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Introduction to Signals and Systems
Laboratory Manual
EECS 216

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¹ With modifications by Professors Grizzle and Wakefield, Fall 2007.

Preface

In the spring of 2006, the EECS faculty decided to revise portions of our curriculum. In particular starting in the winter of 2007, EECS 206 (“DSP First”) was to be eliminated as an EE and CE core course requirement and replaced by a required course on continuous-time, linear systems, EECS 216. A junior-level continuous-time, linear systems course, EECS 306, was already offered as part of our degree program, but it was not a degree requirement. It was anticipated that the *lecture* material in the new EECS 216 would be quite similar to that already covered in the existing EECS 306, i.e., zero-state response, zero-input response, impulse response, convolution, frequency response, Fourier series, filtering, Fourier transform and Laplace transform with applications to signal processing, communications and control. In an effort to enhance the student experience and to make the connection between the mathematics and applications more transparent, it was decided that a hardware-based laboratory would be added to the course. Professor Wayne Stark and myself were the main proponents behind such an approach. Our Department Chair at the time, Professor David Munson, was also a strong advocate for improving and increasing our undergraduate laboratory offerings. I took the responsibility for developing a new set of laboratory projects for EECS 216, and this effort got underway in the summer of 2006, with continuing efforts in the fall of 2006 and the winter of 2007. Four projects were developed and the labs were offered for the first time in the winter semester of 2007. Efforts to refine, modify and make additions to the labs, as well as to improve the student experience, remain an on-going activity.

Acknowledgments

The completion of the laboratory projects described in this manual would not have been possible without the help of others. Professor Wayne Stark assisted with the development of Lab I during the summer of 2006, and Francine Shammami, an undergraduate student, helped test portion of this first lab experiment. The electronic design of the pre-built AM radio front-end used in Lab III was copied from a similar lab experiment offered at the University of Illinois. Special thanks go to James Shuster, an undergraduate. James, with the help of Dr. Kurt Metzger, did the PC board layout, assembled the first prototype of the radio front-end and demonstrated successful operation of the complete AM radio. He also bread-boarded and tested the PD controller described in Lab IV. A substantial amount of work is required to bring a new undergraduate laboratory course on-line for the first time. Lindsay Allen, along with Ben Morris and Xing Zhou, were GSI's for EECS 216, in winter semester of 2007, the first time the course was offered. They accepted and worked through the inevitable frustrations associated with such an effort. Special thanks are due to Lindsay Allen, who was always enthusiastic about the project and was committed to its successful outcome. During the summer of 2007, Lindsay Allen also worked diligently to modify and improve various portions of the laboratory projects based upon our experience of the previous semester. The EECS lab support team, consisting of Dr. Alexander Ganago, Rob Giles and Mike Stander provided outstanding lab support services. Rob Giles assembled multiple copies of the AM radio front-end, Mike Stander ordered parts when necessary, and all three of them upgraded/maintained the lab bench equipment and proffered welcome advice and encouragement. Dr. Kurt Metzger provided valuable technical support in real-time and upon demand, and he was always more than willing to serve as a listening board. Finally a special thanks go to our many excellent undergraduate students who make teaching worthwhile. I hope that they enjoy these lab projects as much as I have enjoyed developing them.

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Introduction

History

Welcome to EECS 216: Introduction to Signals and Systems! EECS 216 is a basic course on continuous-time linear systems. This subject material is an electrical and computer engineering requirement not only here at Michigan, but also at nearly all other universities worldwide. The theory and techniques you will learn in this course can be used to analyze and solve a wide range of important problems, related to signal processing, communications, control, dynamical systems and circuits. Although linear system theory may appear rather abstract and theoretical at times, the subject developed out of a need to understand the principles that govern the operation of important real-life systems. There is hardly any electrical device or algorithm in use today whose operation does not depend in some way or another on linear system theory. Without linear system theory, many of the sophisticated electronic products that we take for granted in our everyday lives, including radios, televisions, cellphones and iPods, would not be in existence.

There is an old Armenian saying that “He who lacks a sense of the past is condemned to live in the narrow darkness of his own generation.” Thus we will digress very briefly to make some comments regarding the history of linear system theory as it relates to the topics covered in EECS 216 [1]. These topics include, but are not limited to, steady-state and transient response, frequency response, filtering, impulse response, convolution, Fourier and Laplace transforms, poles and zeros, linear feedback and stability. As the famous physicist and chemist, Josiah Millard Gibbs (1839-1903) once said, “One of the principal objects of theoretical research in any department of knowledge is to find the point of view from which the subject appears in its greatest simplicity.” This fact has served to drive the development of linear system theory to its current embodiment, which is both elegant and powerful. The reader may find it difficult to appreciate the historical vignette presented below due to a lack of his or her knowledge of linear system theory. Hopefully the completion of this course will serve as a remedy, and it is suggested that the brief history presented below might be profitably re-read at the conclusion of the semester.

The input/output relationship of a single-input/single-output, continuous-time, linear system can be mathematically modeled by a linear, constant coefficient, differential equation. Thus in some sense, the study of linear systems is both a qualitative and quantitative study of these equations and their solutions. The development of differential equations, of course, had to await the arrival of calculus. Calculus was developed in the late 17th century by Issac Newton (1642-1727) and Gottfried Wilhelm Leibniz (1646-1716). After the invention of the calculus, a number of important problems in mechanics were formulated in terms of differential equations by members of the Bernoulli family. The general treatment of constant coefficient linear differential equations was developed by the great Swiss mathematician and physicist Leonhard Euler (1707-1783) in 1739.

In the mid-1800’s George Boole (1815-1864) and Robert Bell Carmichael described powerful symbolic methods for solving differential equations that are known today as operational calculus or operator methods. These methods allow one to change a differential equation into an algebraic one that admits an easy elementary solution. The

English mathematician and physicist Oliver Heaviside (1850-1925) further developed the operational approach in 1893 and was first to apply it to problems involving electricity and electromagnetism.

It is fair to say that the development of linear systems (as covered in EECS 216) was driven primarily by the need to understand and design of AC electrical power generation/transmission equipment and telephone/radio electronics, with these efforts starting in the late 1800's and ending in the early 1930's. In the late 1800's and early 1900's AC motors and power generating equipment were being developed in the United States for the first time by a number of businesses, including the recently formed General Electric Company. Carl Steinmetz (1865-1923), an employee of General Electric, developed mathematical techniques, including the phasor method and complex impedance (topics taught in EECS 215) for analyzing the steady-state response of AC electrical equipment subject to a sinusoidal excitation [2]. This work served as a precursor to more general frequency domain methods, including eigenfunctions and the frequency transfer function concept. It was well-known to Steinmetz and others at the time that changing conditions, such as fluctuations of load, would cause power systems to depart from steady state and exhibit transient behaviors. In 1909 Steinmetz published a classical mathematical analysis of these transients based on the theory of linear, constant-coefficient, differential equations that describe the current and voltages in electric circuits through applications of Kirchoff's circuit laws [3]. His theory for the solution of these differential equations, however, was rather complicated, and this fact provided the impetus to find more efficient and transparent methods of attack. Heaviside's operation calculus was applied

to these problems. In Heaviside's approach, the differential operator $\frac{d^n}{dt^n}$ appearing in these differential equations was replaced by the variable p^n , thus converting the differential equation into one that is algebraic, i.e., a polynomial in the variable p . Heaviside then developed a method to convert this algebraic equation back into a time-domain solution of the differential equation [4]. Heaviside's approach lacked rigor and was difficult to justify and understand. John Renshaw Carson (1886-1940) advanced the theory considerably when he expressed the solution of linear, constant coefficient, differential equations in terms of an integral involving the unit step response of the circuit [4], [5]. Today this integral operation is known as the convolution, and the derivative of the step response is called the impulse response. Carson then related the impulse response to the complex impedance, or equivalently system transfer function, of the circuit through the Laplace transform. He also demonstrated that Heaviside's results were a special case of his theory. Carson's theory and methods now form the backbone of basic linear system courses as currently taught. The American academics, Ernst Julius Berg (1871-1941) and Vannevar Bush (1890-1974) did much to popularize these new methods through their teaching and writings [6], [7]. By the early 1930's, the linear systems tools, such as impulse response, convolution, Laplace transform and frequency response, had taken on the form they currently have today. Using these tools makes it possible to analyze both the steady-state behavior and transient behavior of linear, time-invariant systems with little effort.

Today there are many applications of linear systems that involve feedback, a few of which will be discussed in EECS 216. The concept of electronic feedback was first introduced by Edwin Howard Armstrong (1890-1954) in 1912, while he was an

undergraduate student at Columbia University. At the time, Armstrong was working on radio technology using the recently invented vacuum tube triode. Armstrong observed that by using *positive* feedback he could build high gain (regenerative) amplifiers and oscillators that were to become a staple of early radios. Along with radio, telephone systems were also being developed in the early 1900's. In the 1920's, the development of long-distance telephone transmission systems, however, was being hampered by the inability to build constant gain amplifying circuits. In 1927 at the American Telephone and Telegraph Company, Harold Stephen Black (1898-1983) invented the concept of *negative* electronic feedback to solve this problem [8], [9]. Using this technique, Black was able to build amplifiers whose gain was fixed and relatively independent of the open-loop amplifier parameters. Black's seminal work served as the starting point for the development of modern electronic, linear, control theory. Major contributions to understanding the stability of these negative feedback systems were made by Harry Nyquist (1889-1976) [10] and Hendrik Wade Bode (1905-1982) [11] in the 1930's using frequency domain concepts.

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The Lab Projects

The laboratory component of EECS 216 consists of the four laboratory projects listed below.

Lab I: Introduction to lab equipment. Illustration of basic LTI concepts - linearity, time-invariance, step response, impulse response, convolution integral, frequency response.

Lab II: Filtering, envelope detectors, frequency discriminator and frequency shift keying (FSK) receiver.

Lab III: AM Radio.

Lab IV: PD Controller.

It is a natural tendency of engineering students to categorize courses as being either “theoretical” (i.e. highly mathematical) or “practical” in nature. Such a characterization, however, is usually an oversimplification that obfuscates the true nature of the subject. Both theory and practice go hand-in-hand and are simply different sides of the same coin. Good theory allows one to solve important, practical problems, and the absence of a good theoretical understanding makes it difficult or impossible to design and construct sophisticated systems. On the other hand, the construction of systems and devices validates the theory upon which they are based, and greatly increases the value of that theory. As an engineer you will enhance your value by developing expertise in both theory and practice.

The four laboratory projects in EECS 216 have been carefully chosen to both reinforce and extend the material covered in the lectures. These projects have also been chosen to illustrate the close interplay between theory and practice. You will be building real operational systems, such as FM discriminators, AM radio receivers and controllers.

Laboratory Rules

Safety First

The voltages used in this laboratory are in the range of 12 V and the currents are low, and thus there is little risk of a serious electrical shock. Nonetheless the power supply should be turned off while assembling or making modifications to your circuits. Also you should always put safety first and err on the side of caution. The lab equipment itself runs on 120 V, 60 Hz AC as provided by the wall electrical outlets in the lab room. These are the same outlets that you will find in your home, dormitory room or apartment. This voltage can result in electrocution under some conditions and thus due care is always warranted when working with these voltages. It is important to follow the instructions below at all times.

- Immediately report any dangerous conditions, such as stripped or frayed 120 VAC electrical cords, sparks in lab equipment, loose wall sockets, burning odors, etc to your lab instructor.
- In case of emergency (fire, medical, police, etc.) immediately notify your lab instructor and/or call 911. There is a phone in the lab near the door. Identify your present location, the nature of the emergency and your name to the respondent on the phone.
- No student is allowed to work in the lab alone at any time. The student must be accompanied at all times by either a laboratory partner or a lab instructor.
- Immediately report any equipment failures to the lab instructor.
- Any student who knowingly attempts to apply electrical shocks to either him or herself or to other students in the lab will immediately be denied access to the laboratory for the remainder of the semester.
- When in doubt about safety, always ask your lab instructor for help and do not touch anything.

The Honor Code

The College of Engineering Honor Code applies to all work, including the Pre-Lab and Post-Lab assignments. Every student is expected to abide by the Honor Code. Please write, sign and date the following statement on the first page of all your lab assignments:

“I have neither given nor received aid on this assignment, nor have I concealed any violation of the Honor Code.”

Lab assignments lacking the Honor Code statement and the author’s dated signature will not be graded.

Laboratory Attendance

Attendance in your registered lab section is mandatory. Given the demands on use of the laboratory room by other students, both those in EECS 216 and those in other EECS courses, there is little if any time to make up missed labs. If you need to reschedule a lab, inform your lab instructor (preferably one week) ahead of time.

Laboratory Assignments Pre-Lab, In-Lab and Post-Lab

The first two and the last laboratory projects will occupy one three-hour lab session each, while the third lab may require two consecutive weeks. You will be provided with a detailed set of instructions and problems for each of these four labs. Each lab will consist of three segments – Pre-Lab, In-Lab and Post-Lab. The Pre-Lab will introduce the topic to be studied, will state the goals of the project and will provide detailed technical information related to the subject. This technical information will contain a concise review, and in some cases an extension, of pertinent theoretical material that has been covered in lecture. The last section of the Pre-Lab will contain a set of assigned problems that will help you to draw important conclusions and develop a mastery of the subject material. You will need to turn in your solutions for the Pre-Lab assignment when you first come into the lab at the start each new lab project. **You should make a copy of your Pre-lab assignment for yourself and also bring it to the laboratory, since it will assist you in doing the in-lab work.** You may find some of the Pre-Lab assignments a bit long and a bit difficult, but they are an essential portion of the lab. Failure to complete these assignments will make it difficult for you to fully understand and successfully complete the actual lab project. Once in the lab, you will follow the In-Lab instructions to construct, analyze and measure the performance of your devices/systems. You will collect and save data (in your personal computer workspace, or email it to yourself or place it on a USB memory-stick) for later analysis, and in some cases you will also be asked to demonstrate to your lab GSI, before you leave the lab, that your device/system operates properly. After you have completed the entire project and left the laboratory, you will be required to solve a set of assigned problems, i.e., a Post-Lab, that are related to the data collected in the lab. In many cases, an important part of this Post-Lab assignment will be comparing your collected data against the predictions of theory that you computed as part of the Pre-Lab. You will turn in the Post-Lab assignment the week after you have completed the lab at a place and time to be announced by your lab GSI or course instructor. In general, both the Pre-Lab and Post-Lab assignments will require graphing of both experimental data and theoretical results. These plots will be produced using Matlab. Below you will find some additional comments on plotting. You will need to use the appropriate Matlab plotting commands.

- (1) The points in a theoretical plot should be connected by a line and enough points should be used so that the line is smooth rather than jagged in appearance.

- (2) Lines should not be used to connect the points in experimental data, and each data point should be indicated by a marker, such as an “x”.
- (3) If your plot contains more than one curve or set of data, then it should contain a legend that labels the separate data sets (Matlab **legend** command).
- (4) Each axis in your plot should be labeled and your plot should have a title (Matlab **Title** command).
- (5) Each plot must have grid (Matlab **grid** command).
- (6) Use the specified Matlab **axis** command when requested to draw your plot.

The laboratory contains ten student workstations, with two students per workstation. You will work with a partner of your choosing (it can be a different partner for each lab) while in the lab to construct the necessary circuits and collect data. Your lab circuits will be constructed on the protoboards that are located in racks above each lab workbench. You and your partner will share a single board for each lab project. The lab protoboards are numbered on their back side. You will leave your protoboard assemble for the entire two weeks of each of the four lab projects. You will use the lab supplied tape and markers to label (EECS 216, lab section #, lab project number, and your name) the back side of your board. You will also use the marker and tape to label the rack slot into which your board will be stored between labs. At the conclusion of each lab project, you need to disassemble your board. You will discard all wires and resistors, saving only the op-amps, diodes and capacitors that your lab GSI will collect.

The Pre-Lab and Post-Lab assignments are to be done individually without any assistance from other students in the class or from your lab partner. On the outside cover of each lab assignment PRINT clearly:

- Your Name
- Your e-mail address
- EECS 216 and semester (e.g., Fall 2007)
- The lab project number (1-4)
- Your lab section number
- Your lab instructor’s name
- The signed and dated Honor Code pledge

Your lab assignments should be completed carefully and neatly. Every page should be numbered, and the pages stapled together in consecutive order. For each of your solutions indicate the corresponding number of the assigned problem. There is absolutely no need to type your solutions. You may use either pencil or pen. Your plots must be done using Matlab.

Equipment/Component Issues

Equipment and User Manuals

Each student workstation is equipped with a digital storage oscilloscope (Agilent DSO3102A, 100 MHz, 1 GSa/s), a function generator (Agilent 3320A, 20 MHz, arbitrary function), a DC power supply (HP E3631A, 0-6 V 5A/0- \pm 25 V 1 A), volt-ohm multimeter (HP34401A), and a networked PC. This is the same equipment currently being used for the EECS 215 lab. Data sheets and user manuals, if needed, can be found on-line via the web for each of these instruments:

- Scope data sheet: <http://cp.literature.agilent.com/litweb/pdf/5989-2235EN.pdf>
- Scope user manual anual: <http://cp.literature.agilent.com/litweb/pdf/D3000-97012.pdf>

- Function generator data sheet: <http://cp.literature.agilent.com/litweb/pdf/5988-8544EN.pdf>
- Function generator user manual: <http://cp.literature.agilent.com/litweb/pdf/33220-90002.pdf>

- DC power supply data sheet:
http://www.equipment.com/objects/catalog/product/extras/10386_E363xA.pdf
- DC power supply user manual: <http://cp.literature.agilent.com/litweb/pdf/E3631-90002.pdf>

- Multimeter user manual: <http://www.mecheng.ohio-state.edu/~kingzett/Manuals/34401MultimeterManual.pdf>

Appendix A contains a short tutorial, prepared by Dr. Ganago, on the usage of the Agilent oscilloscope and function generator.

As opposed to the older analog models, digital oscilloscopes are nice, since they allow the data to be saved, manipulated and/or processed after collection. Digital processing, however, can introduce artifacts into the data. For example if the sampling rate is too low, then aliasing will occur. Also if the analog-to-digital (A/D) converter does not have sufficient dynamic range, then the data may take on a staircase (as opposed to smooth) like character due to quantization error. Top-end test and measurement equipment has sufficiently good specifications to minimize these problems, but the teaching scopes in EECS 216 lab have more modest capabilities. You will encounter both quantization errors and sampling problems to some degree in the lab projects, but they will not be a serious issue.

Scope Connect Software

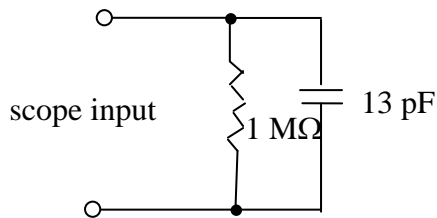
Your oscilloscope is a digital instrument. It can store data that may be transferred to the lab PC on your bench for further processing. Scope Connect, software developed by

Agilent, is available to perform this data transfer. All of the laboratory projects will require you to perform such transfers so that you can process and/or plot your measured data as part of your lab assignments. Appendix B contains a tutorial, prepared by Lindsay Allen, on the use of the Scope Connect software.

Impedance of Laboratory Equipment and Loading Effects

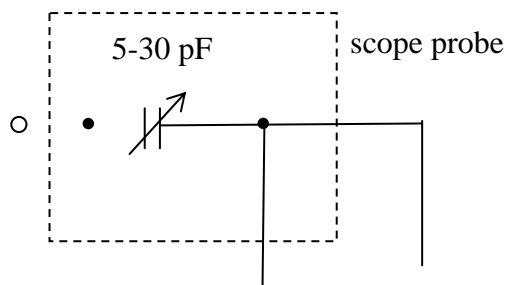
Scope

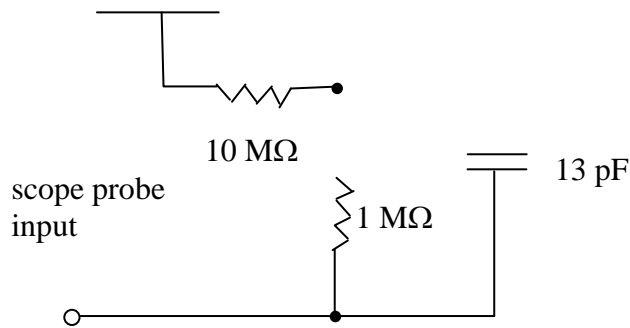
The scope input has a finite, rather than infinite, impedance, and thus the scope will draw some current from the circuit to which it is connected. As a consequence, the scope itself will affect the circuit voltage that it is being used to measure. Typically the scope input impedance is sufficiently high (i.e., $\geq 1 \text{ M}\Omega$) so that this perturbation is small. There are situations, however, where the effect will be significant. The input impedance of your scope can be represented by the following circuit



Circuit Diagram Representation of Scope Input

If the scope, for example, was being used to measure the voltage across a 10 pF circuit capacitor, the circuit capacitance would be increased to 23 pF (i.e., $10 \text{ pF} + 13 \text{ pF}$) due to the addition of the 13 pF capacitance contributed by the scope itself. When a higher scope input impedance is desired, a scope probe may be used in place of the standard BNC connectors. Each lab bench has been provided with a scope probe. When using the scope probe, the equivalent impedance seen by the circuit (see <http://cp.literature.agilent.com/litweb/pdf/5989-2855EN.pdf>) that shown below



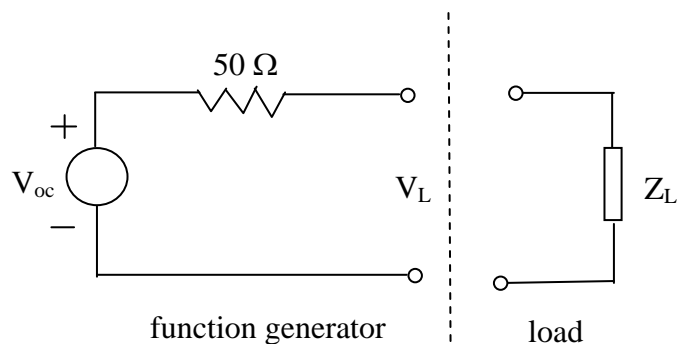


Circuit Diagram Representation of a 10X Scope Input With Circuit Probe

The capacitance of the scope probe can be adjusted, but there will be no need for you to do so in this lab. If, for simplicity, we ignore the capacitances in the above circuit, we note that the voltage drop at the scope input (i.e., across the 1 MΩ resistor) will be approximately 1/11 of that at the probe input. Thus in order for the scope to give a proper voltage reading it needs to know that a scope probe, as opposed to the standard BNC cables, is being used. Usually the scope will automatically recognize the presence of the scope probe. One of the scope menus, however, allows the user to specify that a 10X scope probe is being used.

function generator

The function generator has the following Thevenin equivalent circuit representation, where V_{oc} is the open-circuit voltage set by the user and 50Ω is the Thevenin equivalent impedance set by the instrument.



Thevenin Equivalent Circuit Representation of Function Generator Output

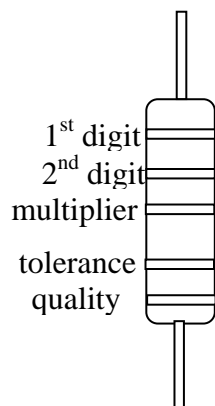
The output voltage the user sets on the function generator via the instrument's front panel is V_{oc} , while the voltage delivered to load, V_L , will be given by $\frac{Z_L}{50 \Omega + Z_L} V_{oc}$, where Z_L is the load impedance. Thus when the load impedance is very high $V_L \approx V_{oc}$ and when the load is 50Ω , V_L is given by $V_L = \frac{1}{2} V_{oc}$. Since loads often have very high impedance

or are designed to be $50\ \Omega$, the function generator has a built in feature that automatically sets the load voltage, V_L , to the user set voltage on the instrument under these two conditions. This feature is activated as follows: On the function generator press the **Utility** button and when the utility menu appears chose **Output setup**. In the output setup menu, the leftmost button is **Load**. The user is given two choices for the load, either **High Z** or **50 Ω** . When high Z (i.e., high load impedance) is selected, V_{oc} is set to equal to the user set voltage on the instrument. Thus with this setting when the load has a high impedance, the voltage delivered to the load will be equal to the user set value on the instrument. Similarly when $50\ \Omega$ is selected, V_{oc} is set to equal to twice the user set voltage on the instrument. Thus with this setting when the load impedance is $50\ \Omega$, the voltage delivered to the load will remain equal to the user set value on the instrument. Note that under all circumstances (i.e., an arbitrary load impedance), the voltage delivered to the load will be given by $\frac{Z_L}{50\ \Omega + Z_L} V_{oc}$. Using the load output set function, merely specifies whether the instrument sets V_{oc} equal to the user specified voltage or twice that value.

Resistance and Capacitance Component Value Codes

You will be using resistors, capacitors, op-amps and diode in the laboratory projects. Both resistors and capacitors have a special code that specifies the resistance and capacitance values, respectively. A description of the color-coded resistor code is given below:

Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Gray	White
0	1	2	3	4	5	6	7	8	9



First find the tolerance band located at or near one of the two ends of the resistor, which is typically gold (5%) or sometimes silver (10%). Starting at the opposite end, identify the number associated with the color of the first band and write this number down. Now identify the color of the next band and write this number down immediately to the right

first number. Next identify the number associated with the color of the next (multiplier) band. Write this number of zeros immediately to the right of the preceding two numbers. This final value equals the resistance in ohms. If the multiplier band is gold, then move the decimal point one to the left, and if it is silver move it two places to the left. If there is one more band past the tolerance band (which is not always the case), then this last (quality) band indicates the percent of these components that will fail per 1000 hours of operation when dissipating the maximum assumed wattage. For example a resistor with the following four bands red, yellow, green, silver will have a nominal resistance of 2.4 M Ω with an uncertainty of $\pm 10\%$.

The code for capacitance values is as follows:

Large capacitors have the value and units printed plainly on them, such as 10. μ F (ten micro Farads). Smaller disk types along with plastic film types, however, often have just 2 or more commonly three numbers printed on them. The units are in pico-Farads. As an example: 93 printed on a small disk can be assumed to be 93 pico-Farads. When three numbers are present, the first two are the first two significant digits, while the last number is the multiplier, i.e., the number of zeros that needs to be appended to the right of the first two significant digits. So for example 461 would denote a capacitance of 460 pF.