# Chapter 1  Introduction to the MAE 221 Laboratory

## 1.0 Introduction

## 2.0 The Laboratory Sessions

The MAE 221 laboratory consists of 12 lab sessions.  In the first four, you will work with basic electric circuits and data acquisition tools that are fundamental to laboratory experiments and general engineering practice.  In the fifth and sixth sessions, you will undertake a small independent project in which you construct a more substantial and practical device using these basic building blocks.  With each new device that is encountered, you will be required to summarize its performance and applications in a brief technical reference sheet which will be handed in and graded.  This will not only serve as an exercise to help you understand each device, but will also be a useful reference in future years.  The final six laboratory sessions will consist of experiments in thermodynamics.  In these experiments your knowledge of electric circuits and data acquisition tools will be applied in your investigation of various thermodynamic phenomena.  After completing each experiment you will present your methods, results, and conclusions in a technical report similar to that which you would prepare in an industrial setting.

## 3.0 Laboratory Assignments and the Technical Reference Sheet

- pre-lab exercises

Grades in the MAE 221 laboratory will be assigned based on written assignments that are handed in at the beginning of the subsequent laboratory session.  During the first six sessions, you will construct basic circuits and prepare a technical reference sheet for each one.  In the final six weeks, you will conduct thermodynamics experiments and prepare a more substantial technical report where you will discuss the purpose of the experiment, the method used, and present, analyze, and discuss your data.  The technical report and experimental error analysis will be discussed at length in Chapters 7 and 8.  The technical reference sheet is discussed below.

The technical reference sheet must contain the following information:

1. A description of the device including relevant drawings and alternative configurations
2. An explanation of how the device works, including equations that govern its operation, and rules of thumb
3. How the device is used, with specific examples of applications
4. Limitations of the device and other caveats
5. Address any questions asked in the lab manual

The following example is a reference sheet for a prototyping board. The prototyping board is a tool that will be used frequently, and it is a good idea to study this example carefully.

**Technical Reference Sheet** MAE 221 Student
Today's date

## Prototyping Board

**1. Description**

A prototyping board is a device on which temporary circuits can be easily built and modified. It consists of a matrix of sockets into which wires and circuit elements can be inserted. Rows are electrically connected. Socket spacing matches the pin spacing on integrated circuits so they may be easily inserted. Figure 1 contains an image of the prototyping board that will be used in the MAE 221 laboratory…

**2. Governing Principles**

**3. Applications**

**4. Limitations and Caveats**

Currents of around __mA should not be exceeded. High currents generate heat which can damage the board.

The prototyping board is only for temporary circuits. Connections are made by friction and are not as reliable as soldered connections. Connections are not as durable and can have a small contact resistance which may become significant in circuits where high accuracy in resistance is important.

Although it is easier to construct a circuit using excessive wire lengths, wires should be kept as short as possible. This results in a neater circuit that is easier to understand and diagnose, and reduces noise in the circuit. In addition, short, well-placed wires are less likely to be accidentally yanked out of sockets.

## 4.0 The Laboratory Notebook

In addition to the documentation that you will submit for grades, it is essential that you use a bound laboratory notebook to record all pertinent observations, ideas, calculations, and data. This will be invaluable in your preparation of reports after the completion of the laboratory session. Keeping good notes is a skill that must be practiced and is essential for your professional career. Not only will it support your daily activities, but your recorded notes can be used to prove ownership of intellectual property or to demonstrate due diligence in case of an engineering failure.

The following guidelines will help you in maintaining an effective notebook:

- Use a bound notebook so that pages are not lost. A spiral notebook is sufficient in this lab. In your professional career, you will probably use a more durable hard-covered notebook with pre-numbered pages.
- Always use ink. Cross out mistakes neatly – do not obliterate them.

- Record the date
- All raw data should be included. Computer printouts should be permanently bonded to the pages of your notebook so that they are not lost.
- Work out your calculations in detail. If you make a mistake, it will be much easier to find.
- Record models and serial numbers of lab instruments that are used. If a problem is later discovered with an instrument, you can easily determine whether or not it could have affected your measurements.
- Include all important observations. The ability to identify important information comes with experience and your understanding of the underlying principles of the experiment or device. If you are unsure whether or not to include an observation, record it and/or discuss it with a lab instructor. It is better to note an unimportant fact than to leave out an important detail and possibly render your data useless.
- In determining what information to include, it is helpful to think about the potential audience that you are writing for. In general, anybody with your level of expertise should be able to understand and use your notes. This person could be your successor, an expert witness in court, or you several years later.

Fall 2002 MAE 221 Laboratory Schedule

| **Week** | **Assignments** |
|---|---|
| 9/16 | Chapter 1: Introduction to the MAE 222 Laboratory<br>Chapter 2: Laboratory Equipment and Basic Resistive Devices |
| 9/23 | Chapter 3: Filters and Operational Amplifiers |
| 9/30 | Chapter 4: |
| 10/7 | Chapter 5: |
| 10/14 | Chapter 6: Independent Projects<br>Chapter 7: Basic Statistics and Error Analysis |
| 10/21 | Chapter 6: Independent Projects<br>Chapter 8: Preparing a Technical Report |
| 10/28 | Fall Recess |
| 11/4 | Chapter 9:<br>Chapter 10:<br>Chapter 11:<br>Chapter 12:<br>Chapter 13:<br>Chapter 14: |
| 11/11 | Chapters 9-14: |
| 11/18 | Chapters 9-14: |
| 11/25 | Chapters 9-14: |
| 12/2 | Chapters 9-14: |
| 12/9 | Chapters 9-14: |

# Chapter 2: Laboratory Tools and Basic Resistive Devices

Objectives:

- Become familiar with lab equipment: power supply, volt meter, and oscilloscope
- Become acquainted with lab software: Labview and OrCAD
- Review basic series and parallel circuit concepts
- Use a resistor as a current limiter, current to voltage converter, and voltage to current converter
- Build a potentiometer and understand its principle of operation
- Understand voltage dividers
- Understand input impedance

2.1 Introduction

2.2 Data Acquisition and Storage: The Digital Sampling Oscilloscope and Labview

2.2.1 Introduction to the Digital Sampling Oscilloscope

2.3 Theoretical Background

| | |
|---|---|
| 1.01 – 1.02: | voltage, current, resistance, resistors in series and parallel |
| 1.03: | voltage dividers |
| 1.04: | voltage and current sources |
| 1.05: | Thevenin equivalents |
| 1.06, 1.25: | diodes, nonlinear impedance |

-Resistor color codes

- Resistors and resistance (temperature dependence)
- series and parallel circuits
- Kirchoff's laws, Thevenin's equivalent circuits
- potentiometers
- voltage dividers
- input impedance

**2.4 Pre-lab questions:** In this lab session you will begin by answering the following questions before you begin the laboratory exercises. For subsequent labs, you must complete the questions prior to arriving in the lab, and hand in your answers at the beginning of the session.

1. For the series circuit shown below, derive the equation for resistances in series:

$R_{eq}=R_1+R_2+R_3$.

Use Kirchoff's laws and Ohm's law.

2. For the parallel circuit shown below, derive the equation for resistances in parallel:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.$$

Use Kirchoff's laws and Ohm's law.

3. For the voltage divider shown in Figure ?? use Kirchoff's laws to derive an equation for Vo/Vi in terms of R1 and R2. What assumptions are necessary?

2. a practical question related to the effect of current on heating and thereby resistance. Use numbers that students are similar to those that the students will see with their potentiometers to generate some intuition on what will happen in the lab.

3. perhaps a theoretical calculation – displacement vs. time of ball or car on ramp

4.

**2.5 Laboratory Activities**

1. **Introduction to laboratory instruments.**

- power supply -- what leads are used? Also the trainer. +ve gnd or –ve gnd. +-15V. Connect +ve % gnd -> 0-30V
- volt meter measure input impedance
- oscilloscope fcn gen on trainer. Learn the knobs.

2. **Basic circuit concepts.** In this exercise you'll review basic principles of series and parallel resistive circuits while gaining familiarity with the trainer board, multi-meter, and oscilloscope. You will measure the current in the circuit by direct means, and also by using a resistor to transform current into voltage through Ohm's law.

a) Series Circuits

i. Construct the series circuit shown in Figure __ on your trainer board. Do not turn on the power supply.

ii. Confirm that the circuit is properly connected using your ohm meter. Make sure that $R_{AD}=R_1+R_2+R_3$. Measure the resistance across the terminals of the power supply. This should be $R_{AD}$.

iii. Turn on the power supply. Using your volt meter, measure the voltages (with respect to ground) at points A through D. With a single voltage supply, we have created three different voltage levels. This is a common and inexpensive way of providing different voltages to devices with differing voltage requirements. Such circuits are found in many electronic devices. We will return to this concept of 'voltage division' in the next section.

iv. We know the impedance of our load ($R_{AD}$) and the voltage applied across it so we can calculate the current using Ohm's law. Calculate it.

v. Now verify Ohm's law using the multi-meter. Connect the multi-meter in series with the resistors as shown in Figure __. Make sure the leads are connected properly to the meter, and it is set to read DC amperage. Make sure that the measured current agrees with your prediction.

b) Parallel Circuits

i. Leaving your series circuit assembled, construct the parallel circuit shown in Figure __ in another area of your trainer board.

ii. Confirm that this circuit is assembled properly. Ensure that

$$\frac{1}{R_{AD}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.$$

- measure resistance of light bulb when circuit is open.
- close circuit and measure current – directly and using Ohm's law
- Using known current, measure resistance of light bulb when circuit is closed.
- introduce parallel component

3. **Voltage division and regulation.** In this exercise we will investigate two methods of reducing a voltage level: the voltage divider and the voltage regulator. You should be quite familiar with the concept of a voltage divider from the pre-lab questions and the previous exercise with a series circuit. On the other hand, the voltage regulator is entirely new. We will deal with each one briefly.

a) The voltage divider. Figure __ contains a schematic diagram of a typical voltage divider. You have already derived an equation describing its transfer function ($V_o/V_i$). If the output voltage does not need to vary, a voltage divider may be constructed from discrete resistors. These are frequently found in electric circuits and it is therefore worthwhile constructing some and studying their properties…
- build one Vo/Vi = 0.5. Use resistances comparable to that of the potentiometer.
- use DSO to confirm that it is working correctly
- keep assembled for step 7.

b) The voltage regulator.

4. **Application of a load to a voltage divider - CAUTION.** You now have two voltage dividers, one is a potentiometer, and the other created from discrete resistors. Both have known ratios of Vo/Vi. We will now see that the combined ratio of Vo/Vi for two voltage dividers in series is not the product of the two individual ratios. You must determine why this is, and be sure to discuss it in your voltage divider reference sheet. What assumption was made that is no longer valid?
- Assemble the circuit by connecting the input of the discrete voltage divider to the output of the potentiometer voltage divider.
- use your oscilloscope to measure voltages at various points within your circuit. What is Vo/Vi for each voltage divider in series? Have both changed or only one?
- What happens when the resistors are replaced with ones that have 10 or 100 times the resistance?

- If the second voltage divider is replaced with some other arbitrary circuit, what property of the circuit is important for proper operation of the voltage divider, and what can be said about this property?

5. **The resistor as a current limiter.** Resistors can also be used in series with other devices in order to limit the current through those devices. Look at diode.
  - also investigate current-limiting capability of light bulb
  - load lines

6. **Construction of a potentiometer.** A potentiometer is a basic resistive device frequently used in electric circuits. It is very important to have a sound understanding of its functional characteristics and the principles by which it operates. We will begin by developing a qualitative understanding of its functionality through the construction of one. - instructions for construction

7. **Potentiometer application: variable resistor.** 2-lead concept
  - light bulb

8. **Potentiometer application: voltage divider.** 3-lead concept
  - light bulb

9. **Performance specifications of the potentiometer.** The variety of applications for potentiometers dictate a variety of performance specifications. There will be requirements for a certain resistance range, current capacity, maximum voltage, resolution and linearity. We will now quantify our understanding of this particular potentiometer by …
  - resistance
  - linearity
  - thermal properties

10. **A potentiometer application: dynamic displacement measurement**

11. **Real potentiometers.**
  Possible activities
  - take apart or study dismantled potentiometers – linear and rotary. What features are the same or different from the potentiometer that you built?
  - study selection of potentiometers. Note resistances, maximum current, perhaps linearity… Use data sheets

12. **Constructing the reference sheets.** You should now be quite comfortable with using potentiometers and voltage dividers. Your assignment is to construct a reference sheet for a potentiometer. If you have time you should try to complete as much of this as possible during the lab session so that you can make certain that you have collected sufficient data and ask questions. In particular, you may need to discuss with the lab instructors what items merit inclusion in the reference sheet. These will be due at the beginning of the next lab session.

# Chapter 3: Filters and Operational Amplifiers

**Objectives:**
- Understand low-pass RC filters and design one to remove noise from a signal.
- Understand Operational Amplifiers and use them in the following devices.
- Construct a voltage follower to solve the input impedance problem in the last lab.
- Construct a linear amplifier to enhance small signals
- Construct a summing linear amplifier and use as a current to voltage converter
- Construct integrators and differentiators. Convert displacement to velocity and vice versa.

### 3.1 Introduction
- -

### 3.2 Background Theory

#### 3.2.1 Complex Impedance and RC Circuits

complex impedance
capacitors

#### 3.2.2 Operational Amplifiers (Op-Amps)

Analysis of op-amp circuits requires use of the two golden rules for op-amps:

**1. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.** The op-amp is essentially a differential amplifier with very high gain. More specifically, $V_o = G*(V_+ - V_-)$ where $G > 10^5$ is the gain. Therefore, when $V_+$ exceeds $V_-$, the output voltage is positive, and when $V_-$ exceeds $V_+$, the output is negative. Of course, the output voltages cannot exceed the positive and negative supply voltages that power the op-amp. When used without feedback, a very small voltage difference at the input would cause the output to quickly saturate (not very useful); however, when feedback is used, this first golden rule applies and …

**2. The inputs draw no current.** This is a result of the very high input impedance of the op-amp. It typically ranges from 1MΩ to __

gain
feedback
active vs. passive component
op-amps
  basic principles
  golden rules
  voltage follower
  linear amplifier

The schematic symbol for an operational amplifier is given in Figure __. It consists of two inputs --- non-inverting (+) and inverting (-) --- and an output. It is an active device with very high gain. Active means that… Very high gain means that the … Because of this high-gain characteristic of the op-amp, it is generally very unstable unless used in a system with feedback.
One input of the operational amplifier is held at

**3.4 Pre-lab Questions**

1. In Chapter 2, we saw that the equation for a voltage divider is:

$$\frac{V_o}{V_i} = \frac{R_2}{R_1 + R_2}$$

where $R_2$ is the resistor in parallel with the load. For a pure sinusoidal input signal, this equation has a more general form which also applies to complex impedances:

$$\frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2}$$

For the low-pass filter circuit in Figure __, write down the expression for Vo/Vi using the above equation. Note that this equation is in the frequency domain, not the time domain. It gives the ratio of the signal amplitudes, not the ratio of the voltages at any particular instant in time.

2.

**3.5 Laboratory Activities**

1. **Removing noise from a signal and a power line.** In the previous laboratory session you constructed a linear potentiometer that you used to measure displacement vs. time of a ball rolling down a ramp. However, the signal was not an accurate representation of the motion of the ball because it contained high frequency fluctuations whereas the motion of the ball was characterized by steady acceleration. These fluctuations in the signal are called **noise**. Unfortunately, noise is a frequent problem in analog data acquisition. Fortunately, if the frequency of the noise is significantly higher than the frequency of the signal you want to measure, there is a very simple circuit that does a good job of removing the noise. In this exercise, we will build a low-pass RC filter such as that shown in Figure __.

2. **The voltage follower – a better solution to the input impedance problem.** For the remainder of the lab, we will focus on operational amplifiers. In Chapter 2, we found that if two voltage dividers are connected in series the voltage ratio of the combined circuit is not the product of the original two ratios. We reduced the effect of loading by increasing the input impedance of the second voltage divider (the load). This is not a practical solution if our load circuit must draw significant current. In this exercise, we will re-address this problem, and solve it with the use of a voltage follower.

A schematic of the voltage follower is given in Figure __. The input voltage is applied to the non-inverting input and the output is connected to the inverting input. Whenever the output is connected to the inverting input, this is called **negative feedback**, and results in a stable system. By considering the gain equation of the op-amp, convince yourself that if the output voltage were to deviate from the input voltage that the op-amp would attempt to restore $V_o=V_i$.

Recall that in Chapter 2 we required that for a voltage divider to obey the voltage divider equation Vo/Vi = R2/(R1 +R2), the load must have a high input impedance. If it does not, we can

3. **The linear amplifier – Amplifying small signals.** The voltage follower has a gain of one. However, with a small modification, the

4. **The summing linear amplifier: current to voltage conversion in a digital to analog converter**

6. **Integrators and differentiators: determining velocity from displacement and displacement from velocity**

## Chapter 4: Power Sources and Power Control

**Objectives:**

- Understand transistor operation
- Construct and understand common transistor devices:
    - Use a transistor as a current regulator to charge a battery
    - Use a transistor as a switch
    - Build a push-pull amplifier to increase current to a motor
- Use a transformer to drive a synchronous AC motor
- Construct an unregulated DC power supply with a bridge rectifier, and study a real power supply

### 4.1 Introduction

- -

### 4.2 Background Theory

Horowitz and Hill:

Chapter 2: Transistors
2.01 basic transistor model (current amplifier)
2.02 transistor switch

### 4.3 Pre-lab Questions

### 4.4 Laboratory Activities

1. **The transistor.**
   - testing with multi-meter
2. **Regulating current with a transistor: a battery charger.**
3. **The transistor switch.**
4. **Amplifying current: driving a DC motor.**
   - torque/speed measurement
5. **Speed control on a 100V synchronous motor**
   - transformer
6. **Construction of an unregulated DC power supply**
   - bridge rectifiers
   - use high-pass RC filter to look at ripple
7. **A real DC power supply**

# Chapter 5: A Variety of Sensors and their Calibration: Measurement of Temperature, Force, Pressure, Position, Velocity, and Acceleration

**Objectives:**

- Become familiar with the implementation and performance of a variety of 'small signal' sensors, including:
    - Optical position detection and communication
    - Piezo-electric pressure transducers and accelerometers
    - Thermocouples
    - Hall effect proximity detectors
    - Acoustic proximity detectors

- Become familiar with the implementation and performance of a variety of 'bridge-type' sensors, including:
    - Strain gauges
    - Thermistors
    - Linear Variable Differential Transformers (LVDT's)

## 5.1 Introduction

## 5.2 Background Theory

## 5.3 Pre-lab Questions

## 5.4 Laboratory Activities

1. linear amplifier + filter + current amplifier
    - photo/light
        - linear (optical proximity)
        - fiber-optic communication
    - piezo-electric
        - pressure transducer
        - accelerometer
    - thermocouple/heat pump
    - magnetism
        - proximity sensor – hall effect tooth detector for gear

2. Bridge + linear differential amplifier
    - strain gauges
        - stretch wire and measure change in resistance
        - DeProny brake

- thermistor

Also:

- Acoustics
  - Acoustic ranging

## Chapter 6: Independent Project

**Objectives:**

- Implement previously studied components in a simple but practical electronic device.

1. Position Servo
2. Temperature Regulator
3. Recording Loop
4. deProny Brake
5. Hotwire Anemometer
6. MUX/DEMUX multi-channel
   - pulse-width to voltage level using integrators