**Physics 41, Winter 1998**
**Lab 1 - The Current Balance**

## Theory

Consider a point at a perpendicular distance d from a long straight wire carrying a current I as shown in figure 1. If the wire is very long compared with the distance d , then the magnitude of the B field is given by the expression

$$B = \frac{\mu_o I}{2 \pi d} \qquad (1)$$

where $\mu_o$ is a constant called the magnetic permeability of a vacuum ( $\mu_o$ = 4 x $10^{-7}$ weber/amp-m). This expression was deduced from experimental observations by Biot and Savart and is known as the Biot-Savart law. Unlike the electric field around a charged wire, which is radial, the magnetic field lines are circles concentric with the wire in planes perpendicular to it.

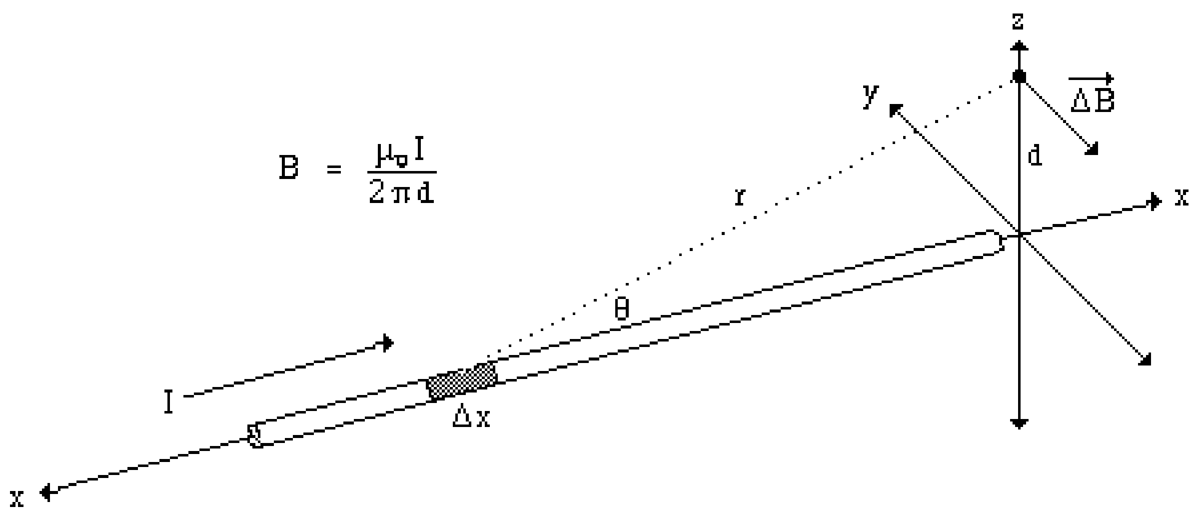
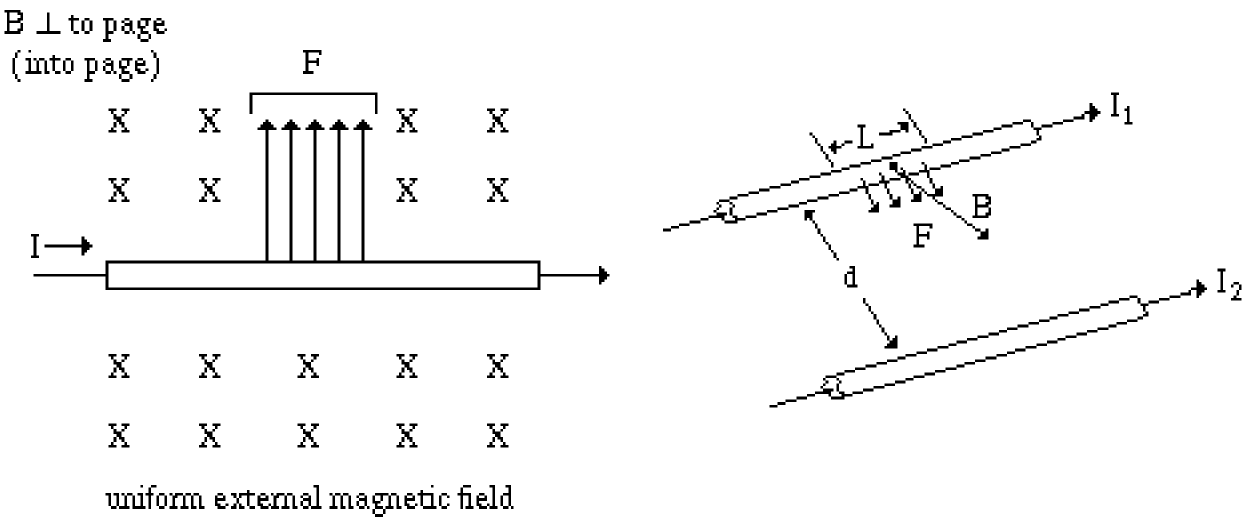



Figure 1

When a current carrying conductor lies in an external magnetic field which is perpendicular to the wire (as in figure 2a), the electrons in the wire experience a magnetic force perpendicular to both the external magnetic field and the wire. These forces are transmitted to the material of the conductor, and hence the conductor as a whole experiences the force. The magnitude of the force (in newtons) is given by the expression

$$F = I B L \qquad (2)$$

where I is the current in amps, B is the magnetic field strength in webers and L is the length of a conductor in meters. The right hand screw rule can be used to find the direction of the force.




(a) (b)

Figure 2

Consider two long straight parallel conductors separated by a distance d and carrying currents $I_1$ and $I_2$ which are flowing in the same direction, as shown in figure 2b. Each conductor will lie in the magnetic field of the other wire and both wires will experience a force. The force on a length L of the upper conductor is found by substituting into equation (2) for B from equation (1). This yields

$$F = I\,B\,L = \frac{\mu_o L\, I_1 I_2}{2\,\pi d} \quad . \qquad (3)$$

Use of the right hand rule gives the direction of the force to be down. The lower conductor will feel a force that is equal in magnitude but opposite in direction. If the direction of either current is reversed, the forces also reverse. Two parallel conductors carrying currents in opposite direction will repel each other.

The fact that two straight parallel conductors exert forces of attraction or repulsion on one another is the basis of the definition of the ampere in the MKS system. One ampere is defined as:

> "One ampere is that unvarying current which, if present in each of two parallel conductors of infinite length and one meter apart in empty space, causes each conductor to experience a force of exactly 2 x $10^{-7}$ newton per meter of length.

## References


Reitz, Milford and Christy, *Foundations of Electromagnetic Theory*, 4th ed. pp. 193-200, 574-576.

## Experimental Purpose

The purpose of this lab is to test the validity of equation (3). If equation (3) is valid, the following will be true:

a. a plot of F vs $I^2$ will be a straight line with y-intercept equal to zero; and

b. from the slope of the graph a value of $\mu_o$ can be computed and will equal the accepted value of $12.57 \times 10^{-7}$ webers/amp-m.

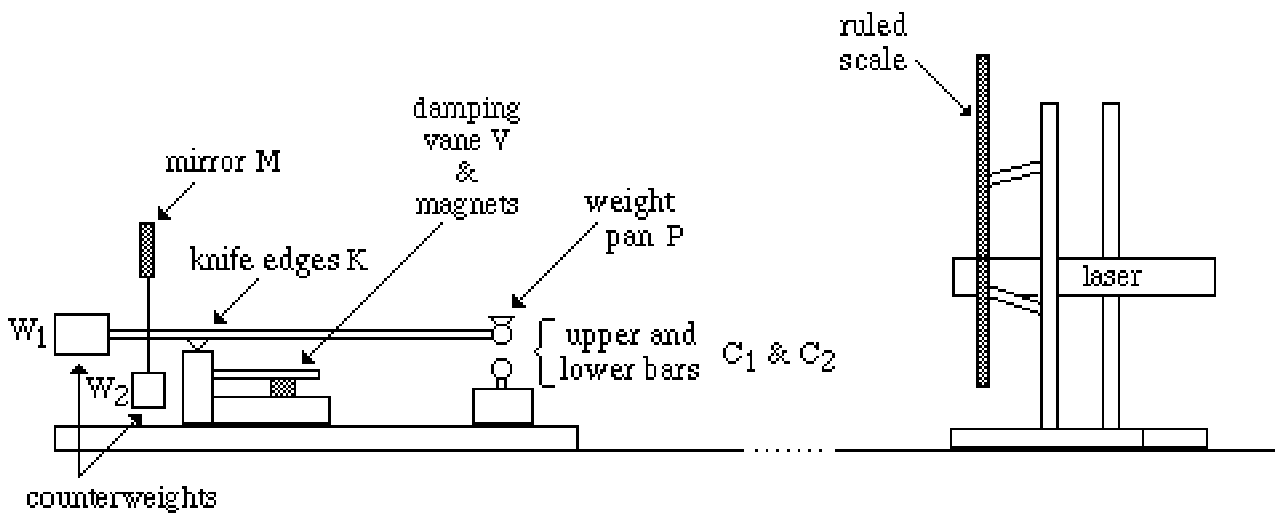
## Apparatus

A schematic drawing of the apparatus to be used is shown in figure 3a on the next page. Current flows along the fixed straight conductor $C_1$ and back through the parallel conductor $C_2$. $C_2$ is part of a balance arm supported by the knife edges, the weight of the conductor being balanced by the adjustable rear counterweight $W_1$. The beam can be lifted off the knife edges by a beam lift (not shown in the diagram). The position of the lower counterweight $W_2$ determines the sensitivity of the balance: i.e. the deflection per unit force. The repulsive force due to the current is balanced by weights placed in the pan P, attached to $C_2$. Oscillations of the beam are damped out by eddy currents in the metal vane V which moves in the field of a permanent magnet. The conductors can be aligned by loosening/tightening four thumbscrews (not shown in diagram). Changes in tilt of the balance are detected by reflecting a laser beam from the mirror M. The reflected beam falls on a ruled scale some distance (~2m) away. The laser intensity is reduced to a safe level by a filter which covers the output. DO NOT REMOVE THIS FILTER! **Never** look directly into the laser beam or look directly into the beam reflected from the mirror on the apparatus.

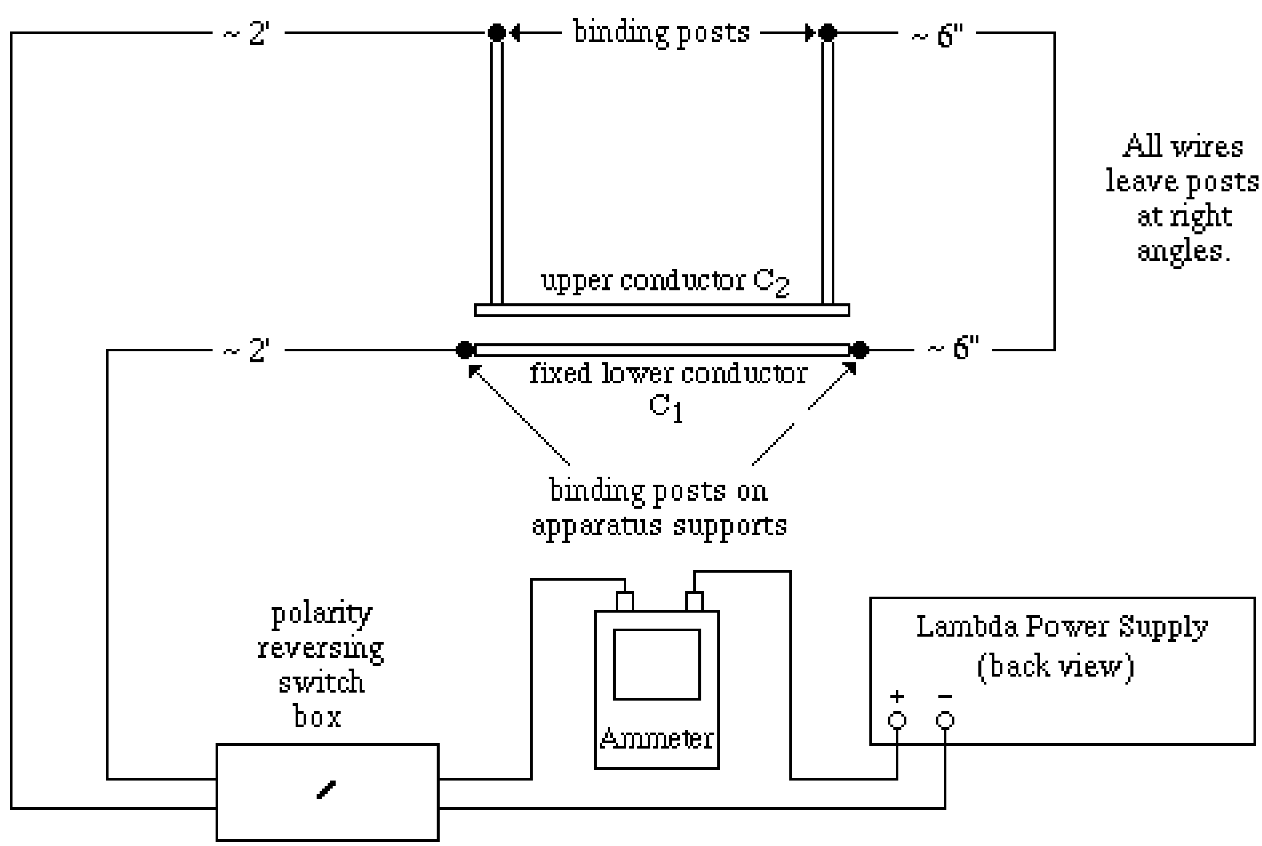
The electrical circuit is shown schematically in figure 3b. (Note: This is not a plane view. $C_2$ is in fact directly above $C_1$). Current from the power supply is measured with the precision ammeter and passes through the conductors $C_1$ and $C_2$. The direction of the current can be reversed by the polarity reversing box. The wires connected to the binding post on the current balance have been arranged in such a way that the magnetic forces that they induce on $C_2$ and its supporting conductors are horizontal rather than vertical, since it's a vertical force that you're going to measure. The power supply itself generates a magnetic field, and is located as far from the balance as practical. (Why are these considerations important?)

The power supply has two controls: "voltage" and "current" limitation, each with coarse and fine adjustment.

To prevent error in reading the ammeter due to parallax, the ammeter has a mirror behind the needle. Use it. The meter should be on the 25A scale: check this. Check the zero, and if necessary adjust it, before you make measurements.


ruled scale
damping vane V & magnets
mirror M
weight pan P
knife edges K
laser
$W_1$
upper and lower bars
$C_1$ & $C_2$
$W_2$
counterweights

(a)


~ 2'
binding posts
~ 6"
All wires leave posts at right angles.
upper conductor $C_2$
~ 2'
~ 6"
fixed lower conductor $C_1$
binding posts on apparatus supports
polarity reversing switch box
Lambda Power Supply (back view)
+
−
Ammeter

(b)

Figure 3

## Procedure

1. Initial Setup.

**CAUTION: Always be very gentle with the balance. The knife edges are easily damaged and the conductors are easily bent. In particular, never drag the knife edges across their support. Use the beam lift when aligning the conductors.**

a. Adjust $C_2$ so that it is parallel to and vertically above $C_1$. To align the bars and to examine them for straightness, place a small coin on the weight pan to bring the bars into contact, but without distortion. Thumb screws on each front post permit either end of the lower bar to be raised or lowered. Similar thumb screws on each block at the rear permit either end of the upper bar to be moved forward or backward. The bars should be aligned as accurately as can be determined by the unaided eye when viewed from the front and from the top. When viewed from the front with a white sheet of paper behind the bars, the two bars may appear to be slightly lacking in straightness. If this is very serious, see Jan Largent (220 Wilder). Do not try to straighten the bars yourself. It is almost impossible to get them so straight that no light may be seen between them, but perfect straightness is not essential to the attainment of good quantitative results.

b. Adjust the apparatus until the period of oscillation of the upper bar is 1-2 seconds and the time it takes for the upper conductor to stop moving is 10-15 seconds. Start this step by gently putting the upper conductor into motion and measuring these parameters. In most cases, you will find the apparatus already adjusted to meet the stated conditions. If it is not, use counterpoise $W_2$ to adjust the period of oscillation and change the separation of the poles of the damping magnets adjust the time it takes for $C_2$ to come to rest.

c. Adjust the position of the laser and the mirror tilt until the laser beam strikes the mirror and reflects onto the ruled portion of the scale. The beam from the laser is rectangular in shape. Position measurements using the ruled scale are much easier to make if the long axis of the beam is parallel to the lines on the ruled scale. If the long axis is not parallel to the lines on the scale, simply rotate the laser in its holder until this condition is met. Gently put the upper conductor into motion and ensure that the beam remains aligned with the ruled scale as it oscillates. Gently place a coin on the pan and record the laser beam position on the ruled scale. Wait a minute or two to check that the spot is steady. If it drifts, find out why. Probably the laser is inadequately secured. Remove the coin and, without disturbing the alignment, put a small piece of electrical tape on each end of the fixed conductor and at the center position under the pan so that the conductors cannot touch. You will have to remove this tape later, without disturbing the alignment, so don't make too permanent a job of it.

d. Check for freedom of movement of the oscillating conductor. With $C_2$ at rest, record the position of the laser beam on the ruled scale. Gently cause the upper bar to oscillate.

When it stops again, record the rest position. If it deviates from the first observation, the knife-edges may not be clean, the base or table may be unsteady, or the balance or telescope may have been jarred. Check the equipment again and repeat this step until the two scale reading are the same.

e. Set the controls on the power supply so only the current control needs to be used to adjust the current in the conductors. Turn the coarse (inner portion of control) and fine (outer portion of control) current control knobs on the power supply fully counterclockwise. Turn the coarse voltage control a half turn clockwise. This will ensure that the voltage control is inoperative in this experiment, and you can then control the current with the right hand knobs alone.

This completes the initial adjustments.

2. Data Taking.

**CAUTION: Do NOT under any circumstances touch the apparatus when the power supply is providing current or allow the bars to touch. The former will seriously damage you and the latter will seriously damage the equipment.**

a. Adjust the position of the of the upper conductor until it is approximately one millimeter above the lower bar when it is at rest. Use $W_1$ to adjust the equilibrium separation of the two bars. Once this adjustment has been completes, place a small piece of electrical tape at the three positions on the lower bar.

b. Calculate the separation d of the conductors. The separation of the two bars at equilibrium is determined as follows. Start by using the 2-meter stick to carefully measure the distance b between the mirror and the scale.

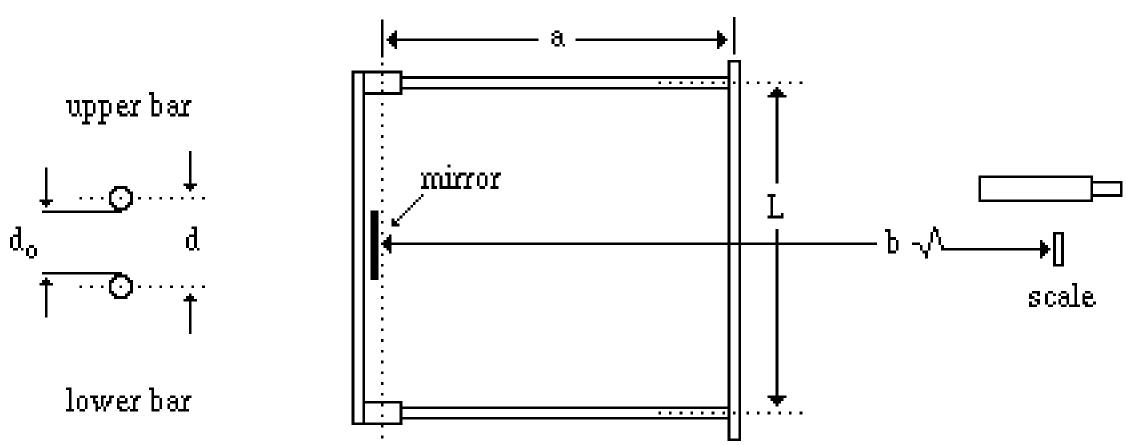



Figure 4

Note the scale reading at equilibrium, depress the upper bar (by placing a coin on the scale pan) until it is in contact with the lower bar, and take a new scale reading. Simple geometry will show that the separation is

$$d_o = \frac{D\,a}{2\,b}$$

where D is the difference in readings, a is the mean distance from knife-edge to bar, and b is the distance from mirror to scale. Center to center distance d is obtained by adding the diameter of rods to $d_o$. In this apparatus,

a = 0.2135 (± 0.0005) m
L = 0.2650 (± 0.0005) m
diameter of rod = 3.180 (±0.005) mm

c. Make a series of F vs I measurements. Record the rest position of the laser beam on the ruled scale. Using forceps, place a 30 mg mass on the pan. Turn on the power supply and adjust the current to bring the laser beam back to its rest position. The repulsive magnetic force is then equal to the weight added. Reverse the current and repeat. By taking the average of the two values of the current you correct for the force on the conductor due the earth's and other stray magnetic fields. Repeat, increasing the weight by successive 30 mg increments, until the limit of the power supply (15A) is reached.

Since $I_1 = I_2 = I$ in (3), where I is the average current in the two directions, a plot of force F vs $I^2$ should be a straight line. Make the plot as you take the data. Does it go through the origin? Find the slope and thus deduce $\mu_o$. Don't forget that d in (3) is the distance between the centers of the conductors.

When you've finished, recheck the beam position for zero weight and current. If it has changed by a small amount (not more than 2 mm), correct your data on the assumption that the drift has been linear in time. To do this you will need to calibrate the scale in terms of weight on the scale: since the correction is small a rough calibration is sufficient. If the drift is larger than ~2 mm, find and eliminate its cause and repeat the experiment.

Repeat the experiment for at least two larger separations of the conductors, going up to about 1 cm. You will probably find that as the separation increases your results get less accurate. Why is this? Make an estimate of the systematic errors in this experiment.

When you have finished, remove the tape CAREFULLY and recheck the zero position of the laser spot. If necessary, correct your values of d on the assumption of linear zero drift.

## Lab Report

Your lab report should be a record of what you did in the lab. It should include a short explanation of what you were trying to do, any deviations from the stated procedure, all raw data, and any conclusions your can draw from the data. Also include the following:

a. a plot of $F$ vs $I^2$ for each different equilibrium setting;

b. a computation of $\mu_o$ from the slope of the graph of the $F$ vs $I^2$ graph and equation (3); and

c. a computation of the speed of light from the experimental values of $\varepsilon_o$ and $\mu_o$ .

Other questions you may wish to consider are:

How does the lower counterweight ($W_2$) controls the sensitivity of the balance?

How does reversing the current and averaging the result eliminate the error due to the earth's magnetic field?

Show that the force (due to the current in $C_1$) on the sides of the frame which supply $C_2$ with current is horizontal and therefore does not introduce error into the measurement if $C_1$ is infinitely long.