Mechanical Measurements and Metrology
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Module - 1
Lecture - 1
Introduction to the Study of Mechanical Measurements

I am going to give a set of lectures on mechanical measurements. The lectures are arranged in a modular form. And today we will just introduce module number 1 and we will see the things we are going to cover in this module.

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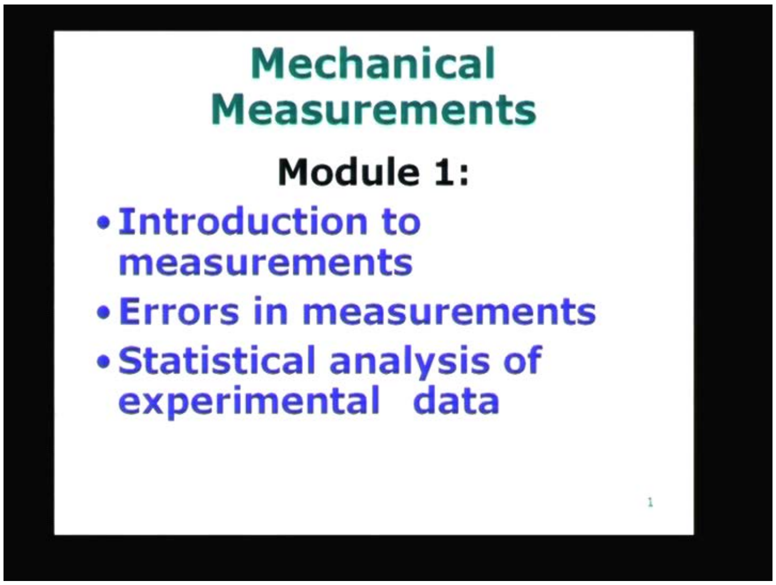

The first topic, which I am going to cover, is introduction to the area of measurements. Mechanical measurement is a sort of a subset of what we can call measurement. Therefore, introduction to measurements will be a general description of what measurements means and then of course, we will later look at what mechanical measurements are.

When you do any measurement, in whatever field it is, the measurement process is prone to some errors. Even before we start looking at the specific measurements and how we do it and so on, it is good and necessary to understand about these errors, how to either minimize them or to characterize them and so on. So the errors in measurements form the topic, which will be given emphasis to start with. When we talk about errors there are some statistical principles, which are required to understand the nature of errors.

Of course, when we go into the specific topic, we will give more details. Right now, it is sufficient to understand that there are some statistical principles involved in characterizing of errors and that will be the topic that we are going to look at.

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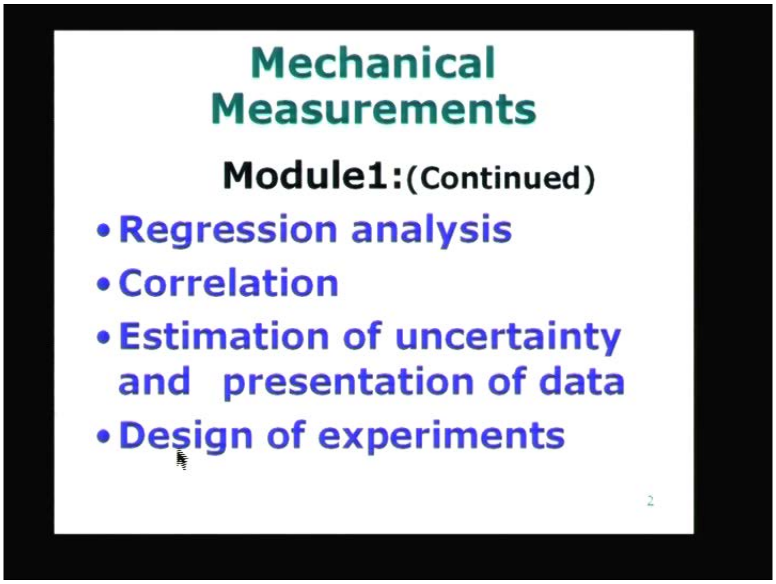

When once we have made or performed a set of measurements, in whatever field it is, one would like to look at the data in the form of a summary and when we want to communicate it to somebody, we should be able to tell him or her what exactly the role of the measurement is, what it has achieved in terms of what is useful to the person who is going to look at it. So regression analysis is a natural thing to do. Regression analysis tries to put everything in the form of a simple formula or simple set of formulae, which will be useful to the user.

Instead of going through various measurements and understanding them, one can simply go to the results in the form of regression analysis and look at that and that will give us information about what improvements are achieved. When we talk about regression analysis, naturally we would like to look at what is called correlation or relations existing between different quantities we have measured and to understand whether these correlations are good or bad, whether the correlations are really not an artifact, which has come out of faulty understanding of what happened, whether it is proper to do the way we have done, the regression analysis and so on. This is understood by looking at what is called correlation.

The next topic that we will look at in module 1 is the estimation of uncertainty and this will be followed by good presentation of data, in what we call good presentation of data. Good presentation means it should be understood by the user without coming to the person who has done the work. He must be able to understand what has been achieved without the help of anybody, so the work should speak for itself.

Therefore the presentation of data is a very important part of this process. And the last topic in module 1 would be the design of experiments, we will talk about how to conduct the experiments, whatever may be the type of experiment we are going to do, how to organize the different instruments, how to look for the proper instruments to be used for the measurement in the particular experiment we may have in mind, then, how many data to collect, what kind of variations or ranges of data we should have and so on and so forth. This is what will be the final part of module 1, which will be on the design of experiments.

With this overview, I am going to start the first lecture in the series, which is just an introduction to the study of mechanical measurements.

Measurements can be classified according to the field in which we are going to be working: electrical engineering measurements of course describe the measurements made in electrical science, measurements in physics or physical sciences, they have their own flavor, and then measurements in biological sciences and their own flavor and so on.

But mechanical instruments pertain to measurements we undertake in mechanical engineering to describe various systems, which we meet with in practice. There may be thermal system, mechanical systems involved in measurement of length, velocity, acceleration and so on. It could be thermal; for example, temperature measurement, pressure measurement, anything to do with thermodynamic characterization or thermal characterization of systems, which will come under that category. There are various ways of classification of measurements, which we will of course come to as we go along.

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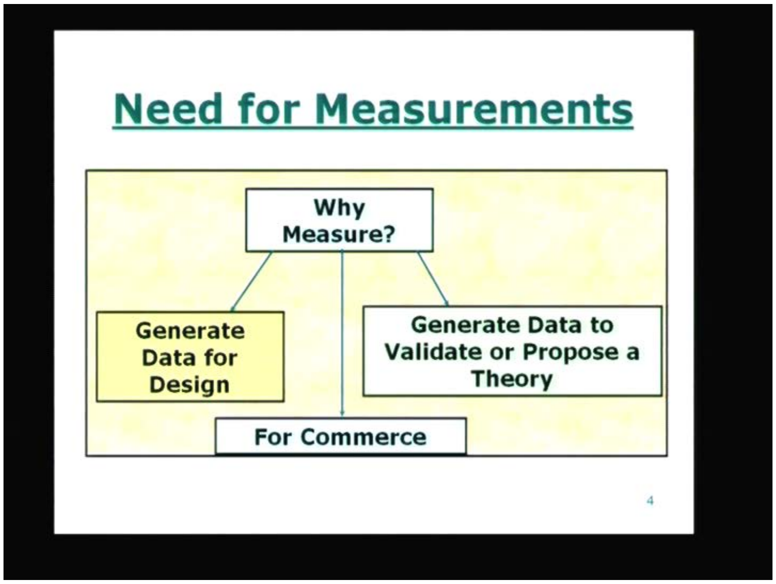

So this slide shows the need for measurements. I am trying to make out a case for why we want to measure, so there are several reasons one would like to make measurements. So the central question is why we want to measure? In my opinion there may be many other reasons depending on who is going to talk about it. In my view there are two important reasons and a third reason, which I am not going to give much importance to. Let me go through the reasons. One is to generate data for design because engineering and mechanical engineering mostly concerns itself with making of things: design of things and making of things or manufacturing things. In this a lot of information is required in the form of data regarding the mechanical behavior, thermal behavior, and other behavior of the system and consultation.

Whatever we are designing requires lot of data to support the design activity. That is one of the most important things and therefore I will concentrate on generation of data for design as one of the most important aspects of why we want to measure. The second and more basic reason measurement is undertaken is to generate data is to validate. That means, there is already a theory proposed and existing; to validate the theory we require a set of data to be collected and experiments to be performed. We want to validate the theory, either validate or we can also have an experiment saying that the theory is not valid. So validation of a theory, which is proposed either by you or somebody else; that is one reason you want to generate data by doing some experiment.

The second one is to propose a theory based on a set of measurements; actually if you go back and go through the growth of science, modern science, science developed as an experimental activity scientific method itself means conducting experiments, then making some theoretical framework and then finding out whether the theory is going to be valid in all cases. If it is not valid, then refine the theory so that it can be made valid. In other words to make predictions based on the theoretical framework and to validate this again we go back to the experimental method and therefore the scientific method and the experimental method are one and the same. So to generate data to validate or propose a theory is one of the most important activities and which is required for the growth of science.

There is a third aspect, which is also very important, is measurement for commerce. We are quite aware that whenever we go to shop or whenever we go out and buy something, the commodity which we measure or which we buy is going to have some measurements. It may be a certain length of a piece of a cloth, the width of the piece of the cloth or it could be volume of some material like petrol or oil.

So we would like to make as accurate a measurement as possible of these quantities. So, commercial aspects also sometimes play a role, as to what kind of measurement method we are going to use, how accurately the measurement has to be made and so on. So the three important reasons for making measurements are: (1) generate data for design, (2) generate data to validate or propose a theory and (3) for commerce. And in this set of lectures, we will be interested only in the first two: generate data for design and generate data to validate or propose a theory.

With that brief idea about why we carry out measurements, let us look at the categories of measurements. In fact different people might put it in different ways. I am going to give a possible way of categorizing the measurements. There are two major categories: first we call the primary quantity, which is shown in the slide, and the second one is called the derived quantity. I will describe more fully in a moment. This is regarding the quantity we are going to measure in our experimental process or in a measurement process.

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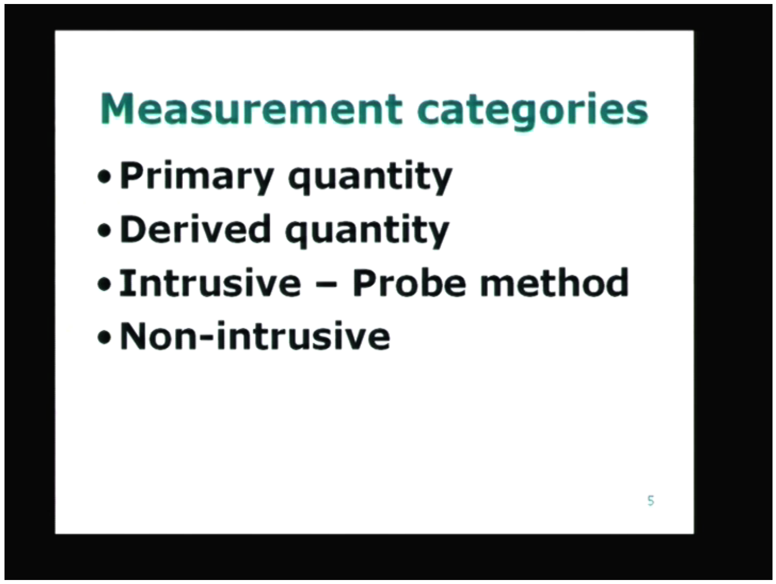

Primary quantity, for example, I can think in terms of temperature of a system, or length of the object is a primary measurement, which can be done possibly using a single instrument. For example, time: I am going to use a clock and I make the measurement. There is nothing more to it, there is no division possible. Time is the measured quantity and the only 1 quantity that I am going to talk about is when I am making measurement of time or time duration of a process. However, when we talk about derived quantity, derived quantity will assimilate into itself several measurements.

For example, velocity is the distance traveled by certain moving object divided by the time it has taken to cover the length of the travel. So the derived quantity requires at least two measurements. One is the measurement of the distance between two points, which has been covered by the moving object, and then the time it has taken for the particular action or activity. So, derived quantity is obtained as a ratio of two measurements.

So in other words, we have a primary measurement of the distance traveled, another primary measurement of the time durations for which this activity took place. To obtain the derived quantity, I have to get it as a ratio of these two quantities. I have taken a simple example; the ratio of two quantities is going to give a derived quantity. Many times it may be a more complex formula, which relates the derived quantity to the quantities, which we are going to measure. The primary quantities may be involved sometimes to the power, sometimes to the logarithm of quantity and so on.

So people who have some idea about measurement will understand that primary quantity and derived quantity are related to each other. The primary quantity is the primary measurement, is the measurement of one thing at a time using one instrument, whereas the derived quantity requires the putting together of various measurements of primary quantities according to some formula. So this is one way of categorizing the measurement as primary and derived quantity. In fact, we are going to use this theme of primary measurement or primary quantity measurement and derived quantity measurement throughout the set of lectures, which are going to be given on mechanical measurements.

Sometimes we also look at the method of measurement—as either be a probe method or intrusive, i.e., we are going to put an instrument into the measuring process, something which you are making. We are going to introduce an instrument right into the system and, of course, the probe, even though it is very small, is going to influence the system. Assuming the disturbance is very small, we will try to make the measurement. So the intrusive measurement is easier to do, many times it is cheaper than the nonintrusive type. The nonintrusive type requires a lot more money to be spent on the method of measurement or instrument. But the nonintrusive, even if it is truly nonintrusive, is not going to affect the measured quantity.

Of course, in a very basic way, any measurement will, some to extent, intrude with the system about which we want to understand and what we are going to measure—that is a philosophical question—but here we talking about it in a very restrictive way. For example, you want to measure the temperature of the bath of water. You have to put a thermometer into it and, of course, the thermometer is going to interact with the system, the bath of water, and it will disturb the temperature right close to the thermometer. Therefore, to some extent, it is going to affect the measurement. Laser beam will also intrude to a small extent, but it is more nonintrusive when compared to the thermometer, which we want to introduce into the system. So just to understand what we have mentioned in the previous slide, let us look at a few examples.

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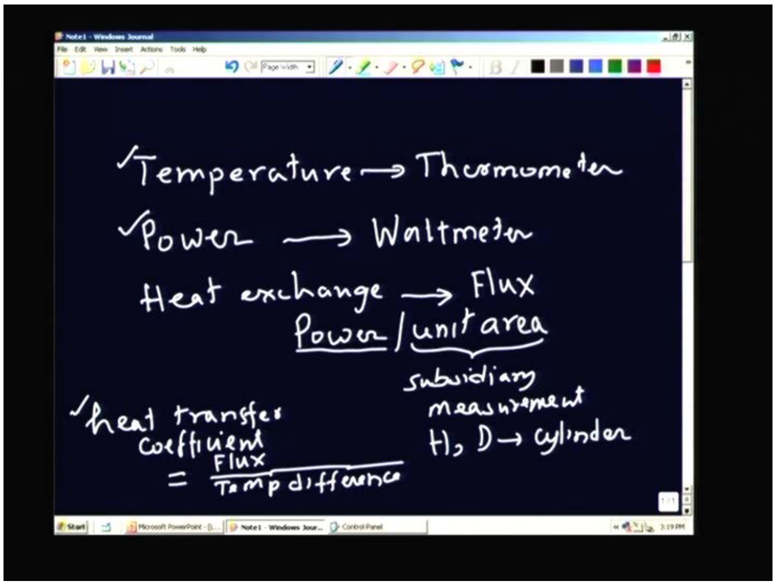

One is we talked about, the measurement of a primary quantity. For example, temperature presumably it can be measured using a single instrument or a simple instrument like a thermometer. Another example will be the measurement of power. Let us take the example of an object, which is heated, and the power can be measured using a wattmeter.

Temperature could be measured using a thermometer. Suppose we want to look at the process of heat transfer. We measure the temperature with the object, we measure the power which is given to the system, then the heat exchange is measured in terms of a flux, which is nothing but power divided by unit area. And you will realize power itself is a quantity which is per unit time.

Therefore, when I say heat exchange process, I am talking about a flux, which is the ratio of power per unit area and the power is measured using a wattmeter. And the area is measured using subsidiary measurement; for example, if it is a cylindrical object I will measure the height of the cylinder and the diameter of the cylinder.

So if I am interested in finding out the effectiveness of the heat exchange process, I would be introducing a quantity like the heat transfer coefficient. So this example will show exactly how many different things we have to measure for obtaining this quantity called heat transfer coefficient. We can define this as power dissipated per unit area, i.e., the flux divided by the temperature difference between the system and the surroundings to which the heat is being transferred. So let us use some symbols and then in the next page, I am going to show what's happening.

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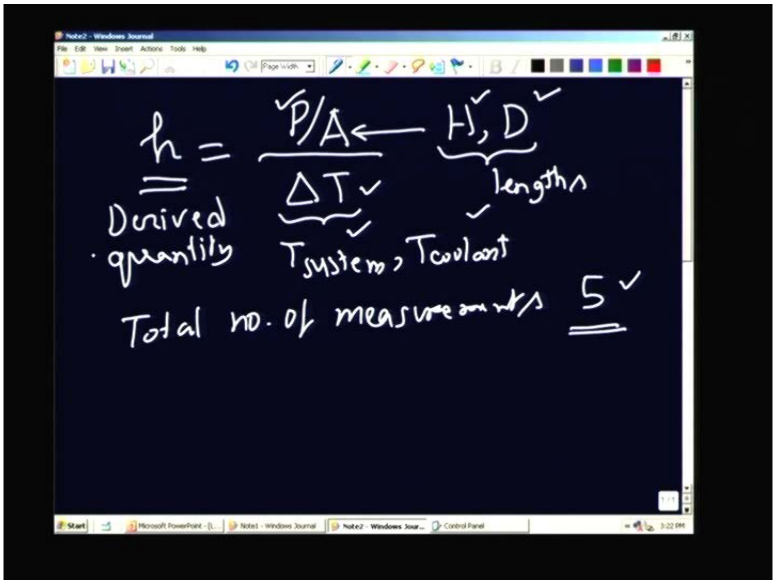

So if I use the heat transfer coefficient as h, this is nothing but the power dissipated per unit area, P divided by A, divided by delta T, the temperature difference. The quantity, which I am interested in finding out, i.e., the heat transfer coefficient, requires measurement of power. One primary quantity to be measured, the area itself, may involve measurement of height of the cylinder and the diameter as I indicated.

Therefore, two measurements are going into this and of course, here I have the temperature of the system and the temperature of the coolant or what is taking away the heat. So essentially, if we look at this simple experiment in determining the heat transfer coefficient or heat transfer for the cylindrical object to a coolant, which is flowing around it, I require 1 power measurement, two length measurements and two temperature measurements. So the total number of measurements is just the sum of 1, 2, 3, 4, and 5.

At least five measurements are required. And all these five different measurements are of different quantities, like power is the amount of heat, which is being dissipated, which may be measured in terms of the amount of heat, input to the heater if it is an electrically heated object. Then the area involves the height and the diameter measurements, these are length measurements, both are length; they may require different instruments.

The height may be measured by one instrument and the diameter may require the measurement using the vernier caliper or something like that. And the temperature may require different thermometers. So the total number of measurements is 5 and what we are going to get is only one derived quantity. So to get one simple derived quantity, the heat transfer coefficient, which is normally used in heat transfer application, I require making at least five measurements to get an idea about the derived quantity. Therefore five primary measurements or five primary quantities are measured, maybe using five different types of instruments and they are combined together using a simple formula like this P by A divided by delta T. Of course, this formula seems to be simple in this case, but there may be cases where the formula may be more complicated.

Let me take one more example; suppose I want to measure the volume of a vessel. This is also an important measurement, which is required in many applications. There are several different methods; let us just look at one of the ways of doing it. One is to measure the internal dimensions of the vessel and using a formula to calculate the value. The second method is measuring the internal dimensions and then combining them using a formula or we can fill the volume with a liquid like water, which is easily available and then empty this into a measuring jar.

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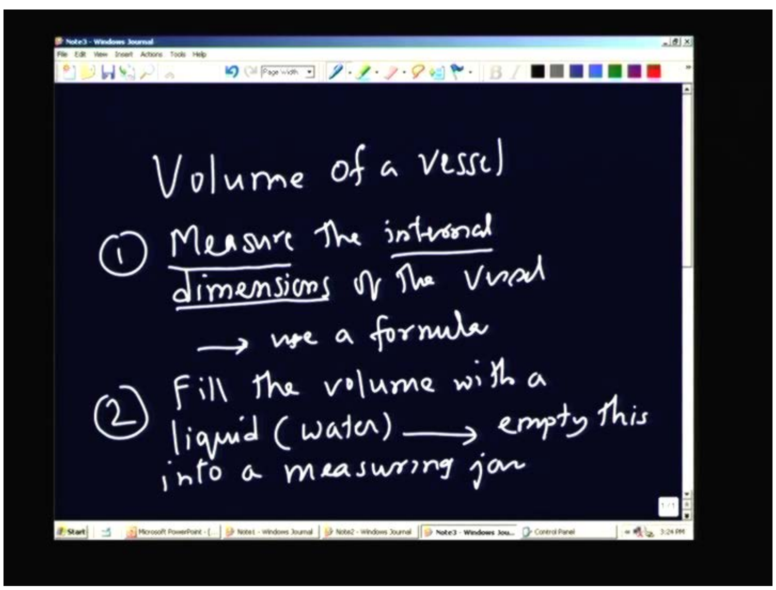

So let us look at the difference between these two methods of measurements. In the first case, I am measuring the internal dimensions; if it is a spherical vessel, for example, if it is known that it is a spherical vessel, I need only one measurement, that is, the diameter of the sphere, the inner diameter of the vessel. If it is a complicated shaped object, it becomes more and more difficult to make these measurements. This is difficult to perform if the shape of the vessel is not very simple. In the case of a complicated shape, it becomes more and more difficult to use this method.

Method number 1 is not necessarily the one, which we are going to adopt. Method number 2 has some great advantages because the shape of the vessel is not a problematic thing in this case. We just fill it with water and then transfer it to the measuring jar. A measuring jar is nothing but a vessel of known shape, so whatever is occupying the vessel is non-uniform; it may be a complicated shaped vessel. I am going to transfer it to a vessel whose shape is very simple and straightforward; may be graduations on the side of the vessel so that they can simply read the volume directly from side of the vessel. So you see that these two examples are given; this example of measuring the volume of vessel is an interesting example, because it shows how you can change the method to suit the particular measurement which we want to perform. If it is very complicated you can reduce the complexity by going for a simplification as I have indicated here.

So we have talked about primary and derived quantities. I have given one or two examples, which indicate the different types of measurements and the number of measurements required for a derived quantity you obtained. I have also given some idea about how to look for a specific method, which is better than another one, which you may think of to start with. We will see later that the errors in measurements are linked with the number of measurements we make and if you can find a method which requires lesser number of measurements, it is likely that the amount of errors we make in the measurement of the derived quantity will also be smaller. So with this background, let us look at the intrusive and the nonintrusive methods slightly in more detail and for this let me use the board.

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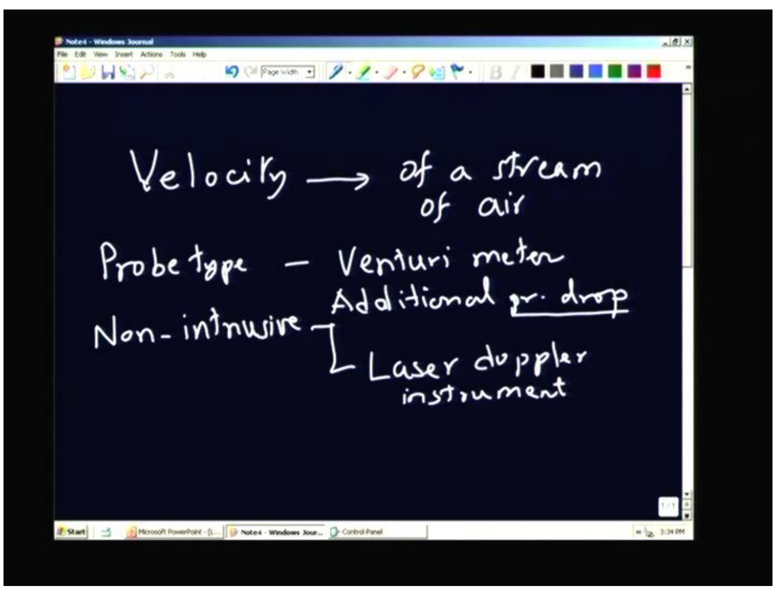

So what I am going to do is to take one or two examples again, like we did in the other two cases. Let us look at the measurement of velocity (refer slide). Now I am interested in measuring the velocity, let us have a stream of a liquid or a fluid; a stream of let us say something like air, velocity of a stream of air.

There are several methods available for doing this and of course we will consider more fully when we take up the measurement of velocity in its own right. Right now what I want to do is to show what the different possibilities are and look at a probe type and a nonprobe type or nonintrusive type. Those of you who have had some exposure to fluid mechanics will know that velocity of stream can be measured by converting the velocity to a pressure head. For example, we can use an instrument like a venturimeter.

So in the case of a venturimeter, we are going to deliberately introduce a change in the area of the cross section of the flowing tube and possibly we will shape it in the form of a converging, diverging nozzle and therefore we are going to change the area of cross section and therefore the velocity of the fluid, which is flowing through that. So when the velocity increases, when it goes through the converging part of the nozzle, the venture, the velocity will increase and so the pressure will drop. So we measure the pressure drop across the venturi and then we try to find out what it corresponds to in terms of the velocity.

So the venturimeter is a probe type because it is going to deliberately introduce a change in the cross-sectional area and therefore there is a change in the velocity. We are not measuring the velocity, which exists originally, but we are trying to modify the velocity to increase it and then try to measure it. In this whole process there will be some additional pressure drop, other than the pressure drop due to the acceleration of the fluid. There will be additional pressure drop due to viscosity and this cannot be recovered. Therefore the probe type will certainly give you the velocity of the fluid stream but it will also introduce some kind of a pressure drop, which is a disadvantage.

Suppose I use a nonintrusive method. For example, I use a laser Doppler instrument; it is considered to be nonintrusive. So what I am going to do is I am going to use 1 or more laser beams, make it cross and go through the medium whose velocity I am going to measure, assuming that the medium has got some dust particles. These dust particles will scatter the laser radiation and by looking at the scatter pattern we will be able to find the velocity of the stream of air.

In these two cases, the probe type, which uses venturimeter, I am only going to get the average velocity of the fluid in the tube. In the case of nonintrusive laser Doppler instrument I can make the measurement of velocity at any point within the flow. That means I can get information from this. By scanning the entire cross section of the flow I can even find out how the velocity is varying across the cross section. Therefore it is not only nonintrusive, it’s also more productive because it is going to give more information about what is happening across the cross section. Nonintrusive is a relative term, we are assuming that some naturally occurring dust particles in the air are going to do the business of scattering the radiation. If not we are going to introduce some small particles in the form of smoke for example. Of course, that will also to some extent interfere, but normally it is considered to be nonintrusive. The advantage of the nonintrusive method is that it gives you the information without any probe and therefore there is no external influence on the flow.

Of course, you may require a window which is transparent to the radiation and so on. So you have to arrange it properly; it may be more expensive to do the nonintrusive measurement. But it can also give you more dividends in terms of better measurements, more accurate measurement possibly and can also give details that the probe type measurement cannot give. With this background, let us look at a general measurement scheme. In fact whatever we are going to cover in this slide is more or less valid but universally valuable for any measurement one is going to make. It need not be a mechanical instrument, it can be any type of measurement and the principles involved are nicely brought out with this simple slide.

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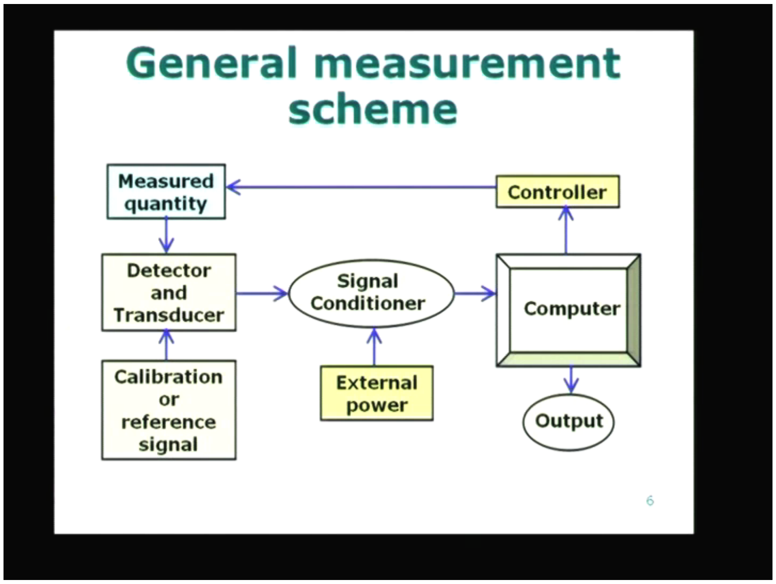

So any general measurement scheme must have a quantity, which we identify as the measurable or measured quantity. A quantity of interest to us, which needs to be measured, is the quantity, which we have to focus on. The measurement focuses itself on the measurement of that quantity which is of interest to us. So the measurement may be a direct one or it may be an indirect one.

When I say direct one, you may measure quantity directly without converting it to another form. So when you want to convert it to another form, most of the time we want to convert it to a form of an electrical signal. Most of the time, it is a yes. Many a times it could also be a motion of a pointer and so on. But in general, we are going to convert the measured quantity using a transducer to another form, may be in the form of an electrical signal and this requires a detector, which will respond to a measured quantity.

For example, if I am talking about temperature measurement, I would require a detector, which would respond to the change in the temperature. There must be a definite relationship between the temperature and the output of the detector. The output can be directly an electrical output or it could be some other output, which can be converted into the form of an electrical output, and therefore we require what is called a transducer: a detector and a transducer go together; the detector, which responds to the variation of the measured quantity and the transducer, to change it to the form of a signal, which is easy to condition, or to manipulate and so on and so forth. And many times, detection and transducer system may have its own calibration or reference signal.

For example, if I am measuring the temperature of an object, I may want to compensate for the variations in the temperature of the surroundings. So, what I have is a reference signal, which is produced either electronically or electrically or by having another instrument such that it is compensating the measurement, which we are doing. If it is prone to any influence of the room temperature, I can produce a signal proportional to the room temperature and incorporate the detector part of it. It means I can compensate if it varies for the changes of that particular point. So, once the detector detects or measures the measured quantity in terms of an electrical signal, it can be conditioned to whatever is required by the rest of the things, which are shown here.

For example, in the case of analog instruments the signal is usually in the form of a current, or a voltage, and it is directly measured by using the ammeter or voltmeter or oscilloscope or whatever. Sometimes, however, we want to condition signal such that it is in the digital form because it is easier to manipulate the signal and therefore signal conditioner can mean many things. It could have some amplifiers, it could also have a digitizer or A to D converter.

When the signal comes out of the signal conditioner, it is in the form of electrical impulses and this could be easily manipulated by a computer. And of course the signal conditioner will require external power, which is shown here to accompany the signal conditioner. Once the signal is converted to the proper form, whatever form is required for the measurement, it goes to the computer through an interface.

It goes to the computer through an interface and the computer can do several things. The computer can take the data and manipulate further, by using software. It can make a presentation on the computer screen itself we can look at the signal as it is coming in and see what is happening to it, for example, over a period of time. Or it could be output in any other form, may be in the form of a chart which is going to be taken out to a printer or it can produce a signal, whatever signal is coming from the measured quantity, detected here by the detector and transducer or signal conditioner, it may be used for controlling the measured quantity.

Suppose we have the measurement of temperature of an oven, for example, I would like to maintain the temperature at a particular value, I can use the signal coming out of the signal conditioner and use a program and use a controller, which will be able to increase or decrease the setting of the heater, so that we can control the measurement to the desired quantity level. So a general measurement scheme is what is shown here. It consists of all the components which I have indicated; in particular some of them may be missing. For example, if we don't want to control the activity of the measured quantity, the controller may be absent. For example, if I don't want the output in the form of a chart, the printer may be absent. If there is no calibration required or reference signal is not needed for the particular instrument, this may be absent. But in general, these are many or various components that go into making a general measurement scheme. This may be for 1 particular quantity I have taken. If you have several measured quantities, you have to have duplicity of this; for example, measured quantity 1, 2 and 3, etc.

There may be different detectors, different calibration signals and they all have to go into the same signal conditioner. Maybe we will have to have a multiplexer, which will get signals from various detectors in a series of readings or it will be stored in 1 buffer and from there, it will be moved to the signal conditioner in a succession and then will be taken into the computer and manipulated and used either for control or output. So the general measurement scheme can be for a single measured quantity like the temperature of a system or measurement of several quantities simultaneously.

Normally, when we set up an experiment in the laboratory; for example, we made the measurement of the power, temperature of the system and the temperature of the ambient, we measured the area of the surface and so on. Several different measurements are involved at the same time.

Therefore, if you want to completely take care of all the signals coming from the various instruments by a central processing unit like the computer here, I would have to duplicate this part: the measured detector and the calibration has to be duplicated and then it has to be conditioned by a single processor and that can be easily done now with the availability of fast A to D conversion and fast computers and it is even possible to do it in real time. Therefore the general measurement scheme is for the measurement of single quantity or several quantities at the same time.

So whenever we talk about measurements I mentioned, even when I introduced the module to you, we have to think in terms of errors, which occur in the measurement. For example, measurement of several quantities, A, B, C, D, etc., for a given derived quantity, all these quantities are measured by using an instrument or different instruments and each instrument has got its own problems in terms of errors and we will have to see how these errors are going to be characterized, whether we can take care of these errors in some sense, whether we can estimate these errors. Therefore the first issue which we have to face is the errors; errors are always present. Even with the best of the instruments, best of measurements, you will have some errors there. The errors may be of two types, systematic or random.

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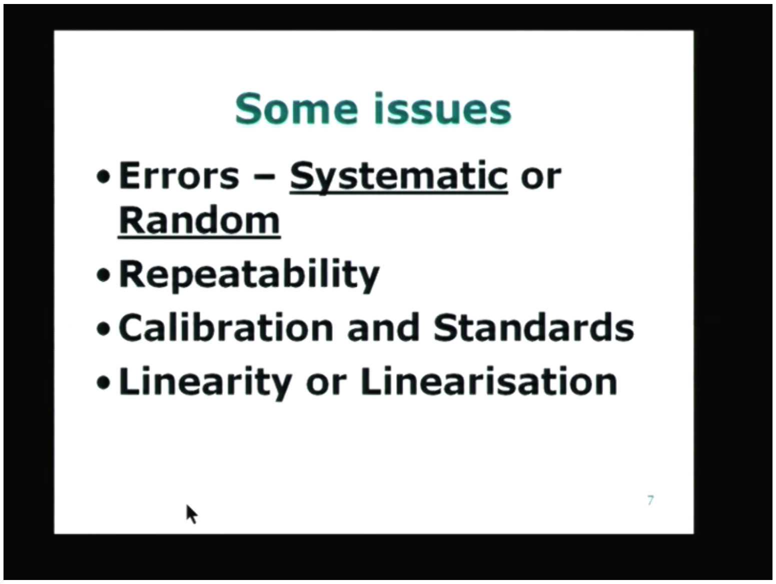

The other issue, which obviously is very important, is the repeatability of the measurement, when we make the measurement on one particular day and repeat the experiment after 2 or 3 days or you make the experiments repeatedly one after the other, you make the measurement for example in the morning, make the measurement in the afternoon and so on.

Repeatability means are these going to be close to each other, measurements made at different times are going to give you the same value. Of course you cannot get the same value or the values close to each other. Repeatability is a thing which talks about the closeness of the repeated measurements. If it is not repeatable, we have to change our method and change the experimental setup; may be we have to give up the whole measurement process because if it is not repeatable there is no need to make the measurements. It is of no use to make the measurements. I will show you later that repeatability and some errors that I have mentioned here are to some extent dependent on each other; we look at it later on.

In order to circumvent some of these systematic errors, we are forced to use calibration. Calibration is the process of comparing a particular instrument with an instrument, which is accepted as of good quality. So calibration means comparing an instrument X with an instrument which is already available, which is proved to be good and somebody has given a certificate saying that the instrument is good. Then you compare your measurement or your instrument with the standard reference.

Calibration can also mean comparison of the measurement using our process. Let us say I am interested in the property of thermal conductivity of the material. I will measure the thermal conductivity with the help of my apparatus and compare this value with what is obtained by somebody else using a calibrated or a standard reference method or I can even use a material, which we call a standard reference material, for which I am going to obtain the thermal conductivity in my lab and then compare with the value that is quoted by the manufacturers. The manufacturer will give you a value; then you find out the value in your laboratory and then compare. So calibration can mean either calibrating the instrument directly with an instrument which is standard or you can use the material for which the property has been measured and is given under a certificate by somebody, or you can use a material of the same property using some material in your laboratory and compare it with them. So calibration and standards go together, calibration either for the instrument or for the material which you are thinking of.

Of course nowadays linearity or linearization is not a very important issue; however, in instrumentation practice, normally people talk about linear, it is best to have a linear relationship between an input and an output. If you are measuring a quantity X and if the output of the instrument is directly proportional, it is very easy, because calibration becomes a simple multiplication by a factor. But nowadays with the data acquisition systems with computers and so on, it is not much of an importance and therefore nowadays we are not bothered about linearity or nonlinearity of the output. Any of them can be taken care of easily by proper signal conditioning and using the proper instruments and so on.

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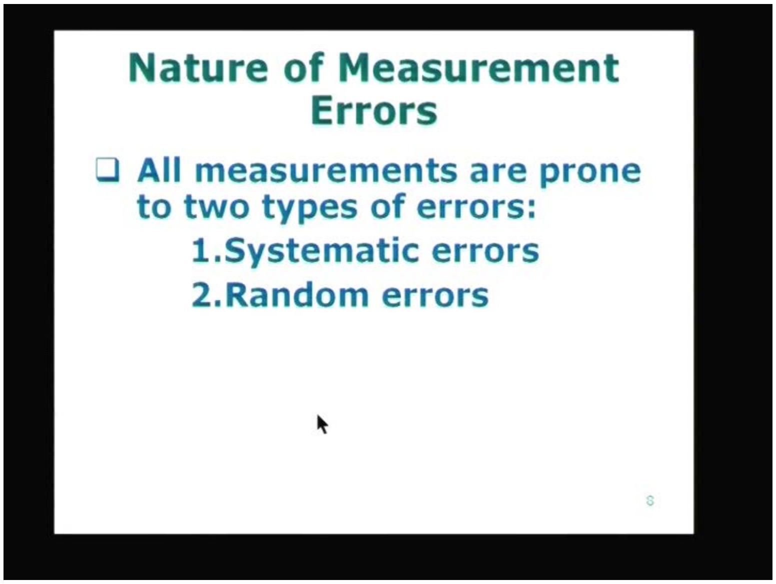

Now let us look at the nature and measurement of errors in more detail. The errors as we mentioned earlier may be of 2 types, and I am just recapitulating them in this slide. They are prone to 2 types of errors: (1) Systematic error, (2) Random error. Systematic means whatever you do, your measurement is always going to have some error, that error is systematic. That means you cannot reduce it; you cannot avoid it; if you are using a particular instrument, which is having some defect.

Whatever measurement you make, that defect will show itself. By calibration and standardizing, we can certainly reduce systematic error or account for it or make a correction for it. So systematic errors are those errors, which can be accounted for by proper evaluation of the instrument or the process of measurement, and then we can remove that or at least reduce it to a large extent. However, if we look at the so-called random errors, no such possibility exists. Random errors are not quantifiable directly in terms of cause and effect relationship. We cannot say that random error is because of a particular reason, random errors occur because of unknown and untraceable reasons.

Therefore what we do is to look at these in little more detail. (1) Systematic error, we also refer to as bias. Systematic errors are due to faulty or improperly calibrated instruments. They may be reduced or eliminated by careful choice of instruments as I indicated just a while ago.

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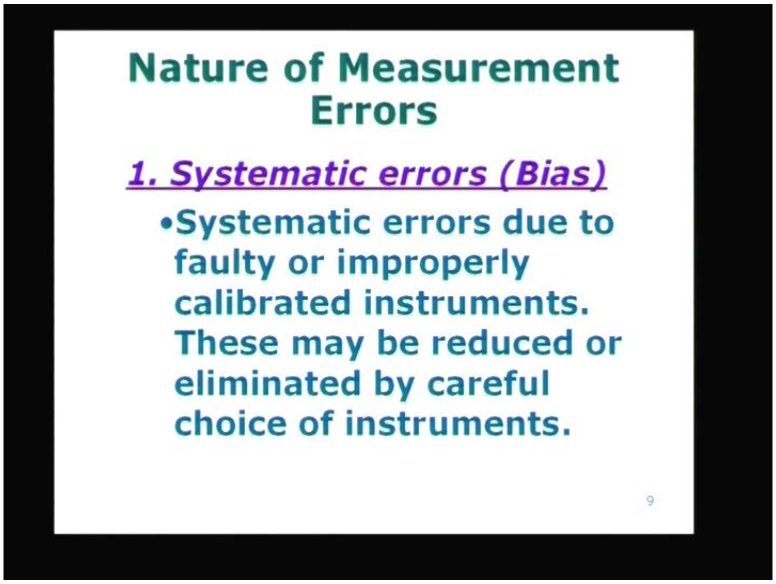

However, if I look at the random errors, these are due to nonspecific causes like natural disturbances that may occur during the experiment. There may be vibration. The vibration, if you are doing a heat transfer experiment, there may be air movement in the room which may affect the heat transfer process or somebody may shake the table, due to which the reading might be altered. And therefore these are some of the things that cannot be quantified. These cannot be eliminated. What we can do is to look at the characteristics of these errors in terms of a statistical analysis.

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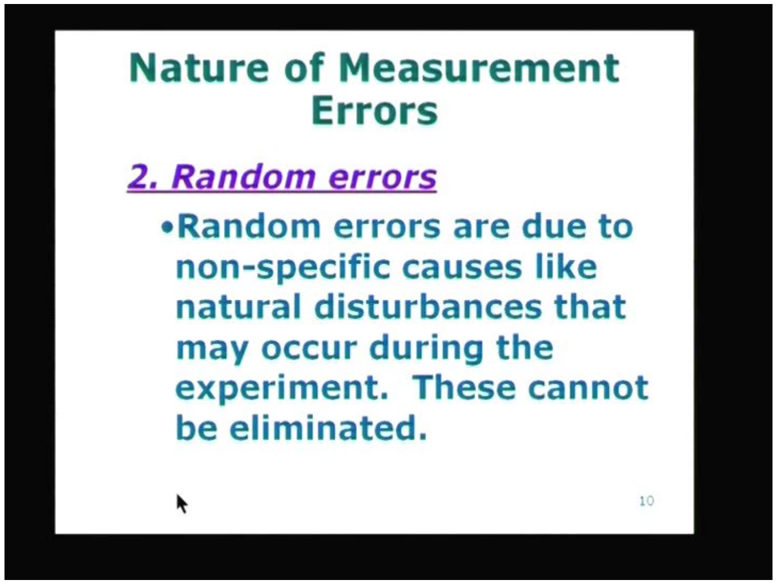

We will go to the next slide. We will see that random errors have some statistical feature, which characterizes them.

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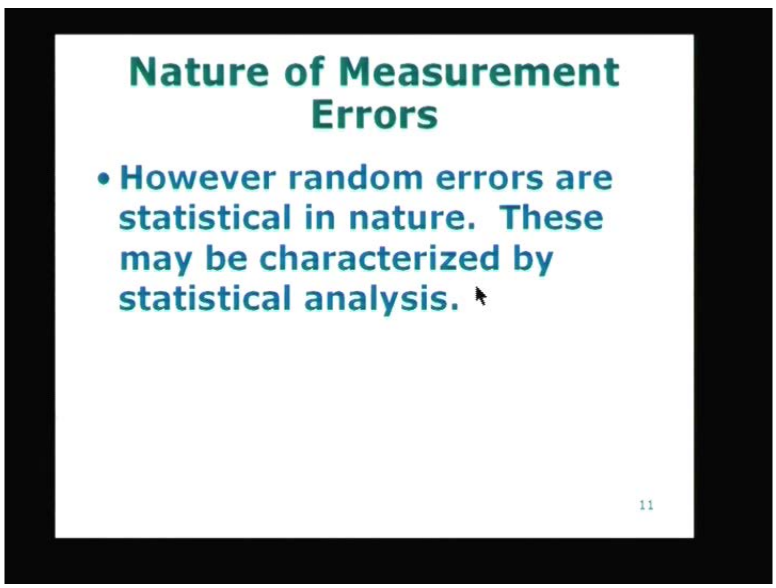

So the statistical analysis of data is going to only talk about the random errors and if you look at the systematic errors, there is no such statistical analysis. Statistical analysis will only apply to random errors because there is statistical variation in them and we can characterize it by statistical analysis and that is what we are going to look at in a little more detail before we proceed along. So let us look at the process of measurement and let us see the qualities we look for in measurement and we will define 2 new quantities. I will call them (1) Accuracy, and the other one is (2) Precision.

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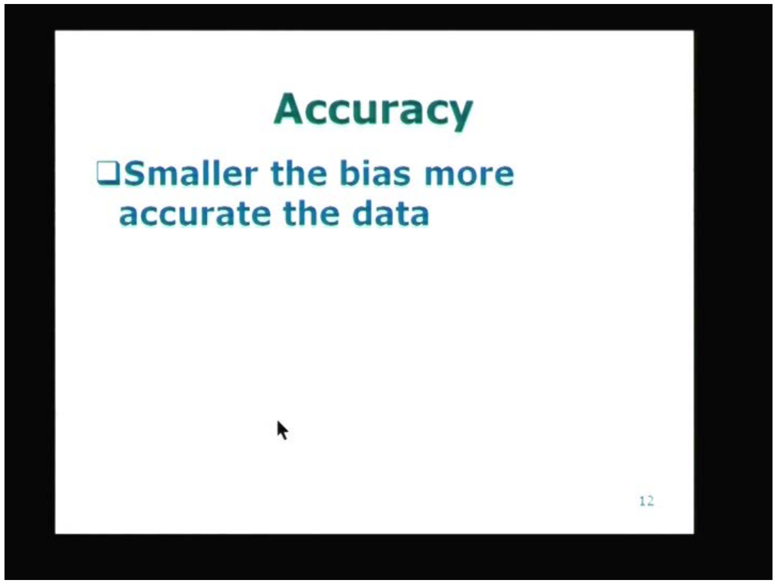

So the accuracy has something to do with the first type of error, i.e., systematic error. For example if I am measuring a particular quantity whose value is already known to me from some reference or somebody has already measured it, then the systematic error (bias) will be the difference between the measurement, which gave the value which I obtained in my laboratory or by using my measurement process compared to the accepted value for that problem.

For example, the acceleration due to gravity (g) is known to be 9.81 meter per second squared. So, if I do an experiment in the laboratory using a pendulum and measure the time period of the oscillation and from that obtain the value of (g), it may either come out to 9.81 or it may be slightly different. If I repeat the experiment in my laboratory I may consistently get a value, which is greater, or less than 9.81, which is accepted as the correct value by most people at the sea level. So now the difference, which I am getting between the measured value and the value quoted by other, we will refer to as the systematic error (bias). So whenever I measure, I am getting a different value. That means my measurement has got some systematic errors in it and if I look at the causes for this and if make a correction or make changes in the setup, I may be able to reduce or even eliminate it.

However, if I look at the random errors, I may make the measurement again and again. I will assume that bias has been removed or reduced by suitable correction factors or correcting the instrument and so on. Still every time I make the measurement I will not get the same value. For example the value of 9.81 is what I obtained or what is quoted, but what I obtained is slightly different from it, may be slightly more or slightly less; it is not on one side. It cannot always be less or always be more, in which case we will talk about the bias. If it is distributed over the correct value of 9.81 by a small amount on either direction, either higher or lower, then we can say that the error is somewhat random. So when the error is random, we can characterize it by statistical means and in order to do that we look at two different quantities: one is the accuracy. Accuracy is good if bias is small; that is, we say the smaller the bias, more accurate the data. I will illustrate it with the help of an example a little later. However, if I am looking at the random fluctuations the smaller the random fluctuation with respect to the accepted value, or a value which I can be confident about, then smaller the random error and more precise is the data. Therefore accuracy and precision refer to two different things.

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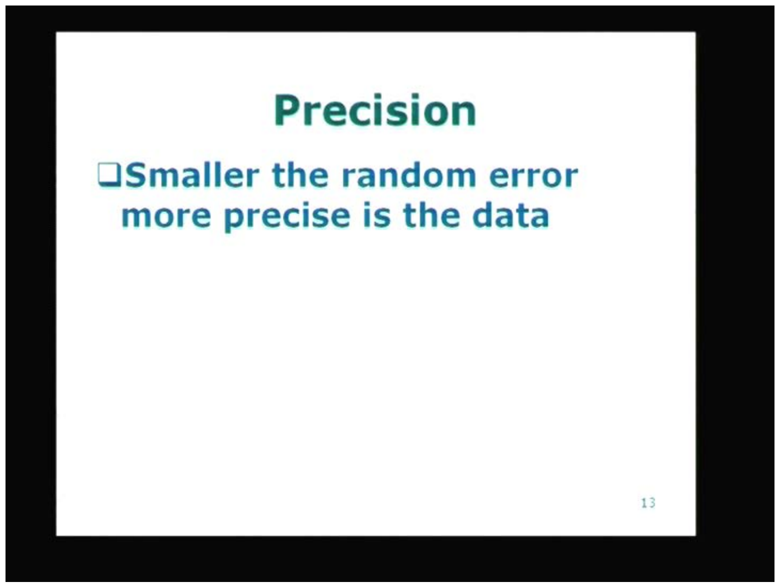

Let us take a typical example. The example, which I have in mind, is familiar to all of us. Somebody is doing target practice, may be there are 2 or 3 persons. There are three examples shown here in the slide.

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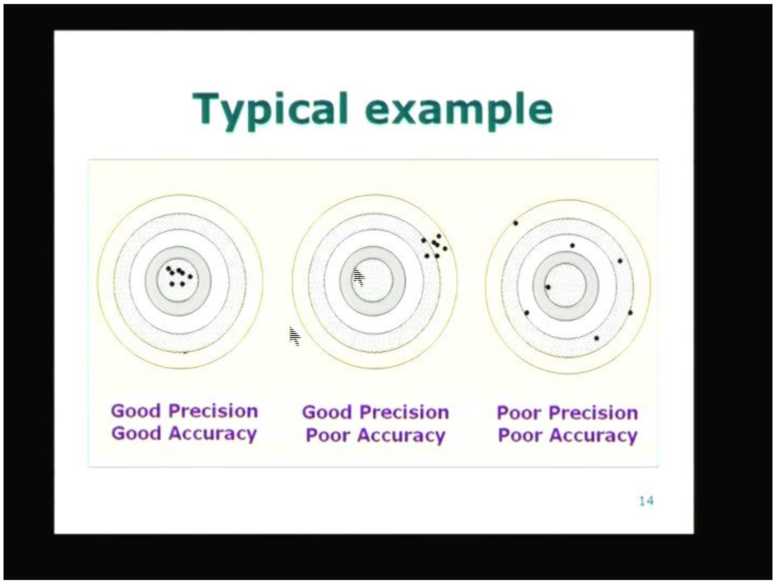

In the first example you can see that each person has taken 7 shots and in the case of the first person, all the 7 are within the first circle, the innermost circle. So let us look at the second person: all his 7 shots have come very close to the edge of the target and they are clustered in a corner. In this case, it is here at the center and in the second case it is in the corner. The third fellow whose shots have gone all over the big circle; they are not clustered but they are distributed throughout. We can immediately come to the conclusion that, if we remember what we described a little while ago about precision and accuracy: in the case of target practice, your idea is to hit at the target at the middle of the bull, i.e., the smaller circle.

As far as the first person goes, the precision is good; the accuracy is good because most of it is within the inner circle. For example I can assign 10 for small circle and 9, 8, 5, 4, etc. for the other circle. So, if you look at the score of the first person, it will be $7 \times 10 = 70$ is what he is going to get.

Look at the second person: he is also clustered in a corner; he is also good, but they are all in the wrong place. He probably gets a lower score. It will be $7 \times 5 = 35$. The third person's is all over the place, his aim is very bad so accuracy is not good and precision is also not good because random fluctuation with respect to the center of the circle here you see that he is all over the place. So an experiment can be like this: the first one, if you go back to the slide, an example can be like this: the value of g is 9.81 + or – a very small value. Or it can be like this, all clustered in a corner. Let us say 8.3 instead of 9.81 and this one, he is getting values of g that are sometimes low and sometimes high, so there is no pattern to it.

Therefore, you can see that these three examples are like examples for, one is for good precision and good accuracy, the second is good precision—he is precise but he is in this corner; accuracy is poor and here is the case where it is neither precision nor accurate. Therefore, to summarize what we are describing, we can generally say that experiments also are like this target practice.

One would try to get the best possible and most accurate value and also one must try to get the most precise value with least amount of random errors.

What we will do in the next lecture is to amplify on some of these things, try to characterize these quantities and look at a few examples for this. Thank you.