Pearson BTEC Higher Nationals in Electrical and Electronic Engineering (QCF)

Unit 22: Electronic Devices and Circuits

Unit Workbook

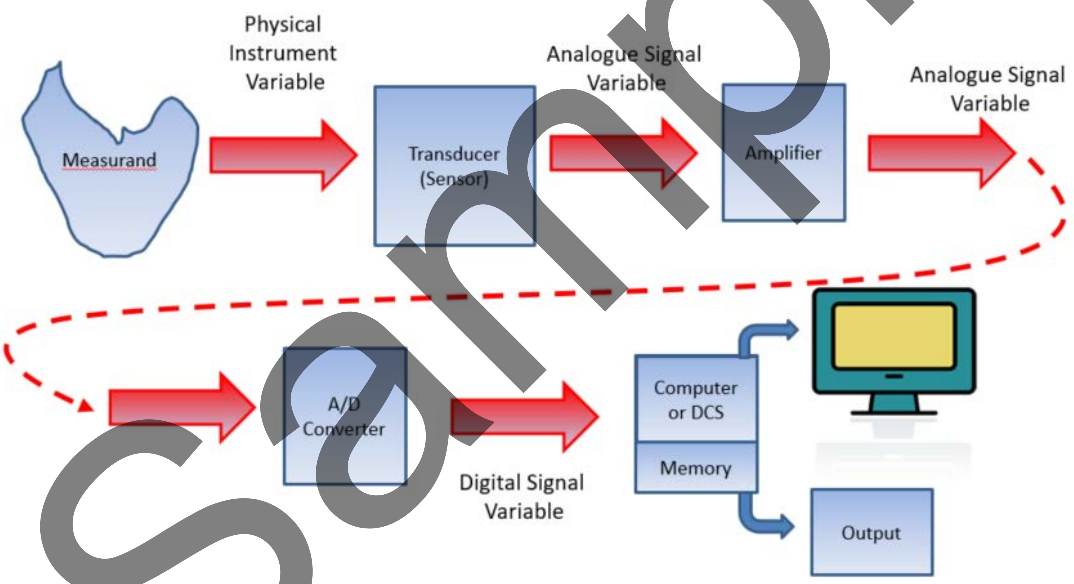
Learning Outcome 4:

Testing Procedures

1.1 Measurement Systems and Terms

1.1.1 Measurement Systems

Measurement systems inevitably collect some form of information from the real world and increasingly the information collected will be processed and stored in a computer. We will deal with the process of making the information compatible with computers later, but it is sufficient to say at this point that most real-world events and their measurements are in an analog form. That is, the measurements can take a wide and continuous range of values. The physical quantity of interest could be temperature, pressure, velocity, position or any other aspect of the system under consideration. In order that the measurement of interest can be processed by our measuring system, these physical quantities need to be converted to some form that can be recognised by the measuring system. These will usually be electrical quantities such as voltage, current, or impedance and the device which undertakes this conversion is a transducer. The analog voltage or current is then converted into a digital signal which can be interpreted and processed by a Digital Control System (DCS) or computer system. Thus, the general arrangement of a measuring system is as shown below.



1.1.2 Transducers

Most data acquisition signals can be described as analog, digital, or pulse. While analog signals typically vary smoothly and continuously over time, digital signals are present at discrete points in time. In most control applications, analog signals range continuously over a specified current or voltage range, such as 4-20 mA dc or 0 to 5 V dc. While digital signals are essentially on or off, analog signals represent continuously variable entities such as temperatures, pressures, or flow rates. Because computer-based controllers and systems understand only discrete on/off information, conversion of analog signals to digital representations is necessary.

Transduction is the process of changing energy from one form into another. Hence, a transducer is a device that converts physical energy into an electrical voltage or current signal for transmission. There are many different forms of analog electrical transducers. Common transducers include load cells for measuring strain via resistance, and thermocouples and resistance temperature detectors (RTDs) for measuring temperature via voltage and resistance measurement, respectively. Transmission channels are many and varied and we will discuss these later in this workbook.

The operation of a transducer can be described by the following simple equation:

$$Output\ Quantity = H * Input\ Quantity$$

Where H is the transfer function.

For the purposes of this course, all transducers convert physical quantities into electrical ones; in other words, they convert one form of energy into another. Given that the transducer is at the front end of measurement operations, its properties and performance are critical to the performance of the measurement system as a whole. Some of these properties are as follows;

- Response; or more accurately, the **Dynamic Response** of a measuring instrument is the change in the output y caused by a change in the input x, where x and y are functions of time t.
- Impulse Response; the **Impulse Response**, of a dynamic system is its output when presented with a brief input signal, called an impulse.
- Frequency Response; **Frequency Response** is the quantitative measure of the output spectrum of a system or device in **response** to a stimulus, and is used to characterize the dynamics of the system. It is a measure of magnitude and phase of the output as a function of **frequency**, in comparison to the input.
- Resolution; **Resolution** is the smallest unit of measurement that can be indicated by the measuring system.
- Sensitivity; **Sensitivity** is a measure of the efficiency of the conversion process. It is the smallest amount of **difference** in quantity that will change an instrument's reading. A measuring tape for example will have a **resolution**, but not **sensitivity**.
- Transfer Function; Transfer Function is the ratio of the output quantity to the input quantity of a system
- Stability; Stability is a measure of how the accuracy and precision of the measurement system perform over time. In other words, it is a measure of how much the output drifts in the face of a constant input. Stability will determine the required interval between calibration of the measurement system.
- Noise; There are many sources of noise in electronic systems, but all electronic systems are subject to it and exhibit random fluctuations of output for no discernible input.
- Signal to Noise Ratio (SNR); Signal to Noise Ratio is simply the ratio between the wanted signal and the unwanted background noise. Obviously, it is desirable that the SNR is as high as possible.
- Dynamic Range; **Dynamic range** is a term used to describe the ratio between the smallest and largest signals that can be measured by a **system**. The **dynamic range** of a data acquisition **system** is defined as the ratio between the minimum and maximum amplitudes that a data acquisition **system** can capture.
- Linearity; Linearity describes how accurate measurements are across the complete expected range of the measurements. It answers the question about how accurate the system is across the dynamic range of the system.

- Fluid Flow Sensors

Many Industrial processes involve fluids and so there is a need to measure and control their flow. A wide range of transducers and techniques are commonly used to measure fluid flow rates. Examples include; Head meters, Rotational Flowmeters, and Ultrasonic Flowmeters.

- Fibre Optic Sensors

These are a new class of sensor which tend to be immune from Electro-Magnetic Interference (EMI) and measure amplitude, phase or polarization of light. The transducer is constructed so that one or more of these parameters varies with the physical quantity of interest.

- Micro-Electro-Mechanical Systems (MEMS)

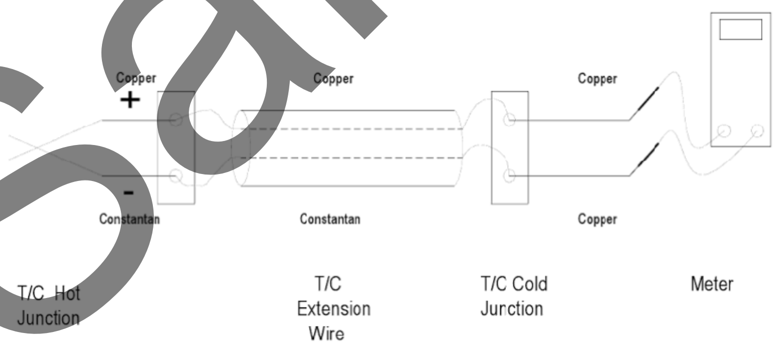
These are small electromechanical devices made using semiconductor integrated circuits.

- Smart Sensors

Smart Sensors cover a wide variety of devices which could range from a traditional transducer that simply contains its own signal conditioning circuitry to a device that can calibrate itself, acquire data, analyse it, and transmit the results over a network to a remote computer. An emerging class of smart sensors is defined by the family of IEEE 1451 standards, which are designed to simplify the task of establishing communications between transducers and networks.

1.1.3 Thermocouples

Thermocouples convert a temperature into a small DC voltage or current. They consist of two dissimilar metal wires in contact with two or more junctions. The output voltage varies linearly and proportionately with the temperature difference between the junctions.



Thermocouple Schematic

The chief advantages of thermocouples are their linearity, their ruggedness, and their ability to operate over a very large temperature range. Including temperatures of over 1000°C.

The chief disadvantages include low output voltage (especially at low temperatures), low sensitivity (typically being only 5mV for a 100°C temperature change), susceptibility to noise (externally induced and caused internally by wire imperfections and impurities), and the need for a reference junction (at a known temperature) for calibration.

When several thermocouples, made of the same materials, are combined in series, they are called a thermopile. The output voltage of a thermopile consists of the sum of all the individual thermocouple outputs, resulting in increased sensitivity but all the reference junctions need to be kept at the same temperature.

1.1.4 Thermocouples; Principle of Operation

A thermocouple is formed by the junction of two dissimilar metals. This junction creates an open-circuit thermoelectric voltage and is called the Seebeck effect. The **Seebeck effect** is the conversion of heat directly into electricity at the junction of different types of metal. It is named after the German physicist Thomas Johann Seebeck, who in 1821 discovered that a compass needle would be deflected by a closed loop formed by two different metals joined in two places, with a temperature difference between the joints. This was because the electron energy levels in each metal shifted differently and a potential difference between the junctions created an electrical current and therefore a magnetic field around the wires. Seebeck did not recognize there was an electric current involved, and so he called the phenomenon "thermomagnetic effect." Danish physicist Hans Christian Ørsted rectified the oversight and coined the term "thermoelectricity".

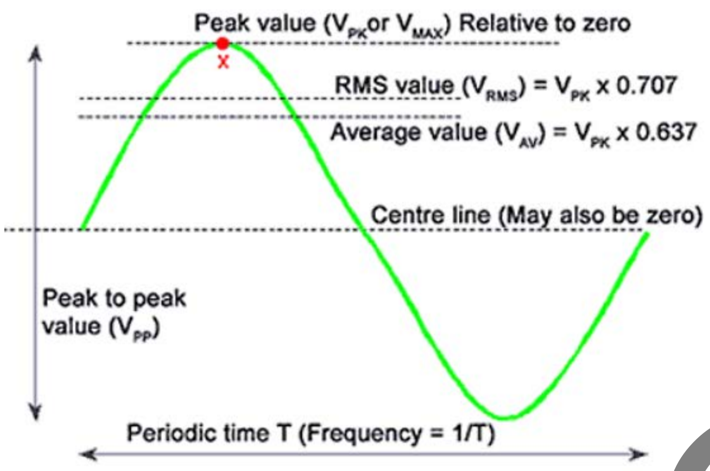
Various types of thermocouples exist and some are listed below. A thermocouple's output voltage increases almost linearly with the temperature difference over a range of temperatures.

Type	Elements +/-	Seebeck coefficient (µV/°C)	Range (°C)	Range (mV)
E	Chromel/constantan	58.70 at 0°C	-270 to 1,000	-9.835 to 76.358
J	Iron/constantan	50.37 at 0°C	-210 to 1,200	-8.096 to 69.536
K	Chromel/alumel	39.48 at 0°C	-270 to 1,372	-8.096 to 69.536
R	Pt (10%) – Rh/Pt	10.19 at 600°C	-50 to 1,768	-0.236 to 18.698
T	Copper/constantan	38.74 at 0°C	-270 to 400	-6.258 to 20.869
S	Pt (13%) – Rh/Pt	11.35 at 600°C	-50 to 1,768	-0.226 to 21.108

1.1.5 Signal Characteristics

One of the common aspects of all measurement systems is that they are required to transmit signals (information) from one place to another, from one instrument to another. The way that this is achieved rests very much on the type of signal (information) that is required to be conveyed. Here we will consider some of the many signal (information) types that measurement systems may have to contend with and some of the features of those signal (information) types.

Generally, signals (information) at the measurement side of the measurement system are analog signals and can be characterised as being either Direct Current (Non-Alternating) Signals or Alternating Current (Alternating Signals), the latter being further characterised as Low and High Frequency.



Characteristics of a Sine Wave

Some of the important characteristics of an oscillating wave are as follow;

1.1.9 Amplitude

The AMPLITUDE of a sine wave is the maximum vertical distance reached, in either direction from the centre line of the wave. As a sine wave is symmetrical about its centre line, the amplitude of the wave is half the peak to peak value, as shown above.

1.1.10 Peak Value

The PEAK value of the wave is the highest value the wave reaches above a reference value. The reference value normally used is zero. In a voltage waveform the peak value may be labelled V_{PK} or V_{MAX} (I_{PK} or I_{MAX} in a current waveform).

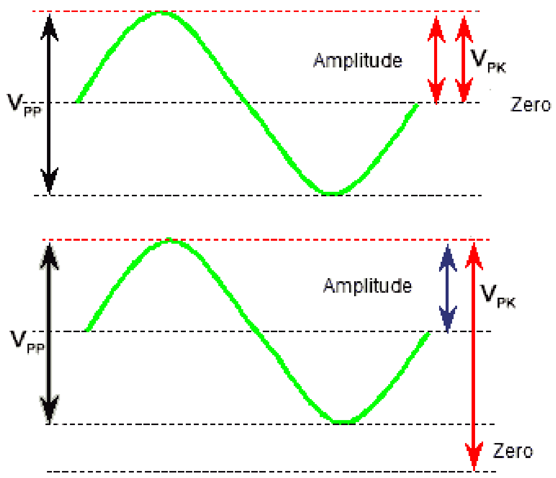
1.1.11 Peak to Peak Value

The PEAK TO PEAK value is the vertical distance between the top and bottom of the wave. It will be measured in volts on a voltage waveform, and may be labelled V_{PP} or V_{PK-PK}. In a current waveform it would be labelled I_{PP} or I_{PK-PK}.

1.1.12 Instantaneous Value

This is the value (voltage or current) of a wave at any particular instant, often chosen to coincide with some other event. For example, the instantaneous value of a sine wave one quarter of the way through the cycle will be equal to the peak value. See point X in the above diagram (*Characteristics of a Sine Wave*).

If the sine wave being measured is symmetrical either side of zero volts (or zero amperes), meaning that the dc level or dc component of the wave is zero volts, then the peak value must be the same as the amplitude, that is half of the peak to peak value.



Defining the Peak Value V_{PK}

However, this is not always the case, if a dc component other than zero volts is also present, the sine wave will be symmetrical about this level rather than zero. The bottom waveform of the two above (*Defining the Peak Value V_{PK}*) shows that the peak value can now be even larger than the peak to peak value, (the amplitude of the wave however, remains the same, and is the difference between the peak value and the "centre line" of the waveform).

1.1.13 Period & Frequency

The PERIOD (given the symbol T) is the time, in seconds, milliseconds, microseconds etc. taken for one complete cycle of the wave. It can be used to find the FREQUENCY of the wave ƒ using the formula T =1/ƒ.

Thus, if the periodic time of a wave is 20ms (or 1/50th of a second) then there must be 50 complete cycles of the wave in one second. A frequency of 50 Hz. Note that when you use this formula, if the periodic time is in seconds then the frequency will be in Hertz (Hz).

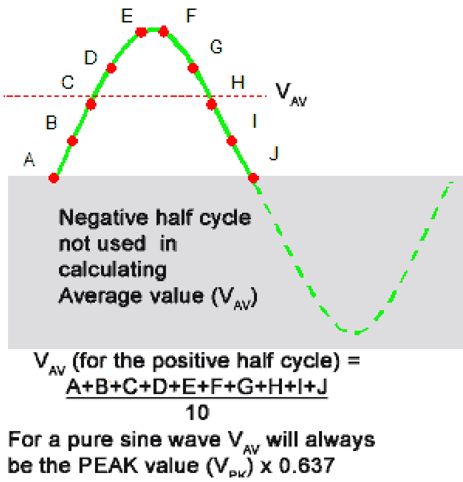
1.1.14 Average Value

The AVERAGE value. This is normally taken to mean the average value of only half a cycle of the wave. If the average of the full cycle was taken it would of course be zero, as in a sine wave symmetrical about zero, there are equal excursions above and below the zero line.

Using only half a cycle, as illustrated below (*The Average Value of a Sine Wave*), the average value (voltage or current) is always 0.637 of the peak value of the wave.

$V_{AV} = V_{PK} \text{ x } 0.637$ or $I_{AV} = I_{PK} \text{ X } 0.637$

The average value is the value that usually determines the voltage or current indicated on a test meter. There are however some meters that will read the RMS value, these are called "True RMS meters".



The Average Value of a Sine Wave

1.1.15 The RMS Value.

The RMS or ROOT MEAN SQUARED value is the value of the equivalent direct (non-varying) voltage or current which would provide the same energy to a circuit as the sine wave measured. That is, if an AC sine wave has a RMS value of 240 volts, it will provide the same energy to a circuit as a DC supply of 240 volts.

It can be shown that the RMS value of a sine wave is 0.707 ($\frac{1}{\sqrt{2}}$) of the peak value.

$V_{RMS} = V_{PK} \times 0.707$ and $I_{RMS} = I_{PK} \times 0.707$

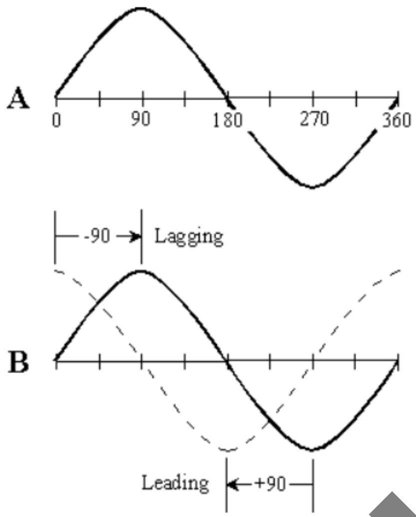
Also, the peak value of a sine wave is equal to 1.414 ($\sqrt{2}$) x the RMS value.

The RMS value is also known as the **Effective Value**.

1.1.16 Phase.

The phase can be expressed as a relative displacement between or among waves having the same frequency. *Phase difference*, also called *phase angle*, in degrees is conventionally defined as a number greater than -180, and less than or equal to +180. *Leading phase* refers to a wave that occurs "ahead" of another wave of the same frequency. *Lagging phase* refers to a wave that occurs "behind" another wave of the same frequency. When two signals differ in phase by -90 or +90 degrees, they are said to be in *phase quadrature*. When two waves differ in phase by 180 degrees (-180 is technically the same as +180), the waves are said to be in *phase opposition*. The Illustration in Figure B (*Phase of a Sine Wave*), below shows two waves that are in phase quadrature. The wave depicted by the dashed line leads the wave represented by the solid line by 90 degrees.

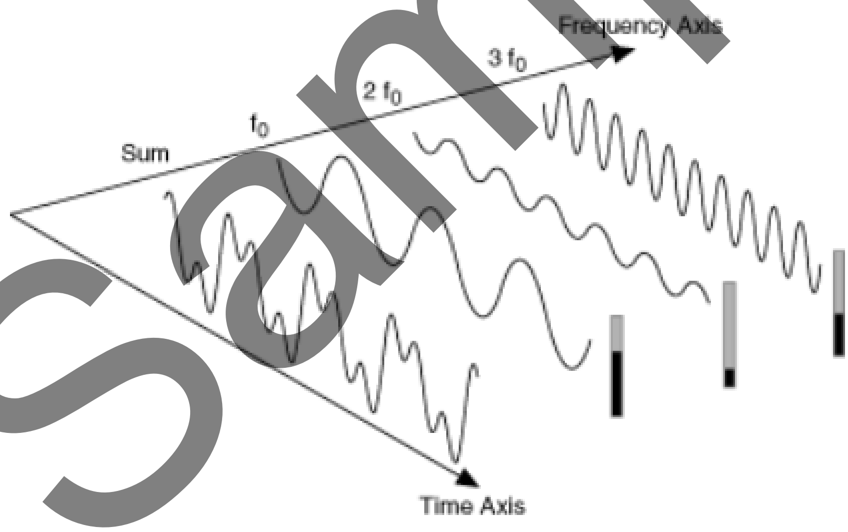
When a circuit causes an oscillating wave to change phase for any reason, this is referred to as a **Phase Shift**.



Phase of a Sine Wave

1.1.17 Time and Frequency Domain

So far, we have looked at the sine wave in terms of its time domain representation, that is, we have looked at the amplitude of the signal at the specific instants in time. However, in many cases it is more important to know the frequency content of a signal rather than the amplitude of the individual samples.



Time and Frequency Domains

Fourier's theorem states that any waveform in the time domain can be represented by a weighted sum of sines and cosines. The same waveform then can be represented in the frequency domain as a pair of amplitude and phase values at each component frequency.

You can generate any waveform by adding sine waves, each with a particular amplitude and phase. The above diagram (*Time and Frequency Domains*) shows the original waveform, labelled **sum**, and its component frequencies. The fundamental frequency is shown at the frequency f_0, the second harmonic at frequency $2f_0$, and the third harmonic at frequency $3f_0$.

In the frequency domain, you can separate conceptually the sine waves that add to form the complex time-domain signal. The previous diagram shows single frequency components, which spread out in the time domain, as distinct impulses in the frequency domain. The amplitude of each frequency line is the amplitude of the time waveform for that frequency component. The representation of a signal in terms of its individual frequency components is the frequency-domain representation of the signal. The frequency-domain representation might provide more insight about the signal and the system from which it was generated.

The samples of a signal obtained from a Data Acquisition (DAQ) device constitute the time-domain representation of the signal. Some measurements, such as harmonic distortion, are difficult to quantify by inspecting the time waveform on an oscilloscope. When the same signal is displayed in the frequency domain by a Fast Fourier Transform (FFT) Analyzer, also known as a Dynamic Signal Analyzer, you easily can measure the harmonic frequencies and amplitudes.

1.1.18 Continuous and Discrete Signals

So far, we have only considered Continuous Signals, that is, signals or quantities that can be defined and represented at any instant of time in the sequence under investigation. These represent an infinite (or at least uncountable) set of number sequences. As we have already seen, these signals are also referred to as analog signals. The sine wave is an example of a continuous signal.

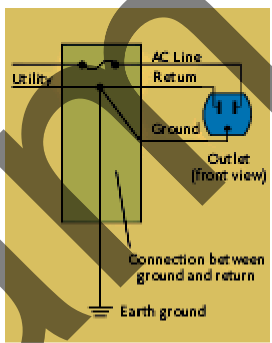
Discrete signals, on the other hand, are signals or quantities that can be defined and represented at certain time instants of the sequence. These represent a finite or countable set of number sequences and are also referred to as discrete or digitized signals. The diagram below (*Discrete Signals*) gives an example of such a signal

Discrete Signals

Even though internal and external interference can be problematic in sending analog signals, analog signal transmission is widely and successfully used in industry. The effects of noise can be reduced with careful engineering design, proper installation, routing techniques of wires and cables, and shielding and grounding.

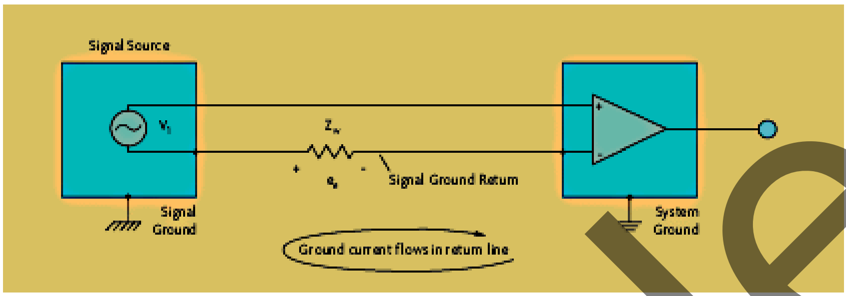
One of the ways in which engineers have tried to minimize the effects of noise is to maximize the signal-to-noise ratio. This involves increasing the power of the signal being sent. Although this works in some cases, it has its limitations. By increasing the signal, nonlinear effects become dominant, as the signal amplitude is increased-it enhances the signal and the noise in the same proportion.

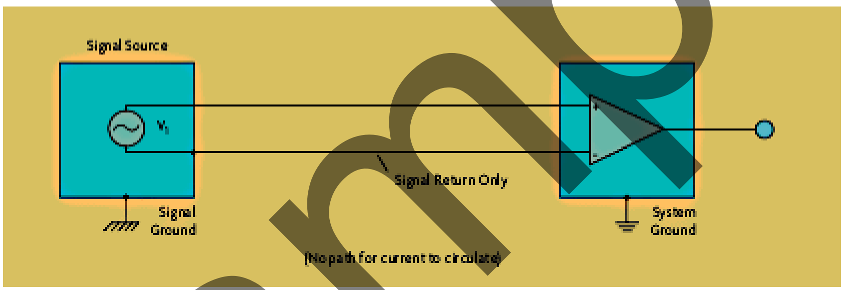
Proper grounding also is essential for effective operation of any measurement system. Improper grounding can lead to potentially dangerous ground loops and susceptibility to interference. To understand the principles involved in shielding and grounding, some terms must first be understood. A ground is a conducting flow path for current between an electric circuit and the earth. Ground wires are typically made with materials that have very low resistance. Because current takes the path of least resistance, the ground wires connected from the system provide a stable reference for making voltage measurements. Ground wires also safeguard against unwanted common-mode signals and prevent accidental contact with dangerous voltages. Return lines carry power or signal currents. A ground loop is a potentially dangerous loop formed when two or more points in an electrical system are grounded to different potentials.



There are many different grounding techniques designed to not only protect the data being transmitted, but to protect employees and equipment. There are two ways in which all systems should be grounded. Firstly, all of the measuring equipment and recording systems should be grounded so that measurements can be taken with respect to a zero-voltage potential. This not only ensures that potential is not being introduced at the measuring device, but ensures that enclosures or cabinets around equipment do not carry a voltage. To ground an enclosure or cabinet, one or more heavy copper conductors are run from the device to a stable ground rod or a designated ground grid. This system ground provides a base for rejecting common-mode noise signals. It is very important that this ground is kept stable.

The second ground is for the signal ground. This ground is necessary to provide a solid reference for the measurement of all low-level signals. It is very important that this ground is grounded separately and isolated from the system ground. If a signal return line is grounded at the signal source and at the system ground, a difference in potential between the two grounds may cause a circulating current. In this case, the circulating current will be in series with the signal leads and will add directly to the signal from the measuring instrument. These ground loops are capable of creating noise signals 100 times the size of the original signal. This current can also be potentially dangerous. In a single-point ground configuration, minimal current can flow in the ground reference. Figure 3-6 shows that by grounding the wire at the signal end only, the current has no path, eliminating the ground loop.





For off-ground measurements, the shield or the ground lead is stabilized with respect to either the low-level of the signal or at a point between the two. Because the shield is at a potential above the zero-reference ground, it is necessary to have proper insulation.

1.2.1 Wire & Cable Options

Another important aspect to consider in analog signal transmission is a proper wiring system, which can effectively reduce noise interference. Analog signal transmission typically consists of two-wire signal leads or three-wire signal leads. In systems that require high precision and accuracy, the third signal lead, or shield, is necessary. In the three-wire configuration, the shield is grounded at the signal source to reduce common-mode noise. However, this does not eliminate all possibilities for the introduction of noise. It is crucial to prevent the noise pickup by protecting the signal lines. For example, in the case where the noise and signal frequency are the same. In this scenario, the signal cannot be isolated/filtered from the noise at the receiving device.

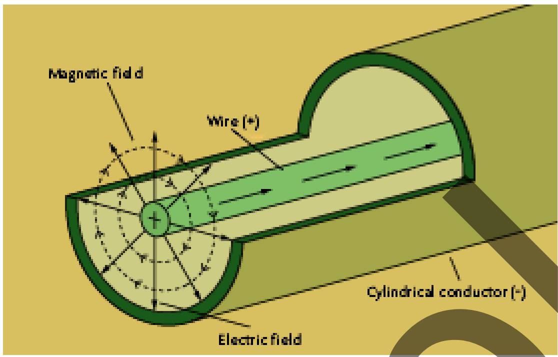
Generally, two-wire transmission mediums are used to carry an analog signal to or from the field area. A wire carrying an alternating current and voltage may induce noise in a pair of nearby signal leads. A differential voltage/noise will be created since the two wires may be at different distances from the disturbing signal. There are many different wiring options that are available to reduce unwanted noise pickup from entering the line. Four types of wires are fundamental in data acquisition-plain pair, shielded pair, twisted pair, and coaxial cable.
While plain wire can be used, it is generally not very reliable in screening out noise and is not suggested. A shielded pair is a pair of wires surrounded by a conductor that does not carry current. The shield blocks the interfering current and directs it to the ground. When using shielded pair, it is very important to follow the rules in grounding. Again, the shield must only be grounded at one source, eliminating the possibility of ground-loop currents.

1.2.2 Twisted Pair Cables

Twisted pair cable consists of a pair of insulated wires twisted together, which help in eliminating noise due to electromagnetic fields, helps to reduce crosstalk on multi-pair cables. Twisted pair cable works well on transferring balanced differential signals, the merits of which are extremely valuable in wide bandwidth and high-fidelity system. Basically, twisted pair cable can be divided into two types: unshielded twisted-pair (UTP) and shielded twisted-pair (STP). The former serves as the most commonly used one with merely two insulated wires twisted together. Any data communication cables and normal telephone cables belong to this category. However, shielded twisted pair distinguishes itself from UTP in that it consists of a foil jacket which helps to prevent crosstalk and noise from outside source. It is typically used to eliminate inductive and capacitive coupling, so it can be applied between equipment, racks and buildings. With the advancement of technology, the twisted pair cables are now being phased out by more technically developed and reliable media. There exist several different types of twisted pair cables, including Cat5, Cat5e and Cat6, etc. Some most commonly used types are listed in the following form:

UTP Category	Description
CAT1	Up to 1Mbps, Old Telephone Cable
CAT2	Up to 4Mbps, Token Ring Networks
CAT3	Up to 10Mbps, Token Ring & 10BASE-T Ethernet
CAT4	Up to 16Mbps, Token Ring Networks
CAT5	Up to 100Mbps, Ethernet, Fast Ethernet, Token Ring
CAT5e	Up to 1Gbps, Ethernet, Fast Ethernet, Gigabit Ethernet
CAT6	Up to 10Gbps, Gigabit Ethernet, 10G Ethernet (55 meters)
CAT6a	Up to 10Gbps, Gigabit Ethernet, 10G Ethernet (55 meters)
CAT7	Up to 10Gbps, Gigabit Ethernet, 10G Ethernet (100 meters)

Coaxial cable acts as a high-frequency transmission cable which contains a single solid-copper core. A coaxial cable has over 80 times the transmission capability of the twisted-pair. It is commonly used to deliver television signals and to connect computers in a network as well, so people may get more familiar with this kind of cable. Coaxial cable has always been the mainstay of high speed communication and has also been applied to network with 10 gigabit links data centres, because it is proved to be cost efficient for short links within 10 m and for residential network. Besides, it features anti-jamming capability, stable transmission of data and money saving. Coaxial cable is widely employed in feedlines connecting radio transmitters and receivers, computer network connection, digital audio and television signals distribution. Moreover, coaxial cable can effectively protect signals from being interfered by external electromagnetic influence.

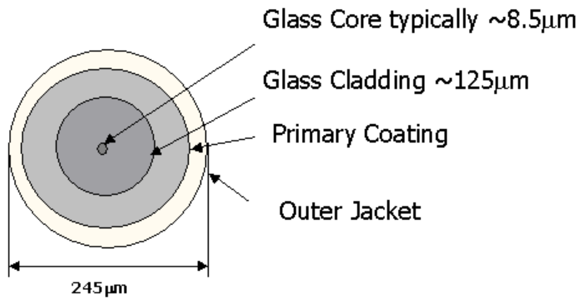


Although noise and interference cannot be completely removed in the transmission of an analog signal, with good engineering and proper installation, many of the effects of noise and interference can be substantially reduced.

1.2.3 Optical Fibre

Computing and data communications are fast-moving technologies. There comes a new generation of transmission media—fibre optic cable. It refers to the complete assembly of fibres, which contain one or more optical fibres that are used to transmit data. Each of the optical fibre elements is individually coated by plastic layers and contained in a protective tube. Fibre optic cable transmits data as pulses of light go through tiny tubes of glass, the transmission capacity of which is 26,000 times higher than that of twisted-pair cable. When comparing with coaxial cables, fibre optic cables are lighter and reliable for transmitting data. They transmit information using beams of light at light speed rather than pulses of electricity.

There exist various types of fibre optic cables, which are determined by the number of fibres and where it will be installed. Besides, the bandwidth of optical fibre transmission is also developed and the maximum connection distance can reach up to over 2 km. Nowadays, two types of fibre optic cables are widely adopted in the field of data transfer—single-mode fibre optic cables and multimode fibre optic cables. A single-mode optical fibre is a fibre that has a small core, and only allows one mode of light to propagate at a time. So, it is generally adapted to high speed, long-distance applications. While a multimode optical fibre is a type of optical fibre with a core diameter larger than the wavelength of light transmitted and it is designed to carry multiple light rays, or modes at the same time. It is mostly used for communication over short distances because of its high capacity and reliability, serving as a backbone application in buildings.



Attenuation
The loss, or attenuation in fibre depends on the wavelength of the light propagating within it. There are three main bandwidth 'windows' of interest in the attenuation spectrum of fibre. The 1st window is at 800-900nm, here there is a good source of cheap silicon based sources & detectors. The 2nd window is at 1260-1360nm, here there is low fibre attenuation coupled with zero material dispersion. The 3rd window of interest is at 1430-1580nm where fibre has its attenuation minimum. Typically, the telecommunications industry use wavelengths in the 3rd window which coincides with the gain bandwidth of Fibre Amplifiers.

Dispersion
Light from a typical optical source will contain a finite spectrum. The different wavelength components in this spectrum will propagate at different speeds along the fibre eventually causing the pulse to spread. When the pulses spread to the degree where they 'collide' it causes detection problems at the receiver resulting in errors in transmission. This is called Inter-Symbol Interference (ISI). Dispersion (sometimes called chromatic dispersion) is a limiting factor in fibre bandwidth, since the shorter the pulses the more susceptible they are to ISI.

1.3 Measurement in practice

People make measurements for many reasons: to make sure an item will fit, to determine the correct price to pay for something, or to check that a manufactured item is within specification. In all cases, a measurement is only useful if it is suitable for the intended purpose.
Consider the following questions:

- Do you know how accurate your measurement result is?
- Is this accurate enough?
- How strongly do you trust the result?

These questions relate to the quality of a measurement. When talking about measurement quality, it is important to understand the following concepts:

1.3.1 Precision, accuracy and uncertainty

Precision is about how close measurements are to one another. Accuracy is about how close measurements are to the 'true value'. In reality, it is not possible to know the 'true value' and so we introduce the concept of uncertainty to help quantify how wrong our value might be.
The difference between accuracy and precision is illustrated below. The idea is that firing an arrow at a target is like making a measurement. Accuracy is a qualitative measure of how close a measurement is to the centre of the target – the 'true value'. Precision is represented by a cluster of consistent measurements, but there is no guarantee that these are accurate.

Accuracy is a qualitative term that describes how close a set of measurements are to the actual (true) value.
Precision describes the spread of these measurements when repeated. A measurement that has high precision has good repeatability.

In practice we are not able to view the target and assess how close to the 'true value' our measurements are. What interests us is the answer to the question "How far from the target could our arrows have fallen?" We also need to ask, "How wrong could we have been?" To answer these questions, we need to look at all the factors that go into making a measurement and how each factor could have affected the final estimate of the answer.
The answer to "How wrong are we likely to have been?" is known as the 'measurement uncertainty', and this is the most useful assessment of how far our estimate is likely to lie from the 'true value'. For example, we might say that the length of a particular stick is 200 cm with an uncertainty of ±1 cm.

Random errors

Random errors arise from the fluctuations that are most easily observed by making multiple trials of a given measurement. For example, if you were to measure the period of a pendulum many times with a stop watch, you would find that your measurements were not always the same. The main source of these fluctuations would probably be the difficulty of judging exactly when the pendulum came to a given point in its motion, and in starting and stopping the stop watch at the time that you judge. Since you would not get the same value of the period each time that you try to measure it, your result is obviously uncertain. There are several common sources of such random uncertainties in the type of experiments that you are likely to perform:

- Uncontrollable fluctuations in initial conditions in the measurements. Such fluctuations are the main reason why, no matter how skilled the player, no individual can toss a basketball from the free throw line through the hoop each and every time, guaranteed. Small variations in launch conditions or air motion cause the trajectory to vary and the ball misses the hoop.
- Limitations imposed by the precision of your measuring apparatus, and the uncertainty in interpolating between the smallest divisions. The precision simply means the smallest amount that can be measured
- directly. A typical metre stick is subdivided into millimetres and its precision is thus one millimetre.
- Lack of precise definition of the quantity being measured. The length of a table in the laboratory is not well defined after it has suffered years of use. You would find different lengths if you measured at different points on the table. Another possibility is that the quantity being measured also depends on an uncontrolled variable. (The temperature for example). Sometimes the quantity you measure is well defined but is subject to inherent random fluctuations. Such fluctuations may be of a quantum nature or arise from the fact that the values of the quantity being measured are determined by the statistical behaviour of a large number of particles. Another example is AC noise causing the needle of a voltmeter to fluctuate.

No matter what the source of the uncertainty, to be labelled "random" an uncertainty must have the property that the fluctuations from some "true" value are equally likely to be positive or negative. This fact gives us a key for understanding what to do about random errors. You could make a large number of measurements, and average the result. If the uncertainties are really equally likely to be positive or negative, you would expect that the average of a large number of measurements would be very near to the correct value of the quantity measured, since positive and negative fluctuations would tend to cancel each other out.

1.3.6 Graphical Techniques

Whereas statistics and data analysis procedures generally yield their output in numeric or tabular form, graphical techniques allow such results to be displayed in some sort of pictorial form. They include plots such as scatter plots, histograms, probability plots, spaghetti plots, residual plots, box plots, block plots and biplots.

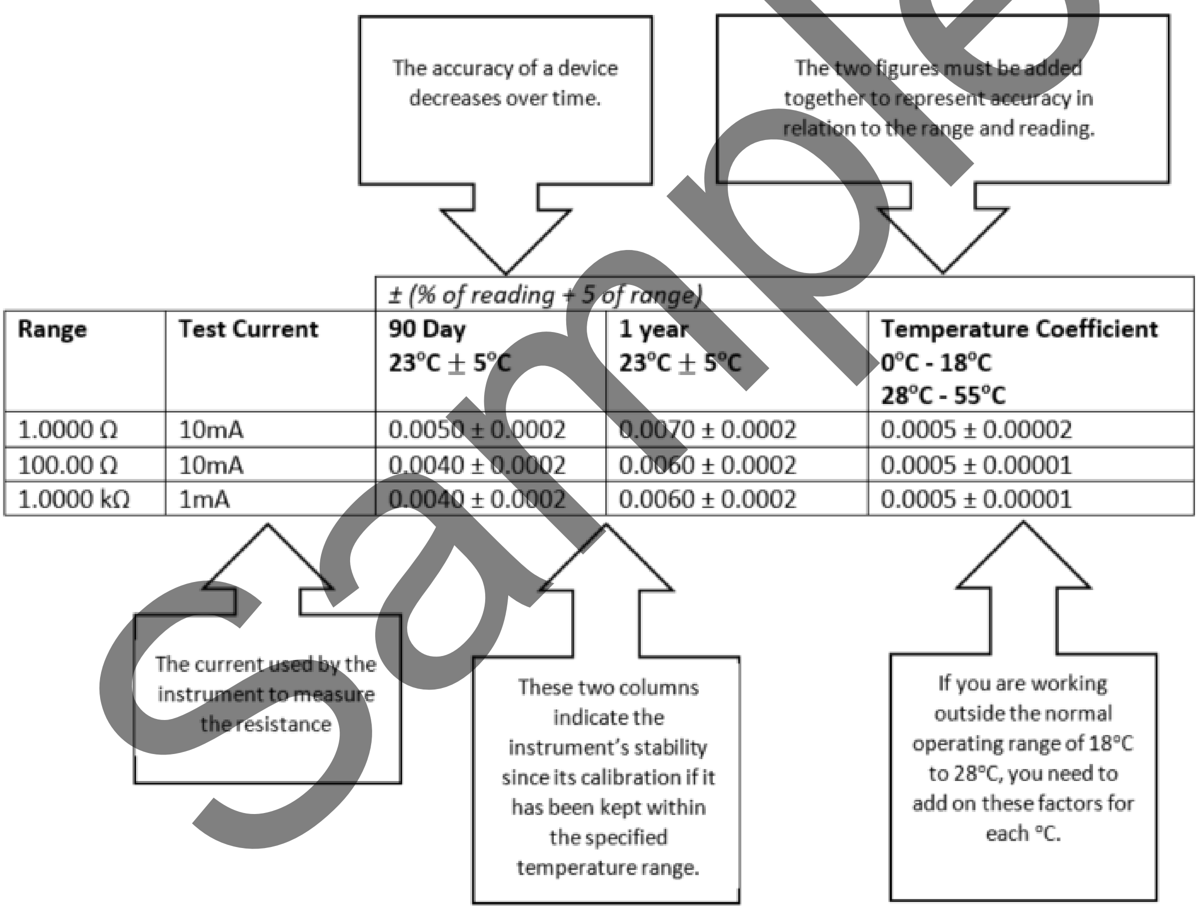
Exploratory data analysis (EDA) relies heavily on such techniques. They can also provide insight into a data set to help with testing assumptions, model selection and regression model validation, estimator selection, relationship identification, factor effect determination, and outlier detection. In addition, the choice of appropriate statistical graphics can provide a convincing means of communicating the underlying message that is present in the data to others.

Graphical statistical methods have four objectives:

1.4.2 Reading Instrument Specifications

When you look at the data sheet for your measurement instrument, you will find many different figures and formulas to help you determine the uncertainty. It is important to recognise the relevant and important sections, and know how to understand them. The tables below show example accuracy specifications for an instrument that measures resistance.

Three important details to know before reading instrument specifications	
1	The test current
2	How long it has been since the device was last calibrated
3	The temperature at which the device is being kept



		± (% of reading + 5 of range)		
Range	**Test Current**	**90 Day 23°C ± 5°C**	**1 year 23°C ± 5°C**	**Temperature Coefficient 0°C - 18°C 28°C - 55°C**
1.0000 Ω	10mA	0.0050 ± 0.0002	0.0070 ± 0.0002	0.0005 ± 0.00002
100.00 Ω	10mA	0.0040 ± 0.0002	0.0060 ± 0.0002	0.0005 ± 0.00001
1.0000 kΩ	1mA	0.0040 ± 0.0002	0.0060 ± 0.0002	0.0005 ± 0.00001

Even if tests are carried out under identical conditions, the measured values will not necessarily be the same. This is caused by a variety of factors, such as thermal noise. The following table shows the noise introduced by an instrument measuring voltage. This would be included in your uncertainty.

The standard deviation of noise voltage is the RMS value. These figures are for a measurement time of 2 minutes

	Observation Period
Range	**2-Minute RMS Noise**
1mV	1.3 nVrms
10mV	1.5 nVrms
100mV	10 nVrms

An alternative to this specification is peak-peak noise, which is approximately 6 times larger

You can also decide to trade off the speed of the measurement against the accuracy by changing the number of digits.

The time the analog-to-digital converter (ADC) samples the input signal for a measurement

The number of digits an instrument can measure indicate its resolution

Digits	Integration Time (plc)	Integration Time
7½	200	4s
7½	100	2s
6½	20	400ms
6½	10	200ms
5½	1	20ms
5½	0.2	4ms
4½	0.02	0.4ms

Integration time is given in seconds or power line cycles (plc). One plc equates to 20ms in the UK

Device may have a filter to reduce the spread of the reading. This can be digital or analog.

Filters affect uncertainty

Filter	
Analog	Low pass 2 pole @ 13 Hz
Digital	Moving average filter, 10 (fast), 50 (medium, or 100 (slow) reading averages

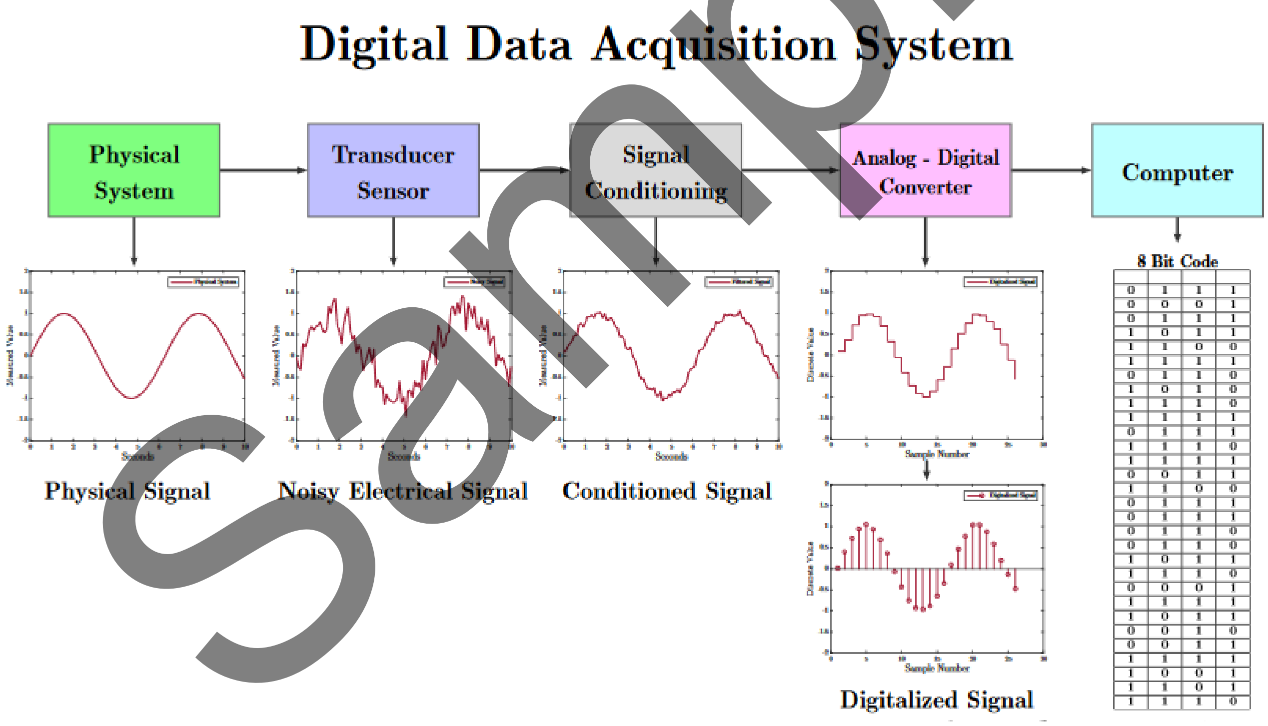
In Summary	
1	**Before making a set of measurements, do you know:** • What the measurements are for, and hence the uncertainty of measurements you are seeking? • How many times you should repeat the measurement? • The acceptance criteria (the tolerance, for example) for the result?
2	**Are you confidant you will be:** • Making the right measurement? • Using the right tools? • Involving the right people? • Carrying out regular reviews? • Able to demonstrate consistency? • Following the right procedures?
3	**Has every measuring instrument you intend to use:** • Been calibrated as and when needed? • Been kept in appropriate conditions, not misused, or damaged?
4	**Will the instrument:** • Be checked before the measurements begin? • Need calibrating before the measurements begin?
5	**In planning your measurement, have you assessed and minimised the effects of:** • Instrument performance limitations from the specification sheet? • The objects to be measured? • Sampling? • Operator skill? • The environment?
6	**To express the results of your measurement, do you:** • Know the SI rules? • Understand how to calculate uncertainty?

1.5 Data Acquisition Systems

Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer. A DAQ system consists of sensors, DAQ measurement hardware, and a computer with programmable software. Compared to traditional measurement systems, PC-based DAQ systems exploit the processing power, productivity, display, and connectivity capabilities of industry-standard computers providing a more powerful, flexible, and cost-effective measurement solution. Standalone DAQs tend to be called Data Loggers.

1.5.1 Parts of a DAQ System

A typical DAQ is illustrated below. Typically, the DAQ will contain, as a minimum;
Sensor, DAQ Device (Signal Conditioning, Analog-to-Digital Converter), Computer System (Computer Bus, Computer, Driver Software, Application Software).



1.5.2 Sensor

The measurement of a physical phenomenon, such as the temperature of a room, the intensity of a light source, or the force applied to an object, begins with a sensor. A sensor, also called a transducer, converts a physical phenomenon into a measurable electrical signal. Depending on the type of sensor, its electrical output can be a voltage, current, resistance, or another electrical attribute that varies over time. Some sensors may require additional components and circuitry to properly produce a signal that can accurately and safely be read by a DAQ device.