EXP. 26 Resistance

1. Section Purpose

A guide to electrical resistance measurement adopting Wheatstone Bridge methodology and an introduction to the appearances and the displayed values on different resistors.

2. Introduction

(1) Sir Charles Wheatstone, applied a device invented by a British mathematician, Samuel Christie to measuring electrical resistance in 1843, known as Wheatstone bridge. The device is renowned for allowing unprecedentedly-accurate electrical resistance measurement, and has been widely used in laboratories ever since.

Please see Figure 1 as below, which gives you a much clearer concept about the Wheatstone bridge. As you can see, a water flow is divided into 2 branches at M and rejoins at N. Now, create a channel connecting (bridging) A and B right in the middle of the 2 branches. The channel is likely to have no water flow passing through under the condition that the water level of both A and B is exactly the same. In other words, the phenomenon appears only when the gaps of the water flow from M to A and that from M to B are the same.

Figure 2 shows how electric currents work under a similar condition. The electric current is divided into two currents at M. Connect A and B with a conductive cord, creating a non- current zone between A and B; namely, there is no electric potential differences lying between A and B. In other words, the electric potentials from M to A and that from M to B are the same. Likewise, the electric potentials from A to N and that from B to N are thus the same, and that is exactly how Wheatstone bridge works.

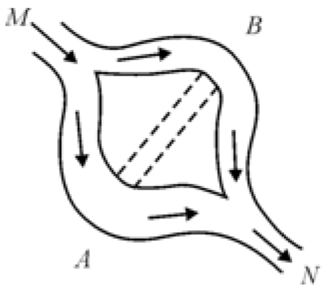


Figure 1

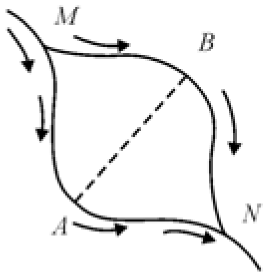


Figure 2

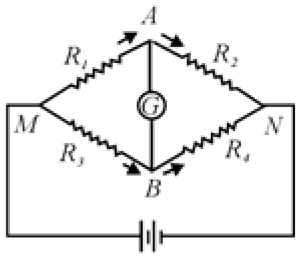


Figure 3

Figure 3 shows how a common Wheatstone bridge works. The reason why the device is called "bridge" is that a "swift" Galvanometer circuit bridge is built across from parallel channel MAN to MBN. By adjusting certain electric resistances' amounts until the hand of the meter is not deviating, the electric potentials of A and B will be balanced, and that is the so-called "bridge balance". Under such a condition, the Galvanometer indicates "no current" passing, hence proving that the electric current passing through R1 and R2 are both I1, and that the current passing through R3 and R4 are both I2.

We thereby have the following equations:

$$R_1 I_1 = R_3 I_2 \tag{1}$$

Corollary: $$R_2 I_1 = R_4 I_2 \tag{2}$$

By dividing the two above, we can have

$$R_1 / R_2 = R_3 / R_4 \tag{3}$$

Namely, $$R_2 = R_1 R_4 / R_3 \tag{4}$$

, providing us that an unknown R_2 can be notated by the other 3 known resistances.

(2) Figure 4 shows the concept of slide-wire Wheatstone Bridge, in which Shunt *MBN* is made of a uniform resistance wire, which is 1m in length. The ratio of R_4 / R_3 can be inferred from the length ratio of *BN* and *BM*. Since Point A is fixed, the other end, B, which the Galvanometer is connected, slides on Line MN; therefore, adjustments of Point B should be made until the electric current passing through the galvanometer diminishes to zero. Obviously, the R_2 in Figure 4 ought to include all the resistances from *A* to *N*, where the

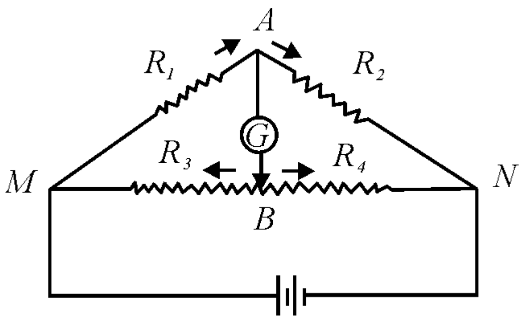


Figure 4

resistances of the contacted points and the resistance of the conductive cord should be both included, especially when R_1 and R_2 are nearly none, such contact resistances as well as wire resistances play crucial roles. Similarly, R_3 and R_4 are pretty much the same. Thus, when devising it, make sure that they're well-contacted and use stouter wires with better quality. When the room temperature is kept constantly the same, the resistance of any material is directly proportional to the length (L) and inversely proportional to the Cross Section Area A, namely:

$$R = \rho L / A \tag{5}$$

ρ is a constant of a certain ratio, called resistance coefficient. When the cross section areas are the same, the resistance ratio equals to length ratio. If the length of the resistance wire from B to N is represented by b, then the length of the resistance wire from B to N is a, and we get an equation (4) as below

$$R_2 = R_1 b / a \tag{6}$$

Owing to the effect of contact resistance, normally, with B getting closer to the midpoint of MN, the result is more reliable. To get such an effect, we will set B at the midpoint, rheostat (resistance) box as R_1. First, make the circuit roughly strike its balance; namely, the value that Galvanometer displays is nearly zero, then slide the B point to gain its best-accurate balanced spot.

(3) Introduction to Resistances in Use:

The most-used resistance on electric circuits is “carbon resistance”. Normally, such types of resistances have low power output and are small in size; directly printing the amount of the gained resistance value onto resistances to be used not only often causes difficulty in printing and binding, encountering directionality while reading, but is also prone to making mistakes. Color bands (rings) are much more ideal since the shape of them allows the resistance to easily judge their resistance values, thereby usually adopting color band codes to express them by coating the target resistance with 4 wheels in specified colors, and using each color band representing different colors to express the resistance value.

As Figure 5 indicates, of these four rings, the front most one represents “tens digit”, the second one being “single digit” and the third representing “10 to the power of certain numbers (n)”, while the fourth is for “errors”.

Information shown in Table 1 tells the numbers represented by different colors, standardized by Electronic Industries Association，abbreviated as EIA.

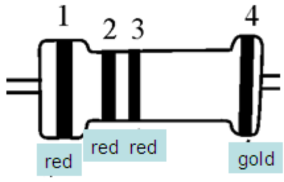


Figure 5

The following is an example adopting the method introduced in Table 1 and illustrated by Figure 5. Set the color order of a certain resistance as red => red => red => gold. According to Table 1, the first red color band represents 2. Now, jot down 2 on a sheet of paper. The second red color band also represents 2, and then jot down 2 again. However, the third red wheel, this time, no longer represents 2, but 2200 ($2000 + 2 \times 10^2$), and its unit is Ω. The fourth wheel is gold, which represents error: ±5%. Figure 6 is another example applying this method. If there are only three color bands, the fourth "non-colored"(invisible) one will be taken as error: 20%.

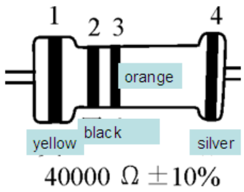


Figure 6

Table (1) Color Code Resistance Interpretation

Color	The First Digit	The Second Digit	Power Number	Error
Black	0	0	10^0	-
Brown	1	1	10^1	±1%
Red	2	2	10^2	±2%
Orange	3	3	10^3	-
Yellow	4	4	10^4	-
Green	5	5	10^5	±0.5%
Blue	6	6	10^6	±0.25%
Purple	7	7	10^7	±0.10%
Gray	8	8	10^8	±0.05%
White	9	9	10^9	-
Red	-	-	10^{-1}	±5%
Silver	-	-	10^{-2}	±10%
Non-colored	-	-	-	±20%

Precision resistances normally come in 5 color bands, the first three of which respectively represents "hundreds digit", "tens digit" and "single digit"; the fourth wheel represents "10 to the Nth power" and the fifth one is for "error". In addition to carbon electrical resistances, other resistances composed of different materials are available as well. Resistors of different types made of other materials are listed in Table 2. Some of the resistors directly labels their resistance values on themselves e.g. 10 MΩ or 5 KΩ, etc., some with error specified, e.g. 5%, 1%, while others can be identified with English alphabets. For the information on which English letter represents which error value, please refer to Table 3.

Table 2 Types of Materials for Resistors

Symbol	Main Resistance Materials
RD	Carbon Film
RN	Metal Film
RS(N)	Metal Oxide Film
RC	Carbon Composition
RK	Metal Composition
RW	Wire Wound (Power Type)
RB	Wire Wound (Precision Type)
RM	Chip Resistor
LP	Temperature Sensor
RA	Network Resistor

Table 3 Letters for Different Error Values Shown on Resistors

Symbol	N	Z	A	B	C	D	F	G	J	K	M
Error Tolerance(%)	±0.02	±0.025	±0.05	±0.1	±0.25	±0.5	±1	±2	±5	±10	±20

3. Instruments Required:

Dry batteries, a standard electrical resistance box, a slide-wire electric bridge, a galvanometer, several resistances to be measured, several cords and several different color code resistances to be measured

4. Steps to the Experiment

(1) R_2 is a set of resistances to be measured. Make sure everything is checked before allowing electrification.

(2) Place Probe B, which is output from galvanometer G, at the midpoint of MN first, and then set

the standard resistance box R_1 to adjust the hand of the galvanometer to nearly 0. Next, adjust Probe B until the hand of the galvanometer is precisely 0. At last, record electrical resistance R_1 and Probe Position, A and B. Try to apply equation (6) to acquire the value of R_2.

(3) Switch the positions of R_1 and R_2 and follow Step (2) to acquire the value of R_2 once again, and have it averaged with the previously-acquired R_2 value.

(4) Follow the approach above to complete the measurements of other electrical resistances

(5) Connect R_2 to color code resistance and repeat the steps given above.

5. Discussions:

(1) What are the relations between cords with the same materials and lengths as well as the relations between electrical resistances and their diameters.

(2) Calculate the coefficient of the cord resistance according to the statistics provided in this experiment, and judge what's the material of the cord. (Please provide the source of the references)

(3) Assume that the nicrome wire resistance's coefficient (ρ) and cross section area (A) are both provided, and that the coefficients of nickel and chromium resistances (ρN, ρC) are given as well, how to estimate the nickel- chromium proportion in a nicrome wire resistance.

6. Appendix

(1) A Guide to Standard Resistance Box Operation

1. A：Circuit Contact B：Electrically-conductive Plug C：Conductive Layer underneath the Board D：Resistance Wire
2. When the plugs are in place, the electric current will enter from A and pass through a short (circuit) without entering Resistance Wire D, thereby the resistance of which is 0.
3. When the conductive plug is pulled off, causing circuit break, the electric current will flow through the resistance wire. As Figure 7 indicates, we can get: the resistance value is 2 + 3 + 4 = 9 (ohms).

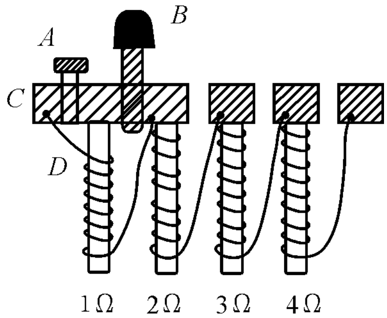


Figure 7

(2) Resistances with More Than 4 Color Codes

5 color code rings surround the metal film precision resistance. Aside from the last two color bands still representing “power numbers” and “errors”, the first three bands respectively represent “hundreds digit”, “tens digit” and “single digit”. Moreover, there are some resistances with two more color code bands available, which represent the coefficient(s) of temperatures.

EXP. 27 Capacitance

1. Section Purpose

A guide to electrical capacitance measurement adopting Wheatstone Bridge methodology and an introduction to the appearances and the displayed values on different capacitors.

2. Introduction

(1) Wheatstone Bridge

Given that the resistors R_3 and R_4 in the circuit of Wheatstone Bridge in Exp. 26 replaced with C1 and C2, and that the galvanometer replaced with an earphone and DC with AC (please see Figure 1.), then Wheatstone Bridge methodology can be applied to the measurement of capacitors' capacitances.

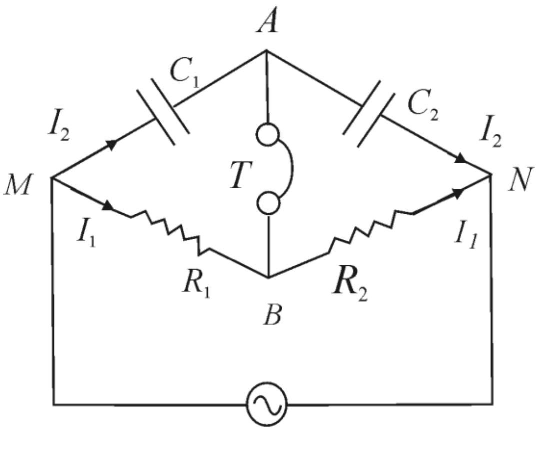


Figure 1

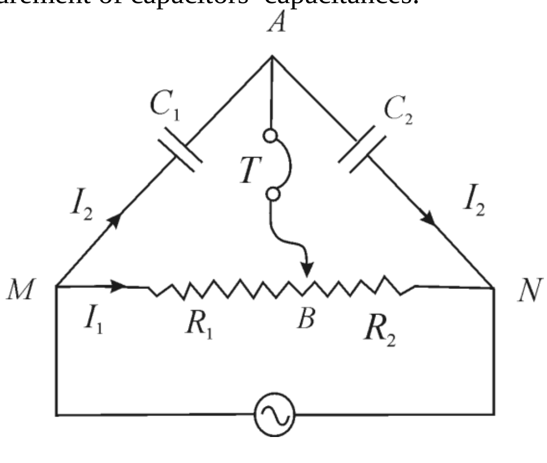


Figure 2

If the Earphone T lying in the circuit of Wheatstone Bridge makes no buzzes, that indicates no electric currents flowing through it. Namely, at a certain flash of time, the electric currents passing through both Resistors R1 and R2 are the same, which now we set as I_1, and similarly, the counterparts of Resistors C1 and C2 are as well the same, which now we set as I_2. At this time, Point A and B lying in the bridge are potentially-equal, thereby proving the electric potentials on ends of both R_1 and C_1 are equal; similarly, the electric potentials on ends of both R_2 and C_2 are equal as well, namely:

$$X_{C_1} I_2 = I_1 R_1$$

$$X_{C_2} I_2 = I_1 R_2$$

By dividing the two above, we can have

$$\frac{X_{C_1}}{X_{C_2}} = \frac{R_1}{R_2} - (1)$$

, in which X_{C_1} and X_{C_2} are respectively the condenses of both resistors. Inferring from the alternating current circuit theory, we can thereby acquire the relations between each capacitors' condense values and capacitance values with the following equations,

$$X_{C_1} = \frac{1}{\omega C_1} \text{,} \quad X_{C_2} = \frac{1}{\omega C_2}$$

where ω is the oscillating angular frequency of the AC supply ($\omega = 2\pi f$)，while f is the oscillation frequency of the DC supply.

Substitute（1）, and then we have the following:

$$\frac{C_2}{C_1} = \frac{R_1}{R_2}$$

Corollary:

$$C_2 = \frac{R_1}{R_2} C_1$$

From the resistance ratios of R_1 and R_2, the resistance value of C_2 is thereby gained.

(2) Resistances and Lengths of Slide-wire Resistance

From the previous experiment, we have learned that the resistances of resistance wires with identical materials and sizes are directly-proportional to their lengths, namely: $R \propto L$.

Therefore, the ratio of R_1 and R_2 will change by adjusting the contact position of the earphone connected to the resistance wire.（Figure 2）

If setting the length of the resistance wire from B to M as L_1, and the length from B to N as L_2, we can get the following:

$$\frac{R_1}{R_2} = \frac{L_1}{L_2}$$

Corollary: $C_2 = \frac{L_1}{L_2} C_1$

, thereby proving that from the given C_1 as well as L_1 and L_2 gained from the experiment, we can acquire C_2.

3. Instruments Required

A slide-wire bridge, a given capacitor, several resistors to be measured, earphones, a function generator (See appendix 8.)

4. Steps to the Experiment:

(1) Connect the wire as indicated in the figures above.

(2) Slide Jack *B* until the buzzing sounds from the earphone stop.

(3) Measure the values of L_1 and L_2 and substitute in Equation (4) to acquire the unknown capacitance(s).

5. Discussions

(1) Whether can dry batteries be used in this experiment? Try to explain your reasons?

(2) Will it be feasible if replacing earphones with galvanometers when doing the experiment? Try to explain your reasons?

(3) Will there be any influence on the experiment if different frequencies are output from the signal generator. Try to explain your reasons?

6. Supplements：

(1) Types of Capacitors

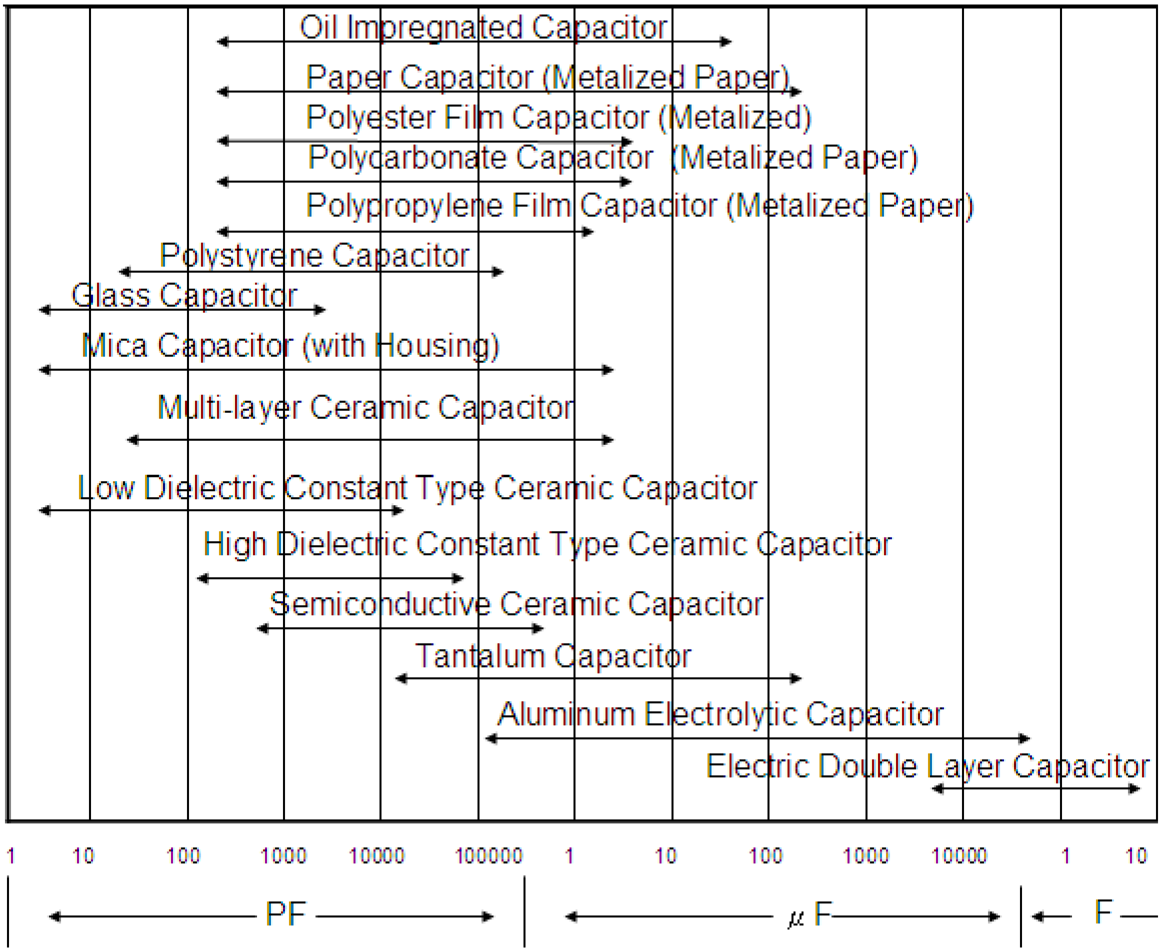
For further information on types or options of capacitors, and their corresponding electrical conductors and electrodes in use, please refer to Table 1.

Table 1 Types of Capacitors, and Their Corresponding Electrical Conductors and Electrodes in Use

Symbol	Types of Capacitors	Main Electrical Conductors	Types of Electrodes
CA	Aluminum Solid Electrolytic Capacitor	Aluminum Oxide Film	Aluminum Solid Electrolyte
CC	Ceramic Capacitor (Type 1)	Ceramic (for temperature compensation)	Coated Metal Film
CE	Aluminum Foiled Dry Electrolytic Capacitor	Aluminum Oxide Film	Liquid Aluminum Electrolyte
CF	Metalized or Plastic Film Capacitor	Thin Plastic Film	Vapor Deposited Metal Film/ Vapor Deposited Metal Film and Metal Foil Co-use
CH	Metalized Paper Capacitor	Paper/ Paper and Plastic Film	Vapor Deposited Metal Film/ Vapor Deposited Metal Film and Metal Foil Co-use
CK	Ceramic Capacitor (Type 2)	Ceramic (High-Dielectric Constant T ype Capacitor)	Coated Metal Film
CL	Tantalum Non-liquid Electrolytic Capacitor	Tantalum Oxide Film	Tantalum Liquid Electrolyte
CM	Mica Capacitor	Mica	Coated Metal Film/ Metal Foil
CP	Paper Capacitor	Paper/ Paper and Plastic Film	Metal Foil
CQ	Plastic Film Capacitor	Plastic Film	Metal Foil
CS	Tantalum Solid Electrolytic Capacitor	Tantalum Oxide Film	Tantalum Solid Electrolyte
CY	Glass Capacitor	Glass	Coated Metal Film
CG	Ceramic Capacitor (Type 2)	Ceramic (semi-conductor)	Coated Metal Film

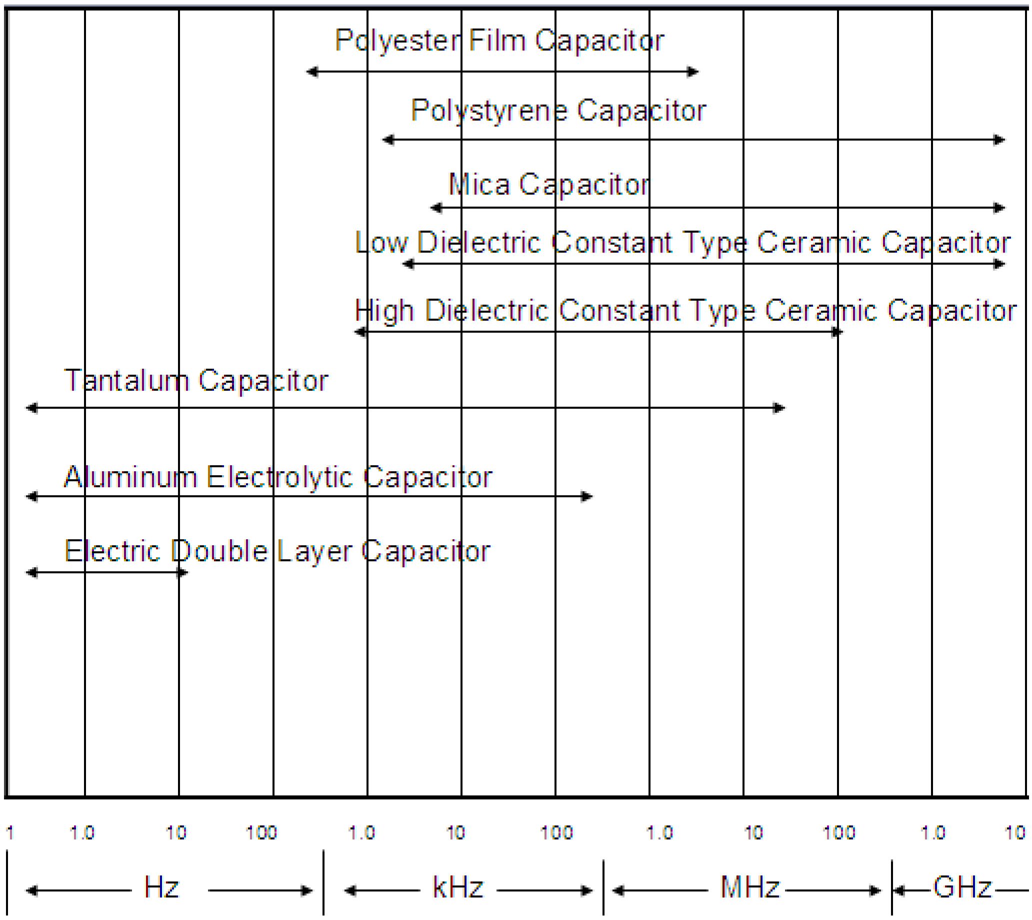
See Table 2 for further information on relations between various ranges of capacitance values and capacitors generated from different types of materials.

Table 2: Static Capacitance Values of Capacitors in Use



For the information on the operation frequency ranges of the capacitors made of different materials, please refer to Table 3.

Table 3: The Frequency Characteristics of the Capacitors in Use.



(2) Capacitor units

1. The commonly-seen units for electric capacitors are：μF，pF.
2. Values of electrical capacitances can be expressed in numbers as below:

   (1) Expressions for capacitance values in use

   a. Directly expressed in units：

      MF、MFD (micro farad)，μF = 10^{-6} F；

      MMFD (micro micro farad) = 1μμF = 1pF = 10^{-12} F；

      nF = 10^{-9}F；pF = 10^{-12} F。

   b. Units of values with decimal points or R(s) are expressed as μF.

   c. Units of 3 digit numbers, e.g. *abc*, are usually expressed as *ab* $\times 10^{c}$ pF unless their units are specified already.

   d. Units of 1 digit, 2 digit and 4 digit numbers are usually expressed as pF except for metalized polyesters, whose expression is μF.

(2) Expressions for error values in use

a. Directly expressed as 5%

b. Expressed in capital letters of English, as used in electrical resistance values (See Table 4.)

Table 4 Error Values Expressed in Capital letters of English

Representative English Letters	Values of Error	Representative English Letters	Values of Error	Representative English Letters	Values of Error
B	±0.1%	H	±3%	N	±30%
C	±0.25%	J	±5%	P	$^{+100}_{-0}$ %
D	±0.5%	K	±10%	V	$^{+20}_{-10}$ %
F	±1%	L	±15%	X	$^{+40}_{-20}$ %
G	±2%	M	±20%	Z	$^{+80}_{-20}$ %

(3) Rated voltage expressions are designed to regulate the voltage range for safe operations

a. WV (Working Voltage)：Voltage values for safe operation

b. TV (Testing Voltage)： The highest voltage tested at a certain flash of time

— jotting down voltage values directly, or

— expressed via color codes, e.g. polyester film capacitors, or

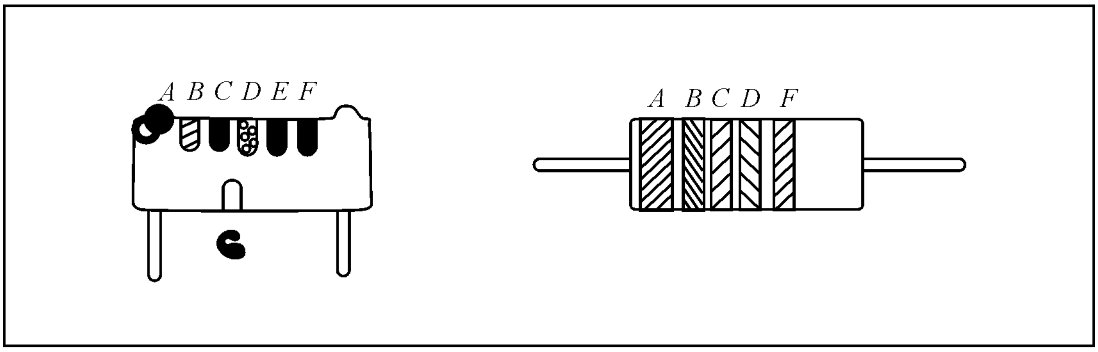
— expressed via numbers and capital letters of English e.g. 2B and 2E, as indicated in Table 5.

Table 5: Withstand Voltage Values (Unit: V) Expressed via Numbers and Capital Letters of English

Letters / Tolerance Limits / Numbers	A	B	C	D	E	F	G	H	I	J
0	1	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0
1	10	12.5	16	20	25	31.5	40	50	63	80
2	100	125	160	200	250	315	400	500	630	800
3	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000

3. Types of color codes for expressing electrical capacitance values:

   The following Figure 2 takes ceramic capacitors as examples to discuss the specific meanings represented by each bands of color codes. A and B both represent the temperature characteristics, which can be ignored for now, whereas C, D and E represent capacitance values and F represents capacitance tolerances (error ranges), on which the numbers that color bands represent share the same rules as those for electrical resistance (see Table 1 in Exp. 24.). The exact expression for such capacitance values will be $CD \times 10^{E} \pm F\%$ pF.



Six-Dot or -Band Code		*Five-Dot or -Band Code*	
A	Temperature coefficient	A	Temperature coefficient
C, D, E	Capacitance	C, D, E	Capacitance
F	Capacitance tolerance	F	Capacitance tolerance
G	Military code number		

Figure 2

4. Other expressions such as color dots won't be discussed here.

(3) Polarities of Capacitors in Use:

1. Capacitors made of tantalum and aluminum possess polarities, while the rest don't.
   (1) Assembling capacitors: Red dots symbolize positive polarities, while black dots represents negative ones.
   (2) Horizontal capacitors: The indented ends represent positive.
   (3) Vertical and assembling capacitors: "+" and "-" are marked on the end closer to conductive cords.
2. If polarities are mistakenly connected, or voltages on both ends exceed the safety ranges regulated, consequent electrificative activities will cause explosions.

EXP. 28 Kirchhoff's Law

1. Section Purpose:

To apply Kirchhoff's law to general direct electric current webs

2. Introduction:

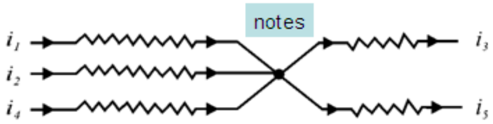


Figure 1

Kirchhoff's law is a fundamental approach to acquiring theoretical values of electric currents and voltages. Detailed as below are two major sections of the law, Kirchhoff's current law and Kirchhoff's voltage law.

(1) Kirchhoff's Current Law：

Intersection points of each branch electric currents within the net are called nodes. From law of charge conservation, we're given a fact that an electric current flowing into a node definitely equals to one flowing out, namely,

$$\sum I_i = 0 \tag{1}$$

As indicated in Figure 1, if a current flowing in is positive, and one flowing out is negative, we can express such a scenario in the equation as below:

$$I_1 + I_2 - I_3 + I_4 - I_5 = 0 \tag{2}$$

(2) Kirchhoff's Voltage Law：

From the law of conservation of energy, we can learn that along a certain closed current, the power generated from electromotive force absolutely equals to the energy consumed on a certain component. The definition of electrical potential difference is the difference in electric potential between the final and the initial location when work is done upon a charge to change its potential energy. Therefore, for any closed loop, the algebra sum of the potential difference will absolutely be 0, namely,

$$\Sigma\Delta V_i = 0 \tag{3}$$

(3) Steps to Kirchhoff's Law Application:

1. Set each branch current as I_1、I_2......

   Notice:

   (1) The direction of each branch current can be presumed at will; however, if the acquired result value is negative, it indicates that the current direction should be opposite to the assumed direction.

   (2) After the current direction is presumed, the polarity of the electric resistance can be determined; the entering end is positive, and the off end is negative.

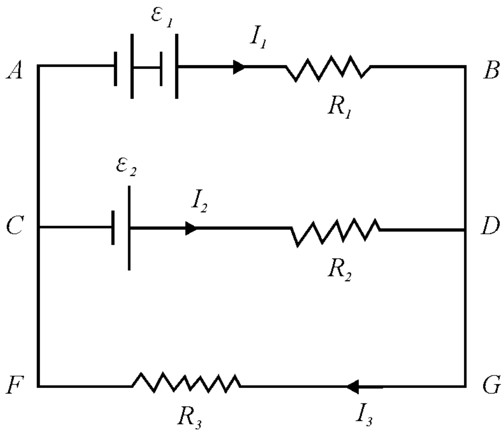
   

   Figure 2

   (3) Polarities of a battery is not subject to the direction of a current.

2. Make equations upon Kirchhoff's current law. If the number of nodes is n, then $n-1$ independent equations can be thereby made.
3. Specify each loop direction.
4. Make equations for each circuit upon Kirchhoff's voltage law. If the number of nodes is n, then $n-1$ independent equations can be thereby made.
5. Solve simultaneous equations so as to acquire the currents of each branch.

(4) Shown in Figure 2 is one of the circuits in this experiment. From node D, the following are gained.

$$I_1 + I_2 - I_3 = 0 \tag{4}$$

From Circuit *ABDCA*, we earn

$$\varepsilon_1 - I_1R_1 + I_2R_2 - \varepsilon_2 = 0 \tag{5}$$

From Circuit CDGFC, we earn

$$\varepsilon_2 - I_2R_2 - I_3R_3 = 0 \tag{6}$$

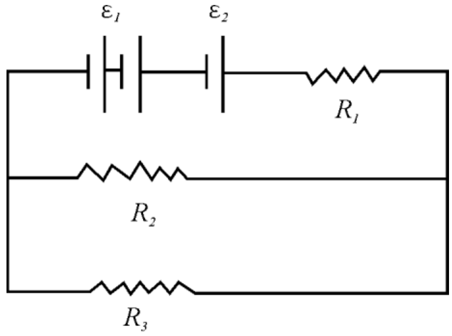
(4)、(5)、(6) are simultaneous equations, from which we can get the following:

$$I_1 = \frac{(R_2 + R_3)\varepsilon_1 - R_3\varepsilon_2}{R_1R_2 + R_1R_3 + R_2R_3} \qquad (7)$$

$$I_2 = \frac{(R_1 + R_3)\varepsilon_2 - R_3\varepsilon_1}{R_1R_2 + R_1R_3 + R_2R_3}$$

$$I_3 = \frac{R_2\varepsilon_1 + R_1\varepsilon_2}{R_1R_2 + R_1R_3 + R_2R_3}$$

Having gained the current and the voltage on the component, by employing Ohm's law, we can have $V_1 = I_1R_1$.



(8)

(9)

Figure 3

3. Instruments Required：

A DC power supply (See Appendix 9.), batteries, a set of power chip resistors, a desktop digital VOM (See Appendix 10.), connection wires

4. Steps to the Experiment:

(1) As shown in Figure 2, set a DC power supply as ε_1, and then set the voltmeter to be $\varepsilon_1 = 5V$.（Never raise voltage values without professional instructors' permission.）Set batteries as ε_2, and them measure the values of ε_2 with a voltmeter and record ε_1 and ε_2.

(2) Resistances within the circuit are respectively set as R_1=20Ω，R_2=50Ω and R_3=200Ω.

(3) Only when the wires are accurately connected and checked by the professor responsible for the class can the voltmeter be energized to take measurements

(4) Parellely connect the voltmeter with R_1，R_2 and R_3, which allows us to acquire the experiment values of V_1，V_2 and V_3. Upon wiring, do use alligator clamps to fix the circuit wires in place to diminish errors.

(5) Use an ammeter to measure the experiment values of R_1，R_2，R_3's current values, I_1，I_2 and I_3.

Notice:

1. The ammeter needs to be parelelly connected with the circuit, so some certain parts of it need to be separated first.
2. Pay attention to the polarities of the ammeter.
3. Before the current is known, to gain statistics required, voltage levels should be employed from the maximum to the minimum until the most proper level is found.

(6) Use Kirchhoff's Law to acquire theoretical values of each current ,voltage as well as voltage

error (%)

(7) To modify circuits in the experiment, please have it done as Figure 3 indicates, and repeat Step 1 to Step 6.

5. Discussions:

(1) Why are ammeters needed ? Why do voltmeters require to be parelelly-connected?

(2) As the circuit layout illustrated in Figure 3, if $\varepsilon_1 = 5V$, $\varepsilon_2 = 1.5V$, $R_1 = 20\Omega$, $R_2 = 50\Omega$ and $R_3 = 200\Omega$, equations required can be inferred from Kirchhoff's Law. What are the theoretical values of the currents passing through each resistance?

(3) As the circuit layout shown in Figure 3 , through circuit analysis, what are the currents passing through each resistance respectively? (Set I_1 to pass through R_1 and turn right ; I_2 to pass through R_2 and turn left ; I_3 to pass through R_3 and turn left.