1st Lec: by Wadut Shaikh (Basic Instrumentation Skills)

True value: standard or reference of known value or a theoretical value

Accuracy: closeness to the true value; closeness with which an instrument reading approaches the true or accepted value of the variable (quantity) being measured. It is considered to be an indicator of the total error in the measurement without looking into the sources of errors.

Precision: a measure of the reproducibility of the measurements; given a fixed value of a variable, precision is a measure of the degree to which successive measurements differ from one another i.e., a measure of reproducibility or agreement with each other for multiple trials.

Sensitivity: the ability of the measuring instrument to respond to changes in the measured quantity. It is expressed as the ratio of the change of output signal or response of the instrument to a change of input or measured variable.

Resolution: the smallest change in measured value to which the instrument will respond, i.e. the smallest incremental quantity that can be reliably measured.
Error: deviation from the true value of the measured variable.

Accuracy and Precision

A measurement isn't very meaningful without an error estimate! No measurement made is ever exact. The accuracy (correctness) and precision (number of significant figures) of a measurement are always limited by apparatus used, skill of the observer and the basic physics in the experiment and the experimental technique used to access it. The goal of the experimenter is to obtain the best possible value of some quantity or to validate/falsify a theory. What comprises a deviation from a theory? Every measurement must give the range of possible value. Let look at the following example:

Accuracy is defined as the degree of conformity of a measured value to the true (conventionaltrue value – CTV) or accepted value of the variable being measured. It is a measure of the total error in the measurement without looking into the sources of the errors. Mathematically it is expressed as the maximum absolute deviation of the readings from the CTV. This is called the absolute accuracy.

$$Absolute\ accuracy = |maximum\ devation\ from\ CTV|$$

$$Relative\ accuracy = \frac{absolute\ accuracy}{CTV} \quad ; \ .$$

$$Percentage(\%)\ accuracy = relative\ accuracy \times 100$$

Example A voltmeter is used for reading on a standard value of 50 volts, the following readings are obtained: 47, 52, 51, 48
Conventional true value (CTV) = 50 volts,
Maximum (VMAX) = 52 volts and minimum (VMIN) = 47 volts.
CTV – VMIN = 50 – 47 = 3 volts; VMAX – CTV = 52 – 50 = 2 volts.
Absolute accuracy = max of {3, 2} = 3 volts.
Relative accuracy = 3/50 = 0.06 and % accuracy = 0.06x100 = 6%

Precision

Precision is composed of two characteristics as conformity and the number of significant figures. Conformity The conformity is the ability of an instrument to produce the same reading, or it is the degree of agreement between individual measurements. So, it is also called repeatability or reproducibility. Mathematically it is expressed as "the absolute maximum deviation from the average of the readings", i.e

Precision (Pr) = max $\{(V_{AV} - V_{MIN}), (V_{MAX} - V_{AV})\}$.

Accuracy versus Precision

The distinction between accuracy and precision can be illustrated by an example: two voltmeters of the same make and model may be compared. Both meters have knife-edged pointers and mirror-backed scales to avoid parallax, and they have carefully calibrated scales. They may therefore be read to the same precision. If the value of the series resistance in one meter changes considerably, its readings may be in error by a fairly large amount. Therefore the accuracy of the two meters may be quite different. To determine which meter is in error, a comparison measurement with a standard meter should be made. Accuracy refers to the degree of closeness or conformity to the true value at the quantity under measurement. Precision refers to the degree of agreement within a group of measurements or instruments. The target-shooting example shown in figure 2.2 illustrates the difference. The high accuracy, poor precision situation occurs when the person hits all the bullets on a target plate on the outer circle and misses the bull's eye. In the second case, all.

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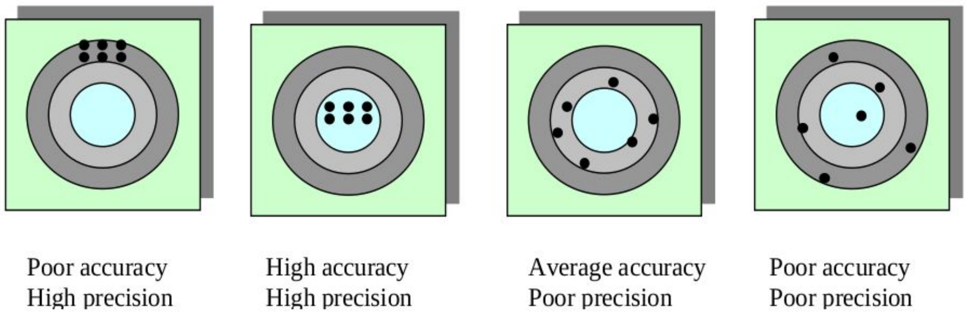
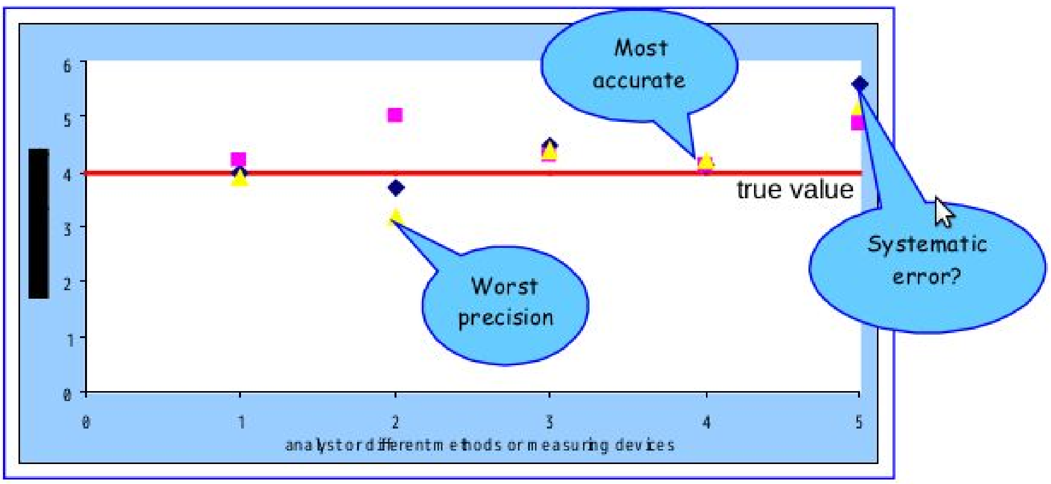


bullets hit the bull's eye and spaced closely enough leading to high accuracy and high precision. The bullet hits are placed symmetrically with respect to the bull's eye in the third case but spaced apart yielding average accuracy but poor precision. In the last example, the bullets hit in a random manner, hence poor accuracy and poor precision.

The scatter graph in the following figure, shows an alternative way of presenting the accuracy and precision. Same quantity was measured three times by 5 different analyst or methods or measuring instruments. Distribution of readings around the true value indicates the most accurate, most precise and least accurate and least precise readings. The last reading is too far away from the true value and from other readings that may indicate a systematic error.



Precision is composed of two characteristics as stated: conformity and the number of significant figures to which a measurement may be made. Consider, for example, that the insulation resistance of a transformer has the true value 2,475,653 Ω. It is measured by an ohmmeter, which consistently and repeatedly indicates 2.5 MΩ. But can the observer "read" the true value from the scale? His estimates from the scale reading consistently yield a value of 2.5 MΩ. This is as close to the true value as he can read the scale by estimation. Although there are no deviations from the observed value, the error produced by the limitation of the scale reading is a precision error. The example illustrates that conformity is a necessary, but not sufficient, condition for precision because of the lack of significant figures obtained. Similarly, precision is a necessary, but not sufficient condition for accuracy.

Too often the beginning student is inclined to accept instrument readings at face value.
He is not aware that the accuracy of a reading is not necessarily guarantied by its precision. In fact, good measurement technique demands continuous skepticism as to the accuracy of the results. In critical work, good practice dictates that the observer make an independent set of measurements, using different instruments or different measurement techniques, not subject to the same systematic errors. He must also make sure that the instruments function properly and are calibrated against a known standard, and that no outside influence affects the accuracy of his measurements.

Wadut Shaikh (11/02/2020)

Introduction

Through measurement, we try to obtain the value of an unknown parameter. However this measured value cannot be the actual or true value. If the measured value is very close to the true value, we call it to be a very accurate measuring system. But before using the measured data for further use, one must have some idea how accurate is the measured data. So error analysis is an integral part of measurement. We should also have clear idea what are the sources of error, how they can be reduced by properly designing the measurement methodology and also by repetitive measurements. These issues have been dwelt upon in this lesson. Besides, for maintaining the accuracy the readings of the measuring instrument are frequently to be compared and adjusted with the reading of another standard instrument. This process is known as calibration. We will also discuss about calibration in details.

Error Analysis

The term error in a measurement is defined as:
Error = Instrument reading – true reading

Error is often expressed in percentage as:

%error = $(Instrument\ reading - \ true\ reading) * 100/true\ reading$

The errors in instrument readings may be classified in to three categories as:
1. Gross errors
2. Systematic errors
3. Random Errors.

Gross errors arise due to human mistakes, such as, reading of the instrument value before it reaches steady state, mistake of recording the measured data in calculating a derived measured, etc. Parallax error in reading on an analog scale is also is also a source of gross error. Careful reading and recording of the data can reduce the gross errors to a great extent. Systematic errors are those that affect all the readings in a particular fashion. Zero error, and bias of an instrument are examples of systematic errors. On the other hand, there are few errors, the cause of which is not clearly known, and they affect the readings in a random way. This type of errors is known as Random error. There is an important difference between the systematic errors and random errors. In most of the case, the systematic errors can be corrected by calibration, whereas the random errors can never be corrected, the can only be reduced by averaging, or error limits can be estimated.

Systematic Errors

Systematic errors may arise due to different reasons. It may be due to the shortcomings of the instrument or the sensor. An instrument may have a zero error, or its output may be varying in a nonlinear fashion with the input, thus deviating from the ideal linear input/output relationship. The amplifier inside the instrument may have input offset voltage and current which will contribute to zero error. Different nonlinearities in the amplifier circuit will also cause error due to nonlinearity. Besides, the systematic error can also be due to improper design of the measuring scheme. It may arise due to the loading effect, improper selection of the sensor or the filter cut off frequency. Systematic errors can be due to environmental effect also. The sensor characteristics may change with temperature or other environmental conditions. The major feature of systematic errors is that the sources of errors are recognisable and can be reduced to a great extent by carefully designing the measuring system and selecting its components. By placing the instrument in a controlled environment may also help in reduction of systematic errors. They can be further reduced by proper and regular calibration of the instrument.

Random Errors

It has been already mentioned that the causes of random errors are not exactly known, so they cannot be eliminated. They can only be reduced and the error ranges can be estimated by using some statistical operations. If we measure the same input variable a number of times, keeping all other factors affecting the measurement same, the same measured value would not be repeated, the consecutive reading would rather differ in a random way. But fortunately, the deviations of the readings normally follow a particular distribution (mostly normal distribution) and we may be able to reduce the error by taking a number of readings and averaging them out. Few terms are often used to chararacterize the distribution of the measurement, namely,

$$\textit{Mean Value}\quad \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (3)$$

where n is the total number of readings and x_i is the value of the individual readings. It can be shown that the mean value is the most probable value of a set of readings, and that is why it has a very important role in statistical error analysis. The *deviation* of the individual readings from the mean value can be obtained as :

$$\textit{Deviation}\qquad d_i = x_i - \bar{x} \qquad (4)$$

We now want to have an idea about the deviation, i.e., whether the individual readings are far away from the mean value or not. Unfortunately, the *mean of deviation* will not serve the purpose, since,

$$\textit{Mean of deviation} = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x}) = \bar{x} - \frac{1}{n}(n\bar{x}) = 0$$

So instead, variance or the mean square deviation is used as a measure of the deviation of the set of readings. It is defined as:

$$\text{Variance} \quad V = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 = \sigma^2 \qquad (5)$$

The term σ is denoted as *standard deviation.* It is to be noted that in the above expression, the averaging is done over *n-1* readings, instead of *n* readings. The above definition can be justified, if one considers the fact that if it is averaged over *n*, the variance would become zero when *n*=1 and this may lead to some misinterpretation of the observed readings. On the other hand the above definition is more consistent, since the variance is undefined if the number of reading is *one*. However, for a large number of readings (*n*>*30*), one can safely approximate the variance as,

$$\text{Variance}\, V = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 = \sigma^2 \qquad (6)$$

The term *standard deviation* is often used as a measure of uncertainty in a set of measurements.

What is the loading effect of Electrical measurement instruments?

Loading effect is the degree to which a measurement instrument impacts electrical properties (voltage, current, resistance) of a circuit.

Example:

Loading effect of voltmeters

A voltmeter always connects in parallel to electronic components for measuring the voltage. Practical voltmeters are designed to possess very high internal resistance (usually 10 or 20 MΩ). There are two cases which might result in fault measurements.

1. When voltmeter connects to a very high external resistance the overall resistance of circuit changes. For example, a voltmeter with 10 MΩ internal resistance while connected in parallel to 7.5 MΩ resistors will change overall resistance to 4.28 MΩ.
2. When internal resistance of voltmeter is small and it connects to external resistance. The overall resistance will be changed.

Both above cases change the working of the circuit and thus lead to inappropriate readings.

Loading effect of the ammeter

The ammeter connects in series for measuring current flow through a circuit. A practical ammeter is built with very small internal resistance (10 – 100 Ω). Two possible cases which impact working of ammeter are:

1. When ammeter connects to a low resistance circuit the overall resistance of circuit stretches to a noticeable amount. e.g when a meter with 50 ohms internal resistance connects to a 100 ohms circuit the overall resistance of circuit increases by 3 times. This also impacts current and voltage by 3 times.

2. When internal resistance of meter is high the same impact results and electrical parameters of circuit vary.

Multimeter: Principles of measurement of dc voltage and dc current, ac voltage, ac current and resistance: It is the basic principle of measurements. You did in your lab.

The handheld digital multimeter (DMM) is the most common of all electrical and electronic test instruments. Following are some important performance specifications that need to be considered. Display Digits - The display must be capable of showing the reading depending upon the application. For a process where the whole 7-digit display is required, a three-and-a-half-digit display would prove useless.

Resolution - Resolution is a measure of the smallest increment that may be discerned. Higher the resolution, better the DMM. Although this is not true in all cases, as other parameters like applications, measuring rate, etc. are also considered.

Accuracy - It is the probability of the reading being accurate. High accuracy is always preferred. Uncertainty - It is a characteristic considered with conjunction to accuracy; i.e. if there is a 1% uncertainty with a DMM, it will give out readings that are 99% accurate. Manufacturers use this term to indicate how the device may go wrong in practice.

Repeatability - It is often more important than absolute accuracy when making a series of measurements. It is the degree of measurement that will give out the same reading each time a measurement is repeated.

Calibration - It indicates how well the DMM has been tested against various quantity measurements and how closer they were to the intended value.

True RMS - RMS measurements are a measure of the equivalent heating effect produced by a voltage and, to be accurate, must include any DC component present along with the AC component that most users associate with RMS readings.

Crest Factor - It is defined as the ratio of the peak or "crest" voltage compared to the RMS voltage.

Form Factor - It is defined as the ratio of the RMS value to the average value and is the factor that when multiplied by the average value of a waveform will equal the RMS value.

Environmental & Safety ratings - The DMM has to be checked for being insensitive to environmental changes, and that they were manufactured by abiding to various safety norms that are enlisted by different international electrical safety commissions.

A Short Guide to Significant Figures

What is a "significant figure"?

The number of significant figures in a result is simply the number of figures that are known with some degree of reliability. The number 13.2 is said to have 3 significant figures. The number 13.20 is said to have 4 significant figures.

Rules for deciding the number of significant figures in a measured quantity:

(1) All nonzero digits are significant:

1.234 g has 4 significant figures,
1.2 g has 2 significant figures.

(2) Zeroes between nonzero digits are significant:

1002 kg has 4 significant figures,
3.07 mL has 3 significant figures.

(3) Zeroes to the left of the first nonzero digits are not significant; such zeroes merely indicate the position of the decimal point:

0.001^o C has only 1 significant figure,
0.012 g has 2 significant figures.

(4) Zeroes to the right of a decimal point in a number are significant:

0.023 mL has 2 significant figures,
0.200 g has 3 significant figures.

(5) When a number ends in zeroes that are not to the right of a decimal point, the zeroes are not necessarily significant:

190 miles may be 2 or 3 significant figures, 50,600 calories may be 3, 4, or 5 significant figures. The potential ambiguity in the last rule can be avoided by the use of standard exponential, or "scientific," notation. For example, depending on whether 3, 4, or 5 significant figures is correct, we could write 50,6000 calories as:

5.06×10^4 calories (3 significant figures)
5.060×10^4 calories (4 significant figures), or
5.0600×10^4 calories (5 significant figures).

What is a "exact number"?

Some numbers are exact because they are known with complete certainty.

Most exact numbers are integers: exactly 12 inches are in a foot, there might be exactly 23 students in a class. Exact numbers are often found as conversion factors or as counts of objects.

Exact numbers can be considered to have an infinite number of significant figures. Thus, number of apparent significant figures in any exact number can be ignored as a limiting factor in determining the number of significant figures in the result of a calculation.

Rules for mathematical operations

In carrying out calculations, the general rule is that the accuracy of a calculated result is limited by the least accurate measurement involved in the calculation.

(1) In addition and subtraction, the result is rounded off to the last common digit occurring furthest to the right in all components. For example, 100 (assume 3 significant figures) + 23.643 (5 significant figures) = 123.643, which should be rounded to 124 (3 significant figures).

(2) In multiplication and division, the result should be rounded off so as to have the same number of significant figures as in the component with the least number of significant figures. For example, 3.0 (2 significant figures) 12.60 (4 significant figures) = 37.8000 which should be rounded off to 38 (2 significant figures).

Rules for rounding off numbers

(1) If the digit to be dropped is greater than 5, the last retained digit is increased by one. For example,

12.6 is rounded to 13.

(2) If the digit to be dropped is less than 5, the last remaining digit is left as it is. For example,

12.4 is rounded to 12.

(3) If the digit to be dropped is 5, and if any digit following it is not zero, the last remaining digit is increased by one. For example,

12.51 is rounded to 13.

(4) If the digit to be dropped is 5 and is followed only by zeroes, the last remaining digit is increased by one if it is odd, but left as it is if even. For example,

11.5 is rounded to 12,
12.5 is rounded to 12.

This rule means that if the digit to be dropped is 5 followed only by zeroes, the result is always rounded to the even digit. The rationale is to avoid bias in rounding: half of the time we round up, half the time we round down.

General guidelines for using calculators

When using a calculator, if you work the entirety of a long calculation without writing down any intermediate results, you may not be able to tell if a error is made and, even if you realize that one has occurred, you may not be able to tell where the error is.

In a long calculation involving mixed operations, carry as many digits as possible through the entire set of calculations and then round the final result appropriately. For example,

(5.00 / 1.235) + 3.000 + (6.35 / 4.0)=4.04858... + 3.000 + 1.5875=8.630829...

The first division should result in 3 significant figures; the last division should result in 2 significant figures; the three numbers added together should result in a number that is rounded off to the last common significant digit occurring furthest to the right (which in this case means the final result should be rounded with 1 digit after the decimal). The correct rounded final result should be 8.6. This final result has been limited by the accuracy in the last division.

Warning: carrying all digits through to the final result before rounding is critical for many mathematical operations in statistics. Rounding intermediate results when calculating sums of squares can seriously compromise the accuracy of the result.

What Is a Chi-Square Statistic?

A chi-square (χ^2) statistic is a test that measures how expectations compare to actual observed data (or model results). The data used in calculating a chi-square statistic must be random, raw, mutually exclusive, drawn from independent variables, and drawn from a large enough sample. For example, the results of tossing a coin 100 times meet these criteria.

The Formula for Chi-Square

$$\chi_c^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

where:

c=degrees of freedom

O=observed value(s)

E=expected value(s)

Curve fitting:

Curve fitting[1][2] is the process of constructing a curve, or mathematical function, that has the best fit to a series of data points,[3] possibly subject to constraints.[4][5] Curve fitting can involve either interpolation,[6][7] where an exact fit to the data is required, or smoothing,[8][9] in which a "smooth" function is constructed that approximately fits the data. A related topic is regression analysis,[10][11] which focuses more on questions of statistical inference such as how much uncertainty is present in a curve that is fit to data observed with random errors. Fitted curves can be used as an aid for data visualization,[12][13] to infer values of a function where no data are available,[14] and to summarize the relationships among two or more variables.[15] Extrapolation refers to the use of a fitted curve beyond the range of the observed data,[16] and is subject to a degree of uncertainty[17] since it may reflect the method used to construct the curve as much as it reflects the observed data.

Digital Multimeter

USE: Multimeters can be used as an ammeter, a voltmeter, an ohmmeter; by operating a multi-position knob on the meter. They can measure DC as well as AC (but you shall rarely require measuring an AC quantity in robotics). There are also special functions in a multimeter like ‘Detecting a Short Circuit’, testing transistors and some have additional features for measuring capacitance & frequency.

They are available in two types in market :

<u>Analog Multimeter:</u>

- Analogue meters take a little power from the circuit under test to operate their pointer (a hand like in a clock to indicate the reading).
- They must have a high sensitivity of at least 20k /V or they may upset the circuit under test and give an incorrect reading.

<u>Digital Multimeter</u>

- All digital meters contain a battery to power the display so they use virtually no power from the circuit under test
- They have a digital display as shown.

Measuring resistance with a multimeter

To measure the resistance of a component it must not be connected in a circuit. If you try to measure resistance of components in a circuit you will obtain false readings (even if the supply is disconnected) and you may damage the multimeter. The techniques used for each type of meter are very different so they are treated separately:

Measuring resistance with a DIGITAL multimeter

1. Set the meter to a resistance range greater than you expect the resistance to be. Notice that the meter display shows "off the scale" (usually blank except for a 1 on the left). Don't worry, this is not a fault, it is correct - the resistance of air is very high!

2. Touch the meter probes together and check that the meter reads zero. If it doesn't read zero, turn the switch to 'Set Zero' if your meter has this and try again.

3. Put the probes across the component.

Avoid touching more than one contact at a time or your resistance will upset the reading! If the meter reads 1, this means that the resistance is more than the maximum which can be measured on this range and you may need to switch to a new position, 2000 k or so, to take a reading.

Note: It is recommended purchasing a multimeter with a 'continuity' feature built in. This mode allows us to 'tone' out circuits. In this mode, if you touch the two probes together (or there is a short circuit), you should hear a tone indicating that there is a direct connection between one probe and the other (obviously - you have them touching!). This feature is used countless times during troubleshooting

Measuring Voltage with Voltmeter

1. Select a voltage range with a maximum greater than you expect the reading to be. If the reading goes off the scale immediately disconnect and select a higher range.

2. Connect the red (positive +) lead to the point you where you need to measure the voltage

3. The black lead can be left permanently connected to 0V while you use the red lead as a probe to measure voltages at various points. (The black lead can be fitted by using a crocodile clip.)

Similarly you can measure the current by choosing a suitable range. If it displays a ‘1’ at left, choose a higher current range.

Testing a diode with a DIGITAL multimeter

1. Digital multimeters have a special setting for testing a diode, usually labeled with the diode symbol.

2. Connect the red (+) lead to the anode and the black (-) to the cathode. The diode should conduct and the meter will display a value (usually the voltage across the diode in mV, 1000mV = 1V).

3. Reverse the connections. The diode should NOT conduct this way so the meter will display "off the scale" (usually blank except for a 1 on the left).

How to measure capacitance

A multimeter determines capacitance by charging a capacitor with a known current, measuring the resulting voltage, then calculating the capacitance.

Warning: A good capacitor stores an electrical charge and may remain energized after power is removed. Before touching it or taking a measurement, a) turn all power OFF, b) use your multimeter to confirm that power is OFF and c) carefully discharge the capacitor by connecting a resistor across the leads (as noted in the next paragraph). Be sure to wear appropriate personal protective equipment.

To safely discharge a capacitor: After power is removed, connect a 20,000 ?, 5-watt resistor across the capacitor terminals for five seconds. Use your multimeter to confirm the capacitor is fully discharged.

1. Use your digital multimeter (DMM) to ensure all power to the circuit is OFF. If the capacitor is used in an ac circuit, set the multimeter to measure ac voltage. If is used in a dc circuit, set the DMM to measure dc voltage.
2. Visually inspect the capacitor. If leaks, cracks, bulges or other signs of deterioration are evident, replace the capacitor.
3. Turn the dial to the Capacitance Measurement mode ( ). The symbol often shares a spot on the dial with another function. In addition to the dial adjustment, a function button usually needs to be pressed to activate a measurement. Consult your multimeter's user manual for instructions.
4. For a correct measurement, the capacitor will need to be removed from the circuit. Discharge the capacitor as described in the warning above.
   Note: Some multimeters offer a Relative (REL) mode. When measuring low capacitance values, the Relative mode can be used to remove the capacitance of the test leads. To place a multimeter in Relative mode for capacitance, leave the test leads open and press the REL button. This removes the residual capacitance value of the test leads.
5. Connect the test leads to the capacitor terminals. Keep test leads connected for a few seconds to allow the multimeter to automatically select the proper range.
6. Read the measurement displayed. If the capacitance value is within the measurement range, the multimeter will display the capacitor's value. It will display

OL if a) the capacitance value is higher than the measurement range or b) the capacitor is faulty.

Difference between analog instruments and digital instruments

Analog instrument	Digital instrument
The instrument which gives output that varies continuously as quantity to be measured is known as analog instrument.	The instrument which gives output that varies in discrete steps and only has finite number of values is known as digital instrument.
The accuracy of analog instruments is less.	The accuracy of digital instruments is more.
The analog instruments required more power.	The digital instruments required less power.
Sensitivity of analog instruments is more.	Sensitivity of digital instruments is less.
The analog instruments are cheap.	The digital instruments are expensive.
The analog instruments are extremely portable.	The digital instruments are not easily portable.
The resolution of analog instruments is less.	The resolution of digital instruments is more.

Block diagram of digital multimeter