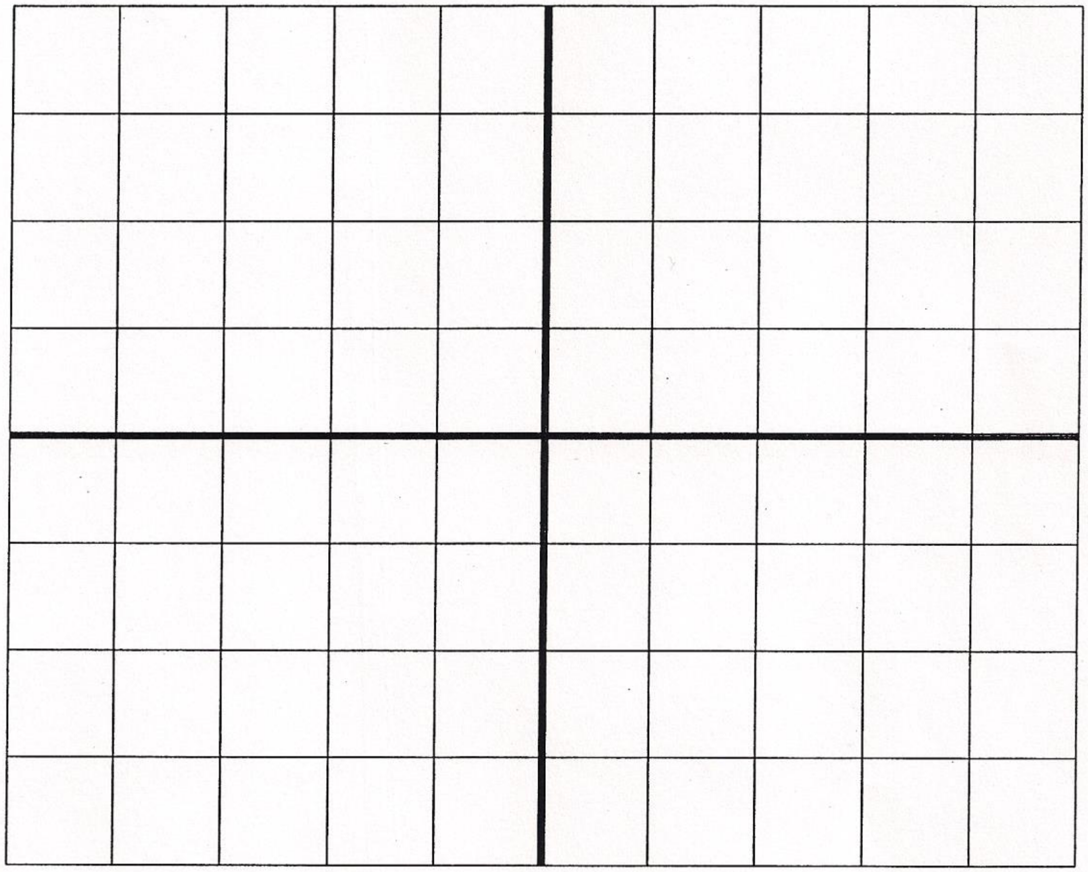
Remember to indicate (along the right side) the positions of the grounds for Channel #1 and #2.

**Secondary Voltage ____________ at time t = ________________**

**Slope of Primary <u>current</u> at that time: ______________________**

**Ratio, M, of secondary voltage to slope of primary current:**

# Grid for Sketching Oscilloscope Waveforms



voltage per division on Channel #1 =

voltage per division on Channel #2 =

time per division on horizontal axis =

shape of generator waveform:

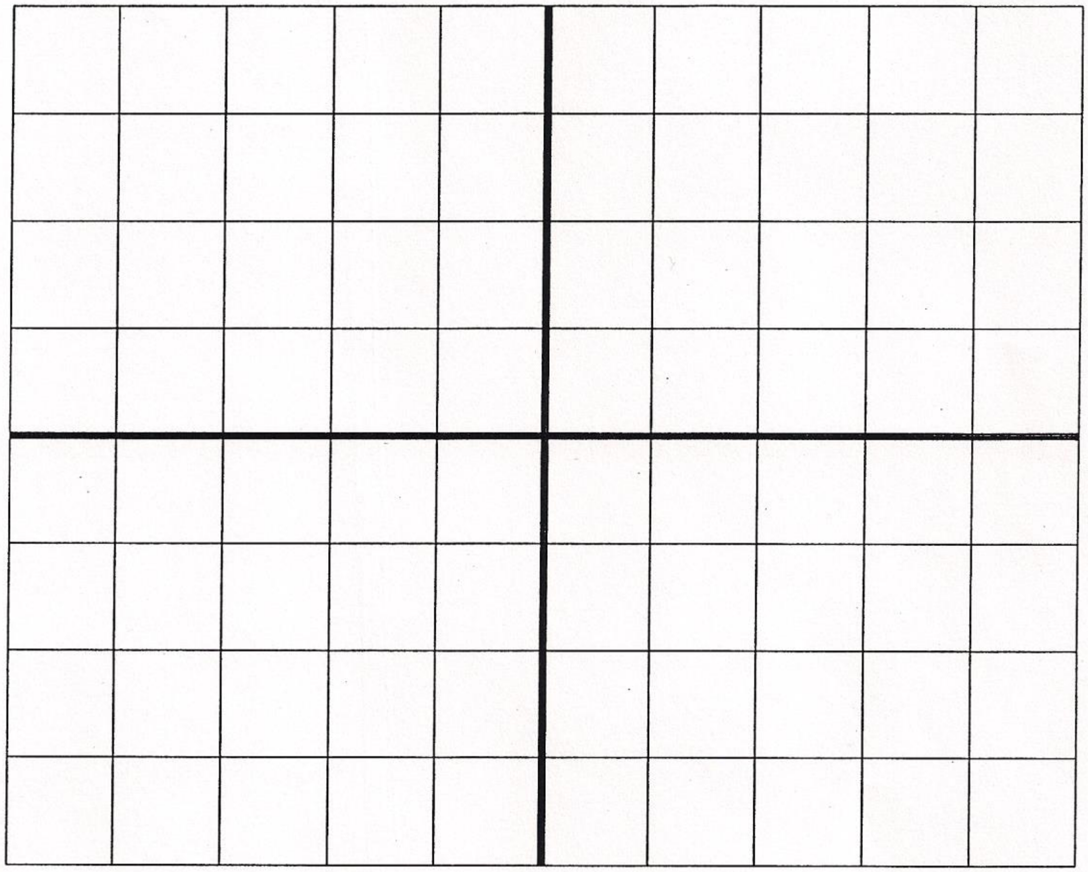
Remember to indicate (along the right side) the positions of the grounds for Channel #1 and #2.

**Secondary Voltage ____________ at time t = ________________**

**Slope of Primary <u>current</u> at that time: ______________________**

**Ratio, M, of secondary voltage to slope of primary current:**

# Grid for Sketching Oscilloscope Waveforms



voltage per division on Channel #1 =

voltage per division on Channel #2 =

time per division on horizontal axis =

shape of generator waveform:

Remember to indicate (along the right side) the positions of the grounds for Channel #1 and #2.

**Secondary Voltage _____________ at time t = _________________**

**Slope of Primary current at that time: _______________________**

**Ratio, M, of secondary voltage to slope of primary current:**