# 13 Hysteresis & the Magnetisation of Iron

## 13.1 Summary

Hysteresis in a physical system arises when the internal state of the system depends on the past history of external forces applied, i.e., the system does not return to its lowest-energy or equilibrium state in the absence of an applied force. This happens during the magnetisation of ferromagnetic material in an external field. In this experiment magnetic hysteresis in iron is explored as a function of the size of the magnetising current, and the energy dissipation due to hysteresis losses is explored.

### Objectives

1. To explore a physical system that demonstrates *hysteresis*: the magnetic response of the sample to a magnetising current depends on the previous magnetisation of the material.
2. To illustrate the relation between the magnetic field $\vec{B}$, magnetisation $\vec{M}$, and auxiliary field $\vec{H}$ in a sample of ferromagnetic material, and to estimate the permeability of iron.
3. To gain familiarity constructing special-purpose circuits and to develop experience working with operational amplifiers ("op-amps").

### Equipment

An iron torus wound with several hundred turns of wire (the *primary coil*), mounted on a board with plugs for circuit connections; a transformer used for a low-voltage AC power supply; a DC power supply; heavy duty rheostats of ≈7.5 Ω resistance; an electrolytic, polarised capacitor; a 5 kΩ potentiometer; integrating amplifier circuit in a black box, plus its DC power supply; an oscilloscope or voltmeter; a computer with data logging software (called *Status*) accepting two voltage inputs; double and single throw switches, and all the leads necessary to connect everything up.

### Principal Data Taken

1. Voltage vs. time to record magnitude of the auxiliary field $\vec{H}$ over a given time interval.
2. Voltage vs. time to record the integrated induced voltage over the same time interval.
3. Associated measurements of currents, voltages, and resistances; dimension and number of turns in the primary and secondary coils around the iron sample.

### Things to Watch Out For

- There are high currents involved in this experiment (up to ≈3–4 A), which can be hazardous to equipment. Leave switches open (inactive) when not actively acquiring data. If in doubt about the safety of a given circuit, consult with your demonstrator before flipping the switch.

- The electrolytic capacitor has an intrinsic polarity; if a current is applied with the revese polarity, the unit will be destroyed and may rapidly release gas, with the potential to produce a hazardous or explosive condition (the dielectric dissolves rapidly into the electrolyte when current flows in the wrong direction). **Do not allow any current to flow into capacitor with the negative terminal at a higher voltage than the positive one!!**.
- The data acquisition cards have a maximum voltage response. If the input levels to the data logger go off scale, you will get garbage results from the analysis software. A symptom of this is voltages that are pegged at the top of the scale with a flat profile instead of a smooth curve. If this happens, make changes to your circuit to lower the voltage and repeat the experiment.
- The op-amp integrating amplifier (black box) can be sensitive to stray voltages. All power supplies, inputs, and meters connected to the black box must be connected to a common earth or the device may function in unexpected ways or not at all, giving misleading results. Do not apply an input voltage to the amplifier until its own power supply has been turned on. The shape of your hysteresis loops may be quite distorted if insufficient care in nulling the integrator drift is taken.

## 13.2 Theoretical Background

The term hysteresis refers to the situation where the response of an object or system to an applied force depends not just on the current state of the system, but on previous applications of the force. Common examples include the response of a mechanical system to a push or a pull where there is backlash in a gear or slack in a cable. Hysteresis is often associated with energy losses (e.g., friction) in a system, because it takes more energy to take the system from state $B \rightarrow A$ than it originally took to go from $A \rightarrow B$.

Hysteresis is observed in certain types of materials in their response to magnetic fields. Ferromagnetic and paramagnetic materials differ in their behaviour after the application and removal of an external magnetic field. In a paramagnetic material, the magnetization drops to zero with an exponential time dependence, whereas in a ferromagnet the magnetization drops to some characteristic value known as the remanent magnetization[2].

For a ferromagnet, the magnetization doesn't depend on the external magnetic field alone, but on the magnetic history of the object. As well as accounting for the creation of "permanent" magnets, this is a prime example of hysteresis in action. While permanent magnets are one of the most familiar examples of magnetism, they are quite complex to explain.

In any material, the electron spins and orbits can respond to an applied magnetic field $\vec{B}$, giving rise to a weak temporary magnetization, but random, thermal motions reassert themselves when the external field is removed. However, in feromagnetic materials, the motions of electrons around individual atoms are highly correlated with those around nearby atoms, so that the magnetic moments of individual atoms reinforce one another in a self-consistent way, and can become both long-lasting and detectable on macroscopic scales. Simply removing the external field from a ferromagnet does not demagnetize the sample; rather, a negative field must be applied in order to flip the system back to its original state.

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[2] In an intermediate class of materials known as "spin glasses", the magnetization drops quickly to the remanent value and then slowly and irregularly either to zero or some very small residual value.

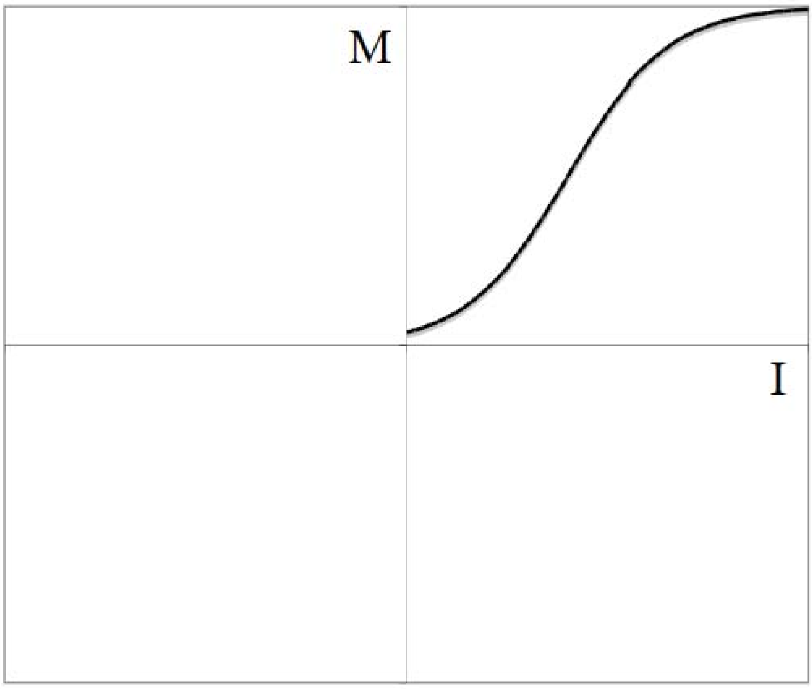

Figure 13.1: Magnetization curve for a ferromagnetic material under the influence of an external current I. As I increases, so too does $\vec{M}$, until magnetic saturation is approached and the slope of the curve levels off. Once $\vec{M_{max}}$ is reached, further increase in I produces no additional magnetization.

The net magnetic moment per unit volume of the material is referred to as the magnetization $\vec{M}$, which has units of amperes per metre ($\mathrm{Am}^{-1}$). A volume of material in which the atoms are magnetically aligned is referred to as a domain. A typical chunk of iron contains many magnetic domains. If the domains are randomly oriented, then the total magnetization from one region will tend to be cancelled out by its neighbours, and $\vec{M} \approx 0$. If all of the domains are aligned with each other, then the magnetization is a maximum, $\vec{M} = \vec{M_{max}}$, and the object is said to be magnetically saturated.

**Magnetization:** A ferromagnet can be magnetized by applying an external magnetic field. The applied field causes domains to align with each other, up to the saturation point (or close to it: true saturation can require fields in excess of 1 tesla). A convenient way to apply a magnetic field to an object is to run an electric current through it or around it; a magnetic field will then be created by induction. A solenoidal wire wrapped around a piece of ferromagnetic material is a very efficient way to magnetize the sample because the fields created by the current in each loop adds together to produce a large total field. For a given material we can learn about its magnetic properties by plotting the magnetization curve of $\vec{M}$ vs. I. An example of a magnetization curve is shown in Figure 13.1.

The total magnetic field $\vec{B}$ is the sum of the component due to the current in the wire (the "free current"), plus the component due to the magnetization (by analogy, the "bound current"). Mathematically, we have

$$\vec{B} = \mu_0(\vec{M} + \vec{H}) \tag{13.1}$$

where $\mu_0$ is the permeability of free space, $4\pi\times10^{-7}$ henries per metre, and $\vec{H}$ is known as the auxiliary field. In a vacuum, $\vec{B}$ and $\vec{H}$ are equal. $\vec{H}$ is the component of the field due to the free, flowing current I around and within the area where $\vec{B}$ is to be measured; in magnetic materials the magnetization $\vec{M}$ must be added in order to find the total field. Be aware that many references refer to $\vec{H}$ as the magnetic field, but this is an unfortunate choice that has led to much confusion (since the total field is clearly $\vec{B}$, and $\vec{H}$ is only one component of the total). Be aware of the ambiguity when you peruse references for help!

**Demagnetization:** A ferromagnet can be demagnetized by removing the alignments between magnetic domains. One way to do this would be to heat the material until the random thermal motions of the atoms have enough energy to overcome the magnetic forces aligning the domains. The temperature at which this occurs is known as the "Curie temperature" ($T_C$); for iron, $T_C$ = 770 °C. Another way to demagnetize a ferromagnet is to apply a decreasing alternating current to the sample in what is sometimes called a "washing machine" circuit. This method repeatedly switches the direction of the free current, eventually randomising the orientation of the individual magnetic dipole moments of the atoms in the material and resulting in a net magnetization $\vec{M} = 0$. This is the technique you will use in this exercise to make sure you are starting your measurements with a demagnetized sample.

The sample used here is iron in the form of a toroid, around which is wound a primary coil of 480 turns (check the label on the sample or count the turns to confirm this number). The toroid is actually a slice cut from a cast iron water pipe. By measuring the current I in the primary, you will determine the resulting value of $\vec{H}$ in the toroid, using the relation:

$$\vec{H} = \frac{n_p I}{2\pi r_m} \tag{13.2}$$

where $n_p$ is the number of turns in the coil and $r_m$ is the mean radius of the coil. It is easy to produce a voltage proportional to I and feed this into the data logger, allowing you to record $\vec{H}$ for analysis.

**Discuss the following in your report:**

1. What is the relationship between $\vec{B}$ and the induced voltage $\mathcal{E}$ generated in the secondary coil? (Review Faraday's law of induction for help). When exposed to an alternating currrent for some amount time dt, there will be a definite relationship between $\int \mathcal{E}$dt and $\vec{B}$; derive this relationship where the relevant area is that of one turn of the secondary coil.

2. Using equation 13.1, derive an expression relating the permeability of the material, $\mu$, to the measured quantities $\vec{B}$ and $\vec{H}$. In the limit where $\vec{M}$ is small, what does this suggest about how you can measure $\mu$ from your magnetization curve?

## 13.3 Procedure

A hysteresis loop for a ferromagnetic material is the graph showing the relation between the magnetic field $\vec{B}$ and the auxiliary field $\vec{H}$. A graph of these loops will be the main observational result of this lab. The loop will resemble Figure 13.1, but with all four quadrants of the graph filled in as the current and magnetization change. The hysteresis loop should be plotted in units of $\vec{B}$ vs. $\vec{H}$, but they will appear similar in $\vec{M}$ vs. I space. The hysteresis loop for a material contains a large amount of information about its magnetic properties, including the permeability and the remanent magnetism of a ferromagnet.

You will need to measure the auxiliary magnetic field $\vec{H}$ created by a current I through the primary coils wrapped around the ferromagnetic toroid, and you will measure the magnetic field $\vec{B}$ in the iron by using the relationship between the magnetic field and the change in current dI/dt in a secondary coil (wrapped around the same axis as the primary). From these data you will explore the shape of the hysteresis loops for various values of the current amplitude, and measure the permeability as a function of $\vec{H}$ for the toroid.

This requires the construction of two circuits: one to demagnetize the toroid, and another circuit to take the sample around the hysteresis loop by applying a variable current, using an integrating amplifier to enhance and record the signal due to the dI/dt term.

While the hysteresis of a ferromagnet is a fundamental datum, obtaining quantitative measurements takes some planning. The basic data to be logged are two voltages, one proportional to $\vec{B}$ and the other to $\vec{H}$. The hysteresis curve is obtained by measuring the inductive response of a ferromagnetic sample to an applied current. We must be sure the sample is demagnetized to begin with in order to obtain useful results. The induced magnetic field is small and proportional to an integral, making it complicated to directly measure.

Therefore no fewer than three different circuits are going to be used to run the experiment and collect the data. Fortunately one of them is trivial to build, and we have supplied another in a black box for you to use.

A) **Integrating amplifier:** We could use a recording meter to take a time series of voltage measurements, and integrate by calculating the area under the curve, but it will save work in the long run if we use a circuit to simultaneously amplify the signal and integrate over the duration of the data-taking.

   There is an integrating circuit provided in the “black box” with the experiment. The black box has one open side so you can see and trace its workings, and read the labels on the connections, printed on the circuit board. The board is arranged as shown in Figure 13.2, and the circuit diagram is shown schematically in Figure 13.3. It is bult around an LM301 integrated circuit chip (the triangle in Fig. 13.3). This chip is a very common, cheap, and powerful device known as an operational amplifier or “op-amp”. For more information on the op-amp see Appendix.

   (a) Connect up the amplifier to its DC power supply and a multimeter or oscilloscope. The $V_+$ and $V_-$ ports should be connected to the appropriate channels of the power supply, with the corresponding correct polarity. Both channels of the power supply should be set to the same voltage, in the range ≈10–15 V. When you are ready to begin, the two inputs to the amplifier will be connected across one of the secondary coils of the ferromagnetic ring; there are a few different ports to choose from, labelled by number of turns. Choose the largest span of turns available; it will be between 35–50 depending on which toroid you are using. However, don’t connect the secondary to the amplifier yet, some tune-up will be required.

   (b) Power up the amplifier and earth both input leads. There should be no voltage difference between them, but you will almost certainly see the output voltage begin to drift up or down, perhaps quite rapidly. Use the screwdriver provided to adjust the

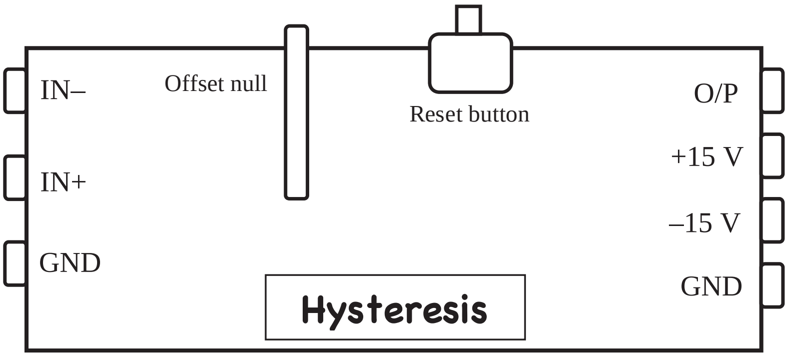

Figure 13.2: Sketch of the integrating amplifier. Connect the two channels of the DC power supply to +15V and −15V. Connect the secondary coil around the iron ring to IN+ and IN− to create the input voltage. The amplified, integrated voltage will be read from the output (O/P) port, which should lead to the data logger. Make sure to earth the circuit where indicated (GND).

offset null voltage on the side of the black box amplifier. With care, you will be able to slow the voltage drift to zero. If the drift rate *cannot* be cancelled out, it will be necessary to add another potentiometer to the circuit to act as a fine control; ask your demonstrator if you are unsure how to do this. In order to get a hysteresis loop that closes (making for a nice legible graph), it is essential that the voltage drift over a roughly 15-20 second interval should be negligible compared to the change in $\int \varepsilon \mathrm{d}t$ produced by the changes in $\vec{B}$.

(c) Make an order of magnitude calculation of the voltage change expected from a trip around a single hysteresis loop, by estimating the change in voltage expected if you change the input current from 0 to 1 ampere, assuming that the relative permeability of iron is about 350 and that Equation 13.3 holds true. Try to reduce the voltage drift to no more than 1% of this estimate over 30 seconds, if possible. The amplifier output will be proportional to $\vec{B}$.

(d) The amplifier output should be fed into the B channel of the data logger.

B) **Adjustable High-Current Circuit:** You will need to design and construct a circuit to take the iron sample around a hysteresis loop. A DC power supply is used for this, and you can take advantage of the potential divider theorem to devise a control for the amount of current flowing through the primary coil around the toroid. That is, you must be able to start with the current at exactly zero, increase it steadily to some chosen maximum value, $\mathrm{I}_{max} \approx$ 2–3 A , and then reduce it steadily to zero again. You must then be able to reverse the polarity of the current, and repeat the process, increasing its magnitude to the same $\mathrm{I}_{max}$ as before and finally returning to zero.

There are numerous potentiometers and switches available for use in constructing this circuit. Make use of the potential divider theorem in your work, and use a meter to confirm the resistance across the primary coil (it should be in the ballpark of 3Ω). It will be extremely convenient to use a double-pole, double-throw switch as a crossover, reversing the direction of current flow downstream of the switch with respect to the power supply. Ensure that no current greater than 4 A will flow in any loop (otherwise the wire leads may heat up dangerously), and design in a way of controlling the value of $\mathrm{I}_{max}$ so that smaller hysteresis loops can be obtained. It may be extremely helpful to start by drawing out the circuit diagram in advance before you connect any wires. Consult early and often with your

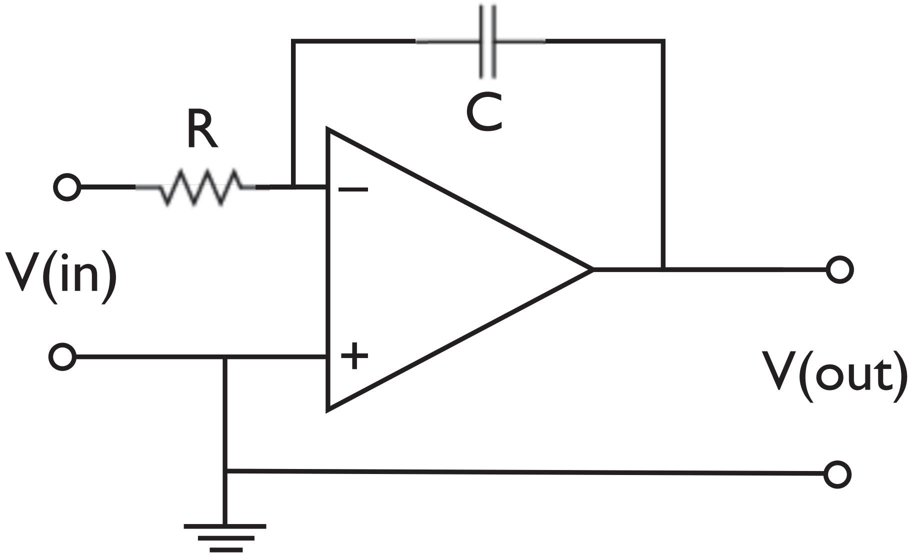

Figure 13.3: Schematic of an integrating amplifier that accepts input voltage V$_{in}$, amplifies it by a factor 1/RC, and shows the integrated output across V$_{out}$. The power supply, reset button, drift adjustment, and additional resistive and capacitive components that protect the circuit are not shown.

demonstrator.

The equipment includes wire-round rheostats. The wire is wound very coarsely, which results in discrete jumps in voltage as the sliding connector moves from one turn to the next. This is a nuisance, but the jumps can be smoothed out by using a very large electrolytic capacitor. **Note: the capacitor has intrinsic positive and negative sides; it will be destroyed if it is reverse-biased, and may explode.** Before you hook up the capacitor, discuss with your demonstrator where it should go to prevent this. *Check with your demonstrator before switching on the circuit to make sure the capacitor is hooked up the right way round.*

**Note:** Log the voltage to channel A of the data-logger. If the expected voltage output from the high-current circuit connected across the primary coil exceeds maximum voltage accepted by the data logger, it will saturate. Think about how to prevent this. Test your circuit with the output connected across a multimeter or oscilloscope before connecting it up to the computer.

(a) When the reversible high-current circuit is connect up across the primary coil, its output will be proportional to $\vec{H}$. Feed this output to the X input of the data logger on the computer.

(b) Include a schematic circuit diagram of your high-current circuit in your written report.

C) **Demagnetising Circuit:** Also called a degausser, or "washing machine" circuit. This circuit takes advantage of the potential divider theorem to vary the current through the primary using an AC power supply. The 12 V, 50 Hz power supply provided will degauss the iron toroid very effectively if connected across the primary using a 7.5 Ω potentiometer. Start with the slider in the middle of the range, and gradually decrease the current through the primary coil over a period of several seconds. Calculate approximately what positioning of the potentiometer will limit the current through the primary to about 3 A. As you sweep the slider on the potentiometer, reducing the current amplitude, the AC current takes the primary through 50 hysteresis loops each second, each one smaller than the last. When the current reaches zero, the sample should be fully demagnetized.

(a) Include a schematic circuit diagram of the washing machine circuit in your written report.

D) **Data Recording:** Now you are ready to take a few practice trips around a hysteresis loop. Don't try to record data yet; it's best to make sure things are working first. Connect a multimater set to measure a DC voltage to the output of the amplifier and see what happens as you increase the current from 0 to some $\mathrm{I}_{max}$, reduce it to 0, and then flip the polarity, taking the circuit from 0 to $-\mathrm{I}_{max}$ and back. You could also connect X and Y voltages to an oscilloscope with its time-base switched off. You should see the spot trace out a hysteresis loop on the screen.

Now have a look at the data logger. We are using PicoLogger with channels A and B. The software is located on the desktop of the PC. Activate the channels and set the maximum voltage and sampling rate suitable for the experiment. You should be able to see the live voltages for each channel. You can also choose a graph view. You may wish to do a practice run and familiarize yourself with recording, saving and downloading the data.

(a) **Demagnetise the Toroid:** Connect up the primary coil to the washing machine, with a maximum current $\mathrm{I}_{RMS} \approx 3$ A. Slowly reduce the current to zero, driving the magnetization to zero as described above.

(b) Connect the high-current circuit to the primary and the integrator to the secondary coil and re-check that the output isn't drifting. Take the iron around 2–3 loops with a relatively large current (say, 3–4 A) in order to establish it in a stable state. Start recording and take the sample around the same loop a few more times. If there is no drift, these loops should appear superimposed on top of each other in your B-H diagram (note that you will need to save the data in a text file and transfer it to one of the computers in the lab to actually see your hysteresis loop, using Excel or some similar program).

(c) Repeat the previous step for a much smaller current, with $\mathrm{I}_{max} \approx 1$ ampere. The hysteresis loops should appear quite different, although the sample is exactly the same.

(d) Demagnetize your sample with the washing machine again. Now the goal is to examine the magnetization curve from $\vec{M} = 0$ to saturation. Start recording data before the first hysteresis loop you initiate. If this is done properly, the resulting B-H diagram will begin at the origin (B = H = 0).

## 13.4 Calculations

1. Using the results of question 1 and your recorded voltages, tabulate and graph the curves of B vs. H (hysteresis loops) for both values of $\mathrm{I}_{max}$ and the demagnetized sample. If the curves are too noisy or skewed for further analysis, you may need to return to take more data. Identify the saturation point, where all of the magnetic domains are aligned and no further increase in $\vec{M}$ occurs. What is the physical significance of the y-intercept (height on the B axis when H = 0) of your graphs, and any differences in the value of this intercept for the high and low current cases?

2. Use your magnetization curve beginning at $\vec{M} = 0$ to plot the curve of relative permeability vs. H. The permeability of a ferromagnetic substance is usually described by $\mu_{max}$,

the highest value of $\mu$ between H = 0 and saturation. Find the value of $\mu_{max}$ indicated by your data and estimate errors as best you can. Is your result consistent with references found in textbooks, online, or in any assumptions you made in constructing your circuit(s)?

3. Describe qualitatively (or sketch/plot) what the hysteresis loops would look like for nickel ($\mu = 100$) and for a high permeability nickel-iron alloy such as "mu-metal" ($\mu \approx 10^5$).
4. It takes energy to align magnetic domains. Where does the energy come from in this setup? Calculate the amount of power dissipated in the sample of iron when an alternating current with amplitude $I_0 = 1$ A and f = 50 Hz passes through it.

subsectionBonus Section

**References**

The magnetism section from any E&M or general physics textbook, including (for example), Halliday, Resnick & Walker, "Fundamentals of Physics", Ch. 32, or D.J. Griffiths, "Introduction to Electrodynamics", Ch. 6

"Introduction: Operational Amplifiers", edited by T.R. Kuphaldt et al. (1996–2013), `http://www.allaboutcircuits.com/vol_3/chpt_8/1.html`.

## 13.5 Appendix: The LM301 Amplifier

Historically a sequence of lectures was devoted to the properties and uses of op amps, but this material has been cut from KYA212/KYA375 for reasons of time. More information can be found by consulting the references listed above, and the notes in the manilla folder near the experiment (National Semiconductor LM301 reference).

In brief, the LM301 has 8 pins that either accept input or produce output. Two of the pins (labelled + and ?) are used as signal inputs (voltages) and another outputs the difference between them, amplified by an enormous factor– the gain is typically on the order of $10^5$. The amplifier draws power from an external supply connected across two of its other ports (V+ and V?). The amplifier and the power supply must be linked to a common earth for best results.

The maximum output of the amplifier is set by the voltage supply to the chip, so in practical terms it outputs either zero volts (for zero difference between the input voltages) or its maximum possible output (e.g., 15 V). The output can be either positive or negative, depending on which input voltage is higher. When the output voltage is pushed to within a fraction of a volt of the voltage of the power supply, the amplifier is said to be "saturated". It typically only takes an input voltage difference of a few microvolts ($\mu$V) to saturate an amplifier being run off a 15 V power supply. This can be useful when the output channel is connected back to one of the input channels, creating a feedback loop.

By placing resistors and capacitors into the feedback loop, one can create circuits that output the result of various operations on the input voltages, e.g., multiplication, division, differentiation, or integration. Consult the web reference above for further information on how this can be accomplished. The chip in the black box used in this experiment is wired up to act as an amplifier, with internal resistor R and capacitor C. If there are no additional losses, the gain of an ideal amplifier is given by

$$Gain = \frac{1}{RC}. \tag{13.3}$$

The component values in the amplifier box were chosen to provide a reasonably easy-to-measure voltage output, after having considered the output of the high-current circuit and the answer to question 1 above. The values are: R = 5.6 kΩ (±10% ), and C = 1 $\mu$F (also ±10% ). Examination of the circuitry inside the box will reveal extra components; these are needed to correct for non-ideal effects: a resistor R′ is added between the one input and earth in order to correct for bias current, and a 100 kΩ potentiometer (external to the black box) provides an adjustment to cancel out any signal from within the chip itself that would contribute to the output. You may find it difficult to zero the offset voltage using the offset null on its own, in which case a much smaller pot or rheostat can be added in series as a fine control.