Mechatronics
Prof. P. M. Pathak
Department of Mechanical and Industrial Engineering
Indian Institute of Technology, Roorkee

Lecture - 09
Force, Fluid Flow Sensors

I welcome you all, in this course on Mechatronics. Today we are going to discuss various types of sensors which are used for Force and Fluid Flow measurement. Let us take first the force sensor. How do we measure the force? A very common use force sensor is the spring balance which you often see available in the market as well as they are in the many of our houses.

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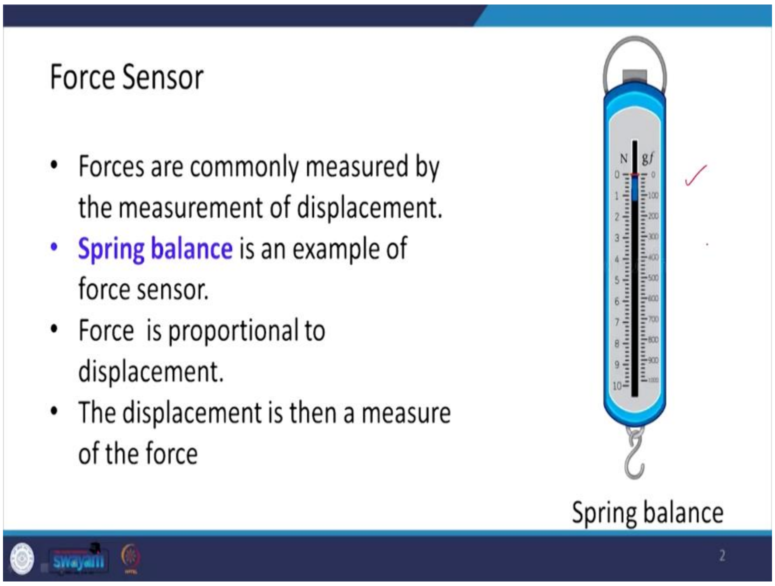

How does the spring balance measure the force? In the case of a spring balance what happens is that the force is proportional to the displacement. Here, we essentially measure the displacement, which is calibrated in terms of the force. Forces are commonly measured by the measurement of displacement and force is proportional to the displacement. By measuring the displacement, we can measure the force. The other type of force measurement device is the strain gauges. The popular form which is available is the strain gauge load cell. Now, you see that based on electrical resistance a strain gauge to monitor the strain produced in a member when a stretched is compressed or bent by application of the force.

In the case of strain gauges, the strain changes, if the strain gauge is placed on a member, and if the strain changes so, with the change of strain the resistance changes. That is how it is measured and their arrangement is called a load cell and in a cylindrical tube usually, the strain gauges are attached.

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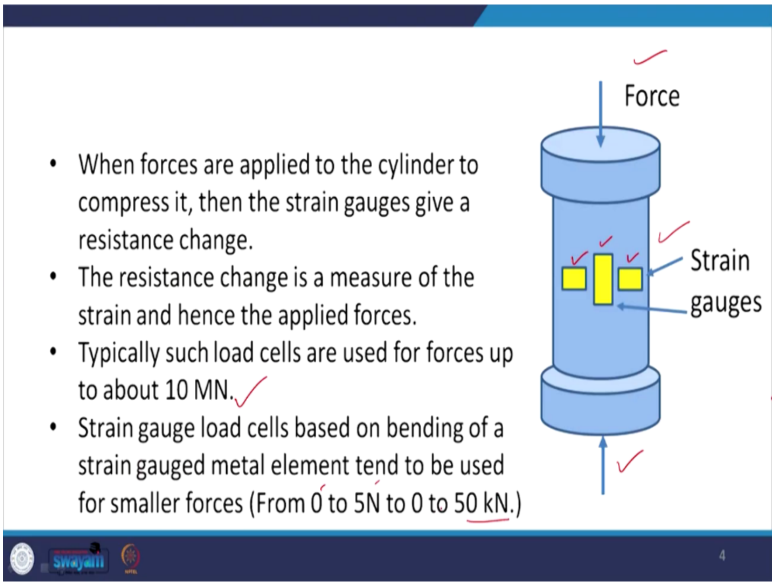

You can see the attachment something like this say this is a cylindrical tube, where a compressive force can be applied, and here are the strain gauges which are put into in this particular fashion. Now, when forces are applied here, then what happens? Strain gauge gives a resistance change and this resistance change is the measure of the applied force. Typically, such load cells are used for forces up to say 10 mega Newton, as you can see here and strain gauges which are based on the concept of the bending of an element can be also used to measure the smaller forces say 0 to 5 Newton to say 0 to 50 kilo Newton. In this range, you can use the strain gauges, which are put on an element that bends. Next, let us see the measurement of the fluid pressure.

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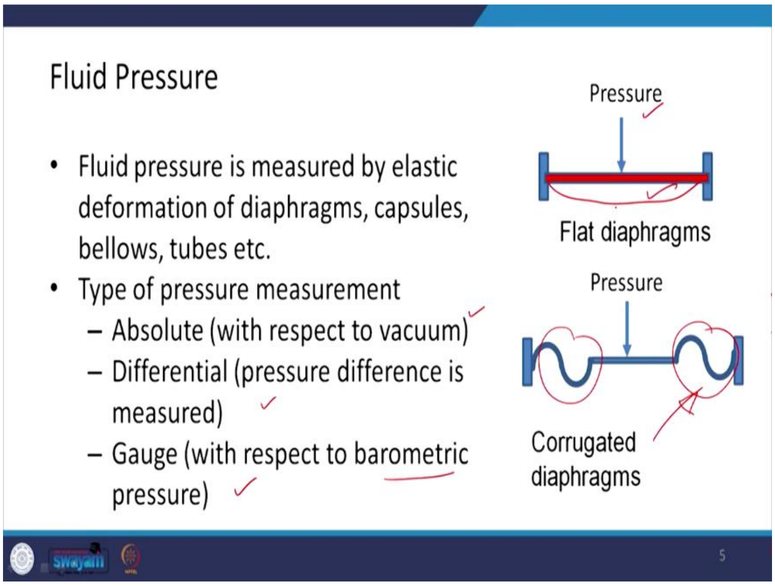

Fluid pressure is measured by elastic deformation of diaphragms, capsules or bellows, or tubes. So, suppose you have a flat diaphragm like this now, when pressure is applied your diaphragm is going to deform. This is how what is the principle of the pressure measurement is, and to increase the sensitivity of the diaphragm, some corrugation is done as you can see over here and this is what we call the corrugated diaphragm. There are essentially the three types of pressure measurement which we come across. One is the absolute, one that is where the pressure is measured with respect to vacuum, then the differential one, where the pressure difference is measured and the other one is the gauge one with where the pressure difference is measured with respect to the barometric pressure, or the atmospheric pressure.

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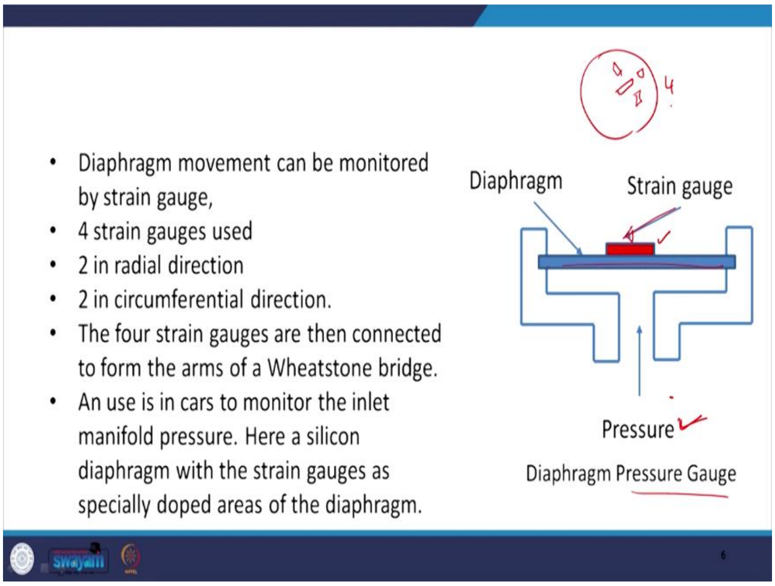

Diaphragm movement here, as I said that the pressure is measured by the movement of the diaphragm. Now, the question is how do we measure the diaphragm movement? If we can measure the diaphragm movement we can measure the pressure. So, the diaphragm movement can be monitored by strain gauges. Suppose you have a pressure diaphragm pressure gauge is here, where pressure is supplied from this site, and here is the diaphragm and the strain gauge is this element. Here the 2 strain gauges can be used in the radial direction. For example, this direction, and the 2 strain gauges can be used in the say your circumferential direction. Total 4 strain gauges can be used over here and these 4 strain gauges, are connected to form the 4 arms of the Wheatstone bridge. From Wheatstone bridge, we can find out the change in the resistances or the voltages, whatever way you want to do it you can do it. Now, the use of this type of device is incurred to monitor the inlet manifold pressure. Here, a silicon diaphragm with the strain gauge as specially doped areas of the diaphragm is used.

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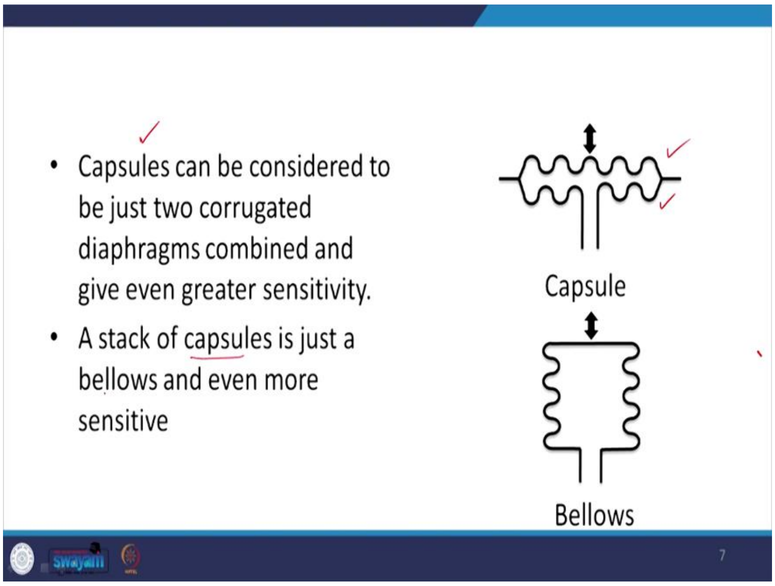

Capsules can be formed where you have the two corrugated diaphragms. You can see that one diaphragm at the top and another one is there. So, this type of combination is what are we call a capsule. So, there are just two corrugated diaphragms combined and they give greater sensitivity. When we stack of capsules are used and they just are what is called as the bellows. So, a stack of the capsule is just below and they are even more sensitive for the pressure measurement. Now, these bellows can be combined with LVDT. To give a pressure sensor with an electrical output.

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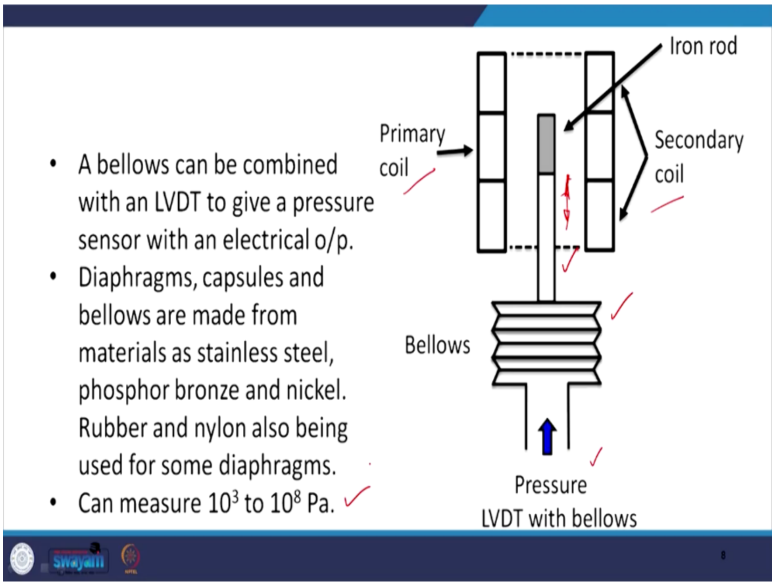

If we combine this bellow with LVDT, where you have the primary coil here secondary coil here and I can put an iron rod in this one attached with this bellow. And when the pressure is applied, there is a movement of the bellow and the intern there is a movement of the LVDT movement of the iron rod, which is there in this LVDT.

So, the diaphragm capsule and bellows here are made from materials such as stainless steel, phosphor, bronze, nickel, rubber, nylon is being used for some of the diaphragms. And, they can measure pressure up to say 10 to the power 3 to 10 to the power 8 Pascal.

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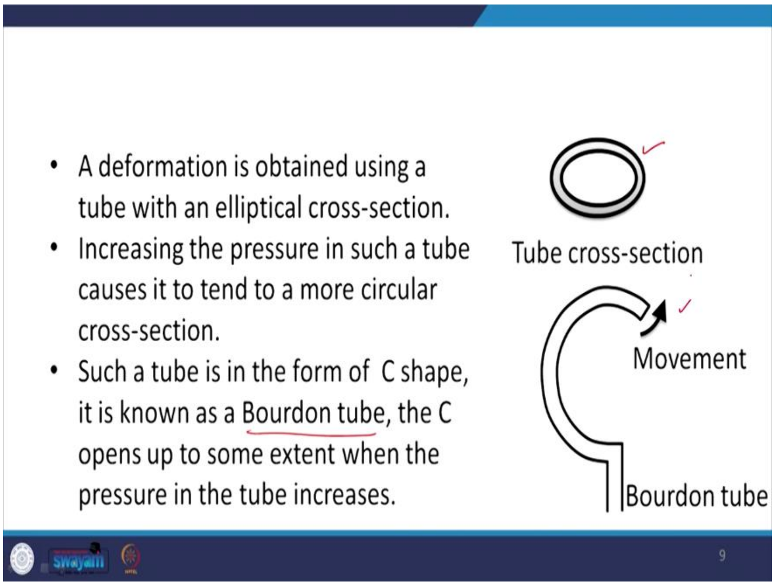

You see a deformation is obtained using a tube with an electrical cross-section. Suppose if there is a tube with an electrical cross-section. If you supply pressure, then with an increase in pressure what will happen? It will try to bend the take of the form of the circular cross-section. Such a tube in the form of a C shape is what is called the Bourdon gauge, which you must have studied in your school classes. Here the C opens up to some extent when the pressure in the tube is increased.

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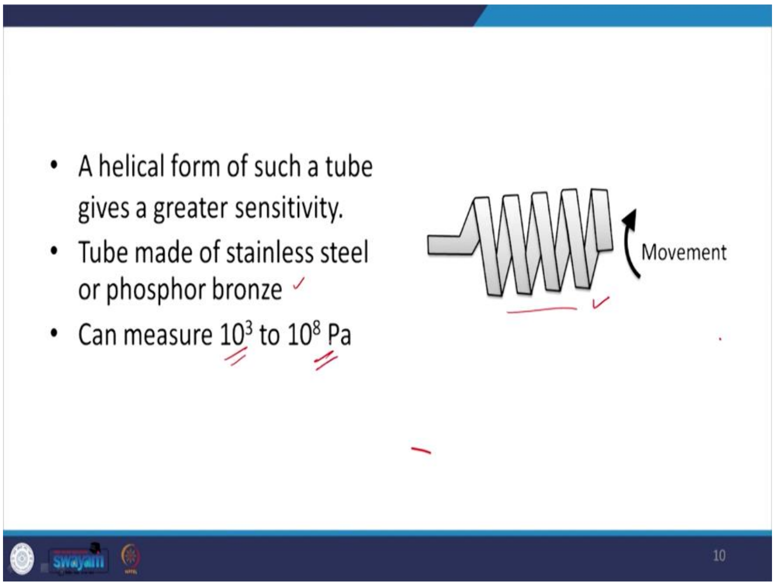

We can also have a helical form of such a tube and that gives greater sensitivity and these tubes can be made of stainless steel or phosphor bronze material. And, they can measure pressure up to 10 to power 3 to 10 to power 8 Pascal.

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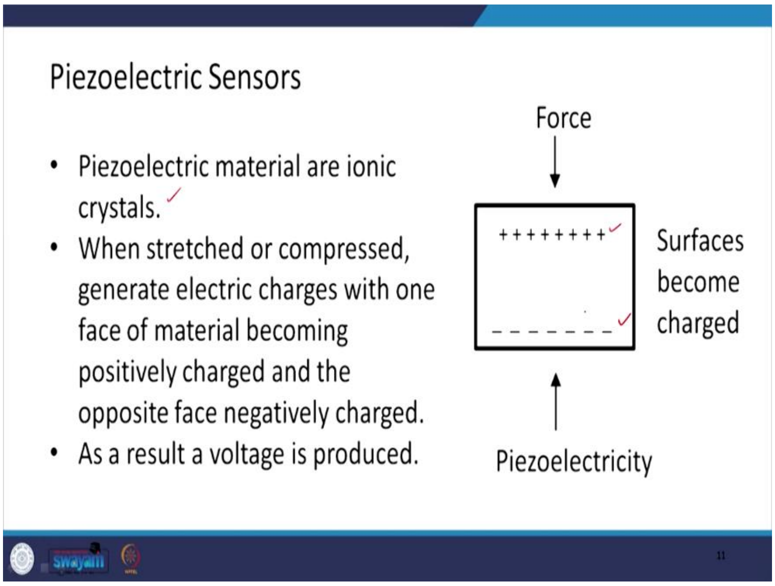

Next, let us look at the piezoelectric sensor. So, piezoelectric sensors work on the principle of piezoelectric. These are devices use piezoelectric material which is ionic crystals and you see that when these crystals are stretched or compressed there is a generation of electric charges with one face, becoming in the one face you have an accumulation of positive charges and another face you have an accumulation of the negative charges. So, as a result, a voltage is produced.

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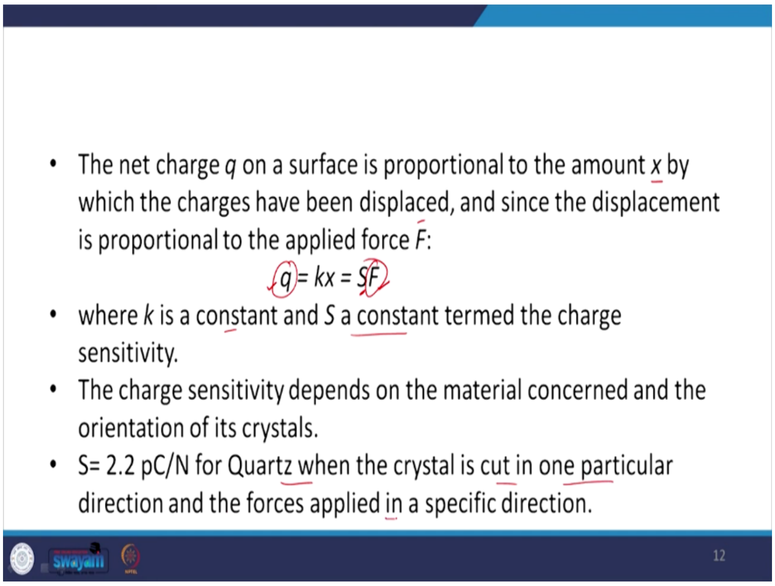

The net charge q on the surface is proportional to the amount x by which the charges have been displaced and since this displacement is proportional to applied force, we can write,

$$q = kx = SF$$

So, here this k is a constant and S is a constant term, that is called the charge sensitivity. The charge sensitivity depends on the material concerned and the orientation of the crystal. The value of s is usually say 2.2 Pico coulomb per Newton for the Quartz when the crystal is cut in one particular direction and the forces applied in a specific direction. These metal electrodes can be deposited on the opposite faces of the piezoelectric crystal as you can see here.

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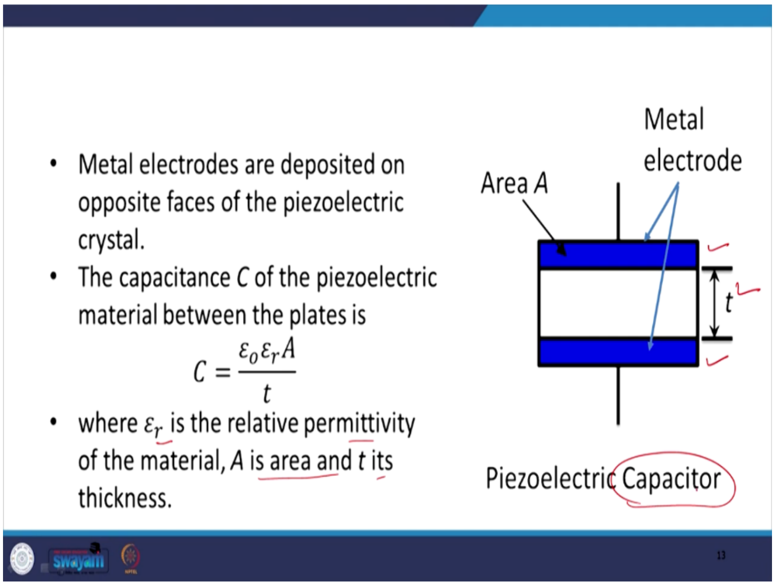

At the opposite faces of this piezoelectric crystal, I am putting the metal electrode over here and then the capacitance of the piezoelectric material between these two plates can be given by,

$$C = \frac{\varepsilon_o \varepsilon_r A}{t}$$

where ε_r is the relative permittivity of the material, A is the area of these plates and t is the thickness over here. What happens that by putting the metal electrode? we are forming a piezoelectric capacitor.

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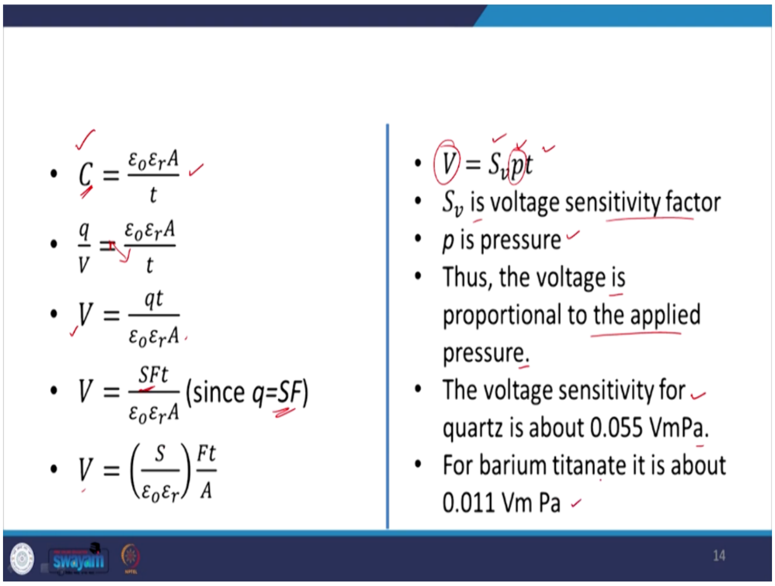

The capacitance of this piezoelectric capacitor can be given by this expression. Now, I can write this C as charge per unit voltage.

$$\frac{q}{V} = \frac{\varepsilon_o \varepsilon_r A}{t}$$

$$V = \frac{qt}{\varepsilon_o \varepsilon_r A}$$

$$V = \frac{SFt}{\varepsilon_o \varepsilon_r A}$$

$$V = (\frac{S}{\varepsilon_o \varepsilon_r})\frac{Ft}{A}$$

Here, S_v is the voltage sensitivity factor and you can see p is the pressure. The voltage across the capacitor plate, that is going to be proportional to the pressure. This is how this pressure is a measurement with the help of this piezoelectric capacitor. The voltage sensitivity for the quartz is about 0.055-volt meter Pascal for barium, for titanium, it is about to say 0.011 voltage meter Pascal.

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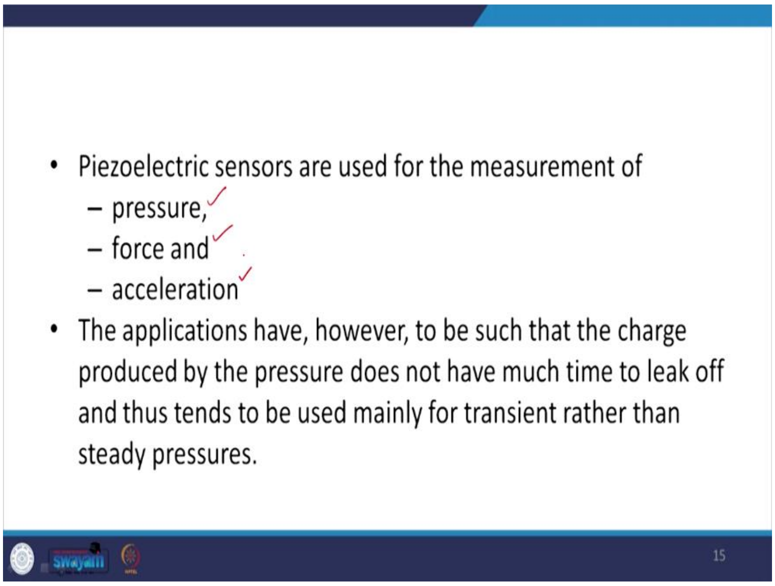

Piezoelectric sensors are used for the measurement of pressure. They can also be used for the measurement of forces, as well as the measurement of acceleration. The application has to be such that the charge produced by the pressure, does not have much time to leak off and thus tends to be used mainly for that transient pressure rather than for the steady-state steady pressure.

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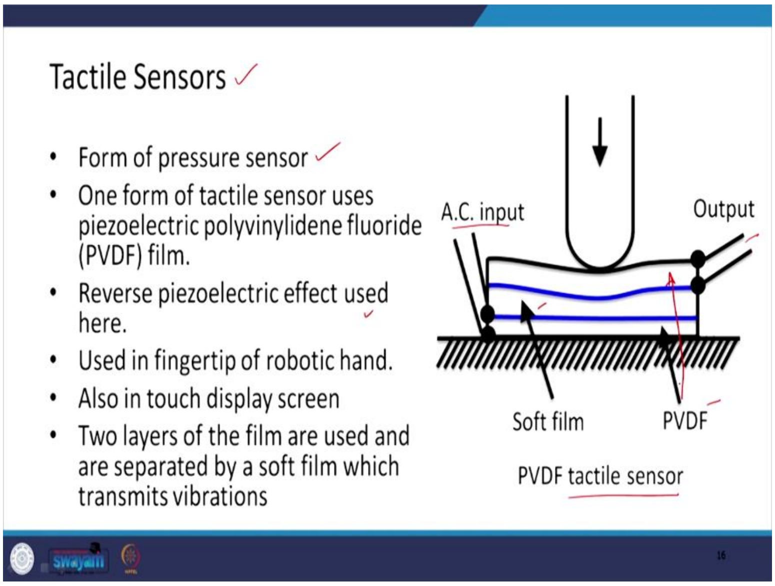

Next, let us look at the tactile sensors. Tactile sensors are touch sensors and they can be used to sense the touch and because of this they can be used in the fingertip of the robotic hand and also in the display screen. So, let us see what is the principle for these tactile sensors. As I said these are forms of pressure sensors and one form of the tactile sensor uses, piezoelectric polyvinylidene fluoride is PVDF film. You can see that the PVDF tactile sensors have the PVDF film is there and there is a soft film, and you have the AC input from here and the output can be taken out from here.

Here, in this case, the reverse piezoelectric effect is used. As I already told you they are used in the fingertips of the robotic hand and also used in the touch screen. The two layers of the film are used and are separated by a soft film that transmits vibration. So, this is PVDF film and this also is the PVDF film.

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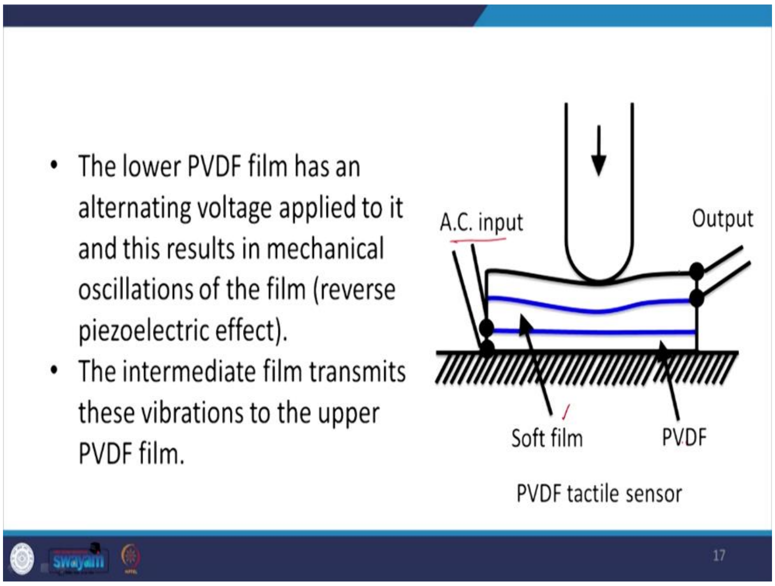

Let us look at the working principle of it. The lower PVDF film has an alternating voltage applied to it and this results in mechanical oscillations of the film, which is because of the reverse piezoelectric effect. These oscillations are transmitted to the upper film, with the help of the soft film. The intermediate film transmits this vibration to the upper PVDF film.

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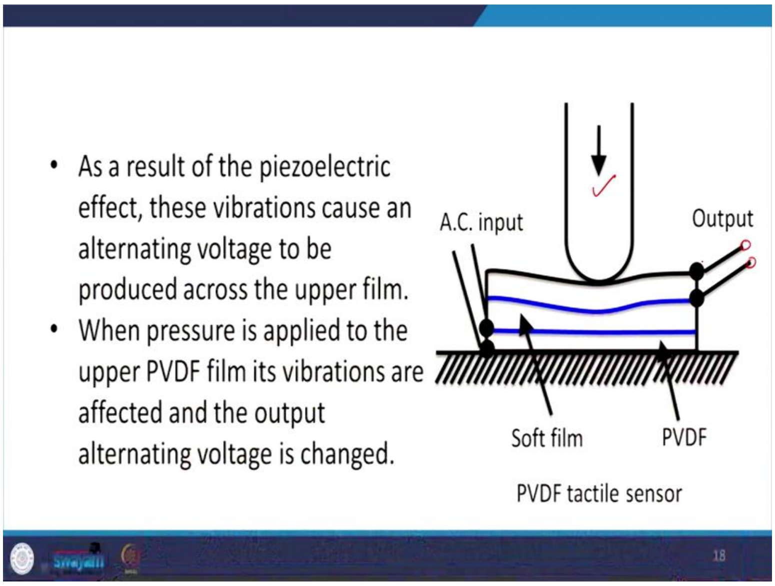

As a result of the piezoelectric effect, these vibrations cause an alternating voltage to be produced across the upper film. When pressure is applied here by the fingertip to our PVDF film, upper PVDF film its vibrations are affected and the output alternating current is changed. That change is the sense that something has pressed the surface. Next, let us look at the liquid flow, you see that the liquid flow measurement is based on the principle of the change in the pressure. The method of measuring q is based on the measurement of the pressure drop occurring when the fluid flows through a constriction. This constriction could be either you have a reduction in the cross-section, as it is there in the Venturi meter or as it is there in the orifice meter. This is the basic principle, there is going to be a reduction or the flow is going through be a constriction.

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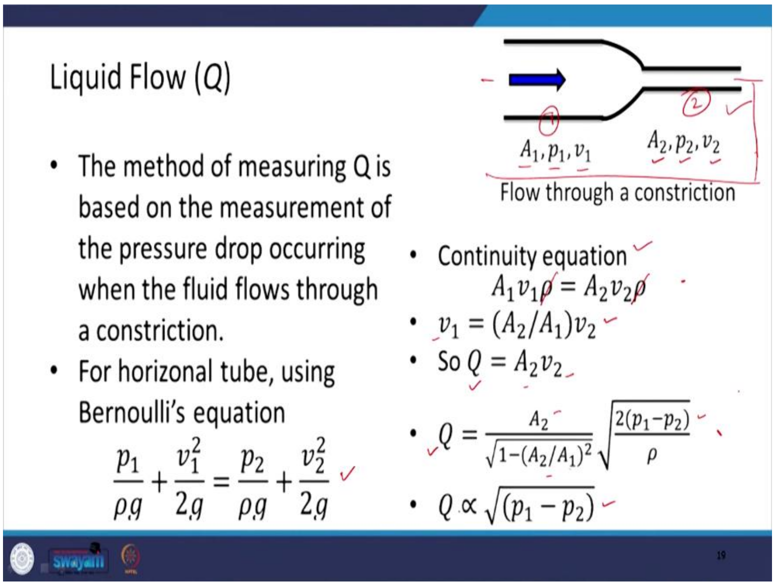

For horizontal tube here, as you can see here say this side A you have the area of cross-section A 1 pressure p 1 and velocity v 1 whereas, say side 2 these values are A 2 p 2 and v 2 .

Now, this is a horizontal tube here so, we can apply the Bernoulli's theorem.

$$\frac{p_1}{\rho g}+\frac{v_1^2}{2g}=\frac{p_2}{\rho g}+\frac{v_2^2}{2g}$$

Then, we can use the continuity equation that is,

$$A_1 v_1 \rho = A_2 v_2 \rho$$

that is for the conservation of mass. From here this rho gets canceled, so we get

$$v_1 = (A_2/A_1)v_2$$

So, then I can find out Q as,

$$Q = A_2 v_2$$

$$Q = \frac{A_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2(p_1-p_2)}{\rho}}$$

Q is proportional to the square root of the pressure drop

$$Q \propto \sqrt{(p_1 - p_2)}$$

So, if you could measure this pressure drop, we can find out the Q. So, that is the principle for the liquid flow.

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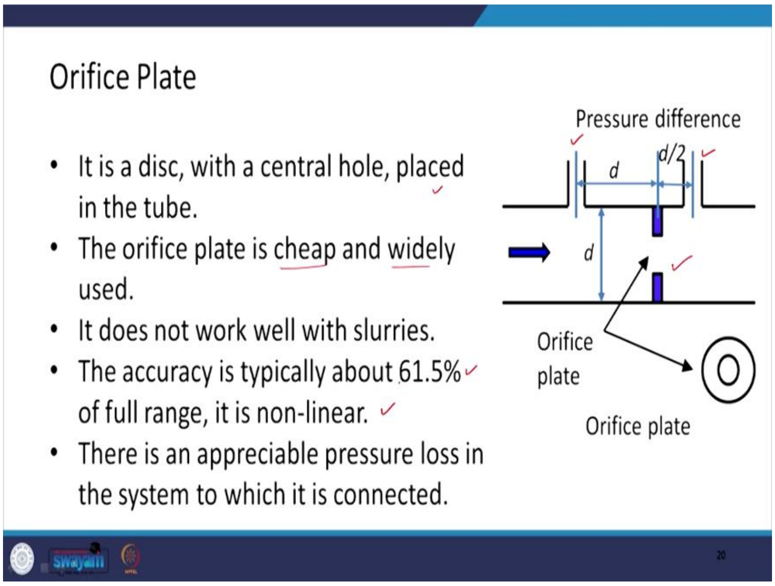

I was explaining to you the orifice plate is also a type of constriction and which can result in a drop of pressure. If in a pipe, I have an orifice plate over here. And say upstream side and downstream side, I put a tapping from where, I can find out the pressure difference, then this arrangement can be used to measure the flow. It is a disc with a central hole placed in the tube and the orifice plate is simply cheap and very widely used. But, again because there is a constriction here, so it will be difficult or constriction can choke your orifice so because, of that, it does not work well with the slurries. If slurries are there orifice plates cannot work very well on that. The accuracy is typically about say 61.5 percent of the full range and it is non-linear. Why it is non-linear? Because, we have seen the relationship that is here, the Q is proportional to a square root of p 1 minus p 2, so this is a non-linear relationship. There is an appreciable pressure loss in the system to which it is a connected.

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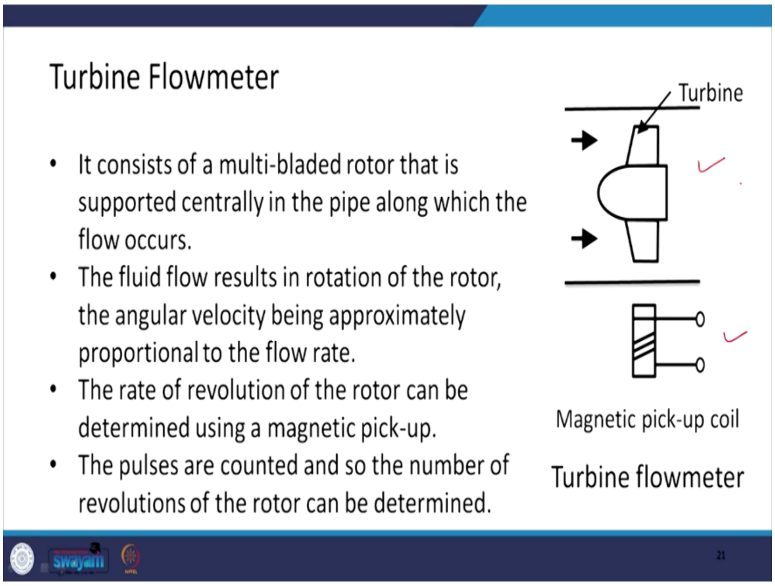

Next type of flow measurement device is the turbine flow meter, where you have a turbine blade here. The flow takes in this direction and there is a magnetic pickup coil here. It consists of the multi-bladed rotor that is supported centrally, in the pipe along which the flow occurs, and the fluid flow results in the rotation of the rotor, and the angular velocity is proportional to the flow rate. The angular velocity of the rotor is going to be proportional to the flow rate and the rate of revolution of the rotor can be determined using the magnetic pickup. The pulses can be counted and so, the number of revolutions of the rotor can be determined. In this way, we can measure the flow. Next, let us lo at the measurement of the liquid levels. So, how does the liquid level is measured? One of the basic ways could be that we just measure directly the position of the liquid surface or indirectly by measuring some variable related to the height, that way we can measure the liquid level.

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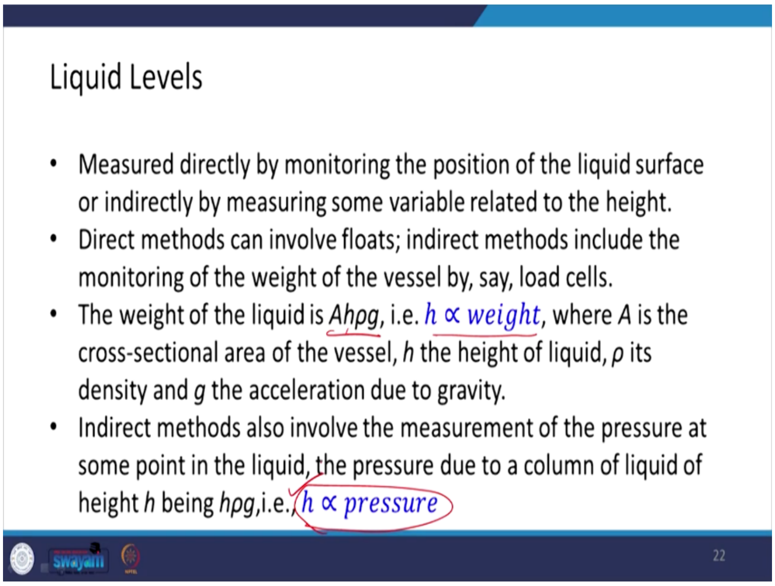

The direct method can involve floats as they are used in our water tanks in our houses and the indirect method can include the monitoring of the weight of the vessel. How do you monitor the weight, which is a type of force? Then again we can use the load cell.

The weight of the liquid you can say see that it is $Ah\rho g$ and so, this h is proportional to the weight. The more the weight more the height. This is the principle by which we can measure the weight, measure the height. There is an indirect method also, but the indirect method involves the measurement of the pressure at some point in the liquid, and you know that the pressure is proportional to the height of the liquid column. So, we can also have that is a height we can measure, by knowing the value of the pressure at that particular point.

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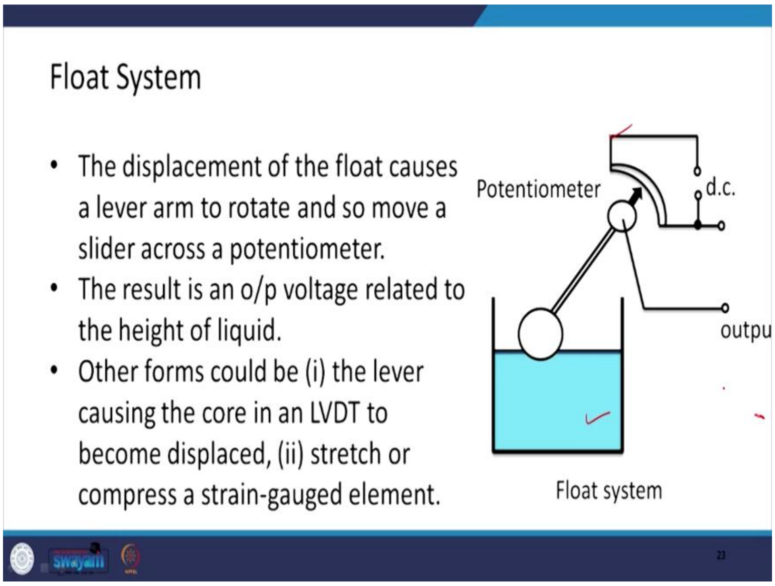

Let us look at the float system. Here the float system you can see that, there is water over here and we have a float. This float could be contacted with a potentiometer. The displacement of the float causes a lever arm to rotate and so, move across a slider in a potentiometer, and the resultant is an output voltage related to the height of the liquid.

In this way, we can use the float system to measure the height of the liquid. There could be another form also where the lever causes the causing the core in an LVDT to become displaced or stretch or compress a strain gauge element.

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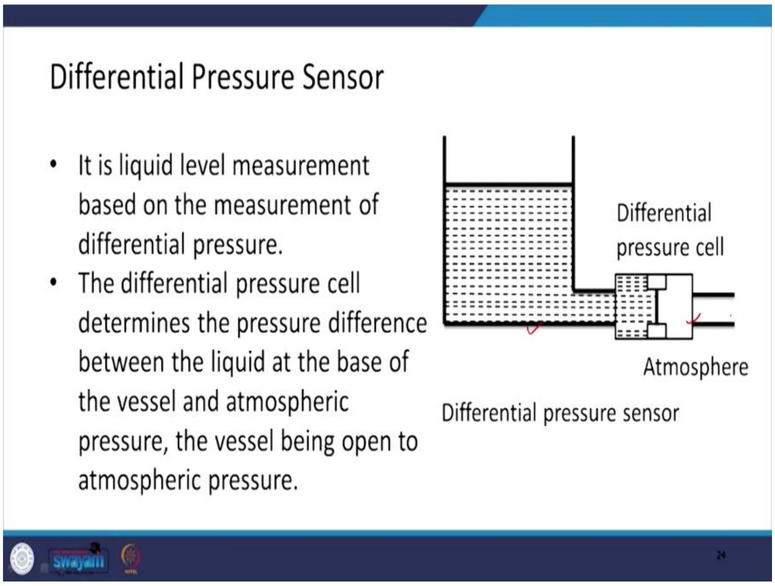

Then, there are differential pressure sensors. Differential pressure sensors is a liquid measurement based on the measurement of the differential pressure. The differential pressure cell determines the pressure difference between the liquid at the base of the vessel and atmospheric pressure. The vessel is open to the atmosphere. So, that way we can find out the differential pressure. Now, let us look at the temperature sensor.

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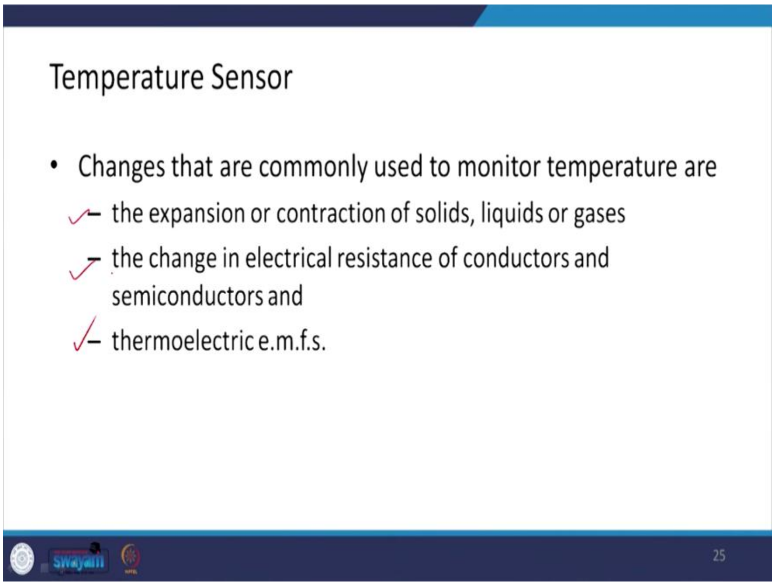

Changes that are commonly used to monitor the temperature or the expansion or contraction of solid-liquid or gases. So, with the help of this expansion or contraction of the solid-liquid gases, we can measure the temperature. Change in electrical resistance of conductor and semiconductor, that can be a way of measuring the temperature. The thermoelectric e m f change also can be used for the measurement of the temperature. So, either of these three ways can be used for the measurement of the temperature. Let us look at the first example that is the bimetallic strip.

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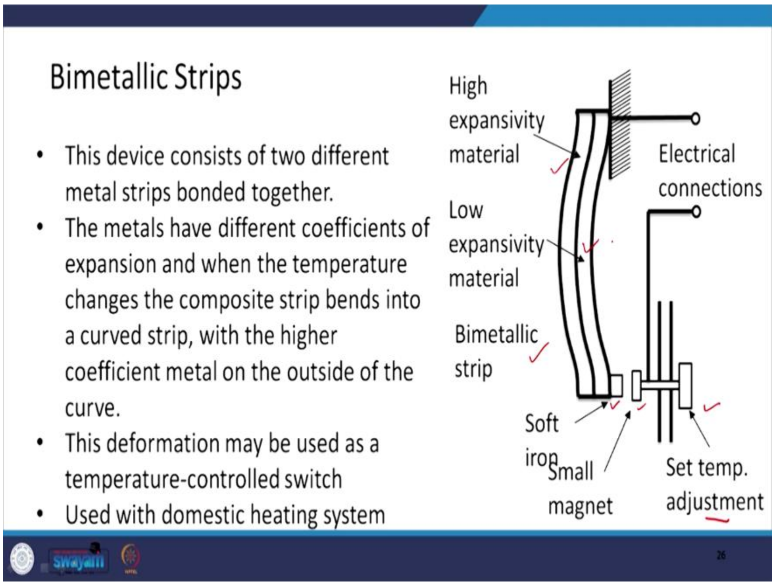

In case of bimetallic strip as you can see that there are two strips, with different expansivity. You have the high expansivity material here and the low expansivity material here. So, they both put together and this is what we call the bimetallic strip. There could be a soft iron over here and say there is a small magnet. You have the set temperature adjustment and then you have the electrical connections over here. So, this device consists of two different metallic strips, which are bonded together and these materials have different coefficients of expansion. When the temperature changes the composite strips bend to the curve bend into a curved strip, and with the higher coefficient material on the outside of the curve. And this deformation may be used as a measurement of the temperature. So, the deformation may be used as a temperature-controlled switch and this type of device is the bimetallic strip, which is used in the domestic heating system.

Next, let us look at the RTDs, that is the Resistance Temperature Detectors. So here, the temperature is detected with the help of a change of resistance alright. So, the resistance of most metals increases over a limited temperature range in a reasonably linear way with temperature.

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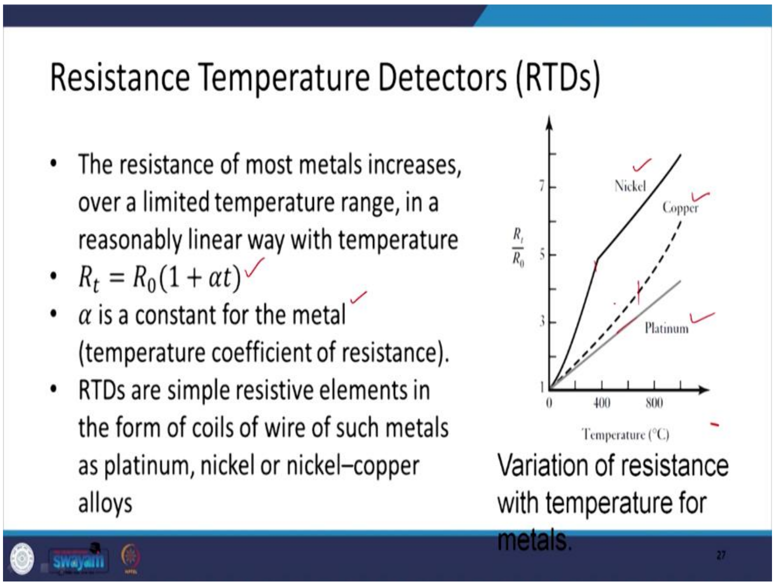

We know this very popular equation which you might have a studied in your intermediate classes,

$$R_t = R_o(1 + \alpha t)$$

wherer, α is a constant for the metal or temperature coefficient of resistance.

Now, RTDs are the simple resistive element in the form of a coil of wire of such metals, as a platinum nickel, or nickel-copper alloy. Here we can see the variation of resistance with temperature for some of the metals it is shown here, we can see nickel, copper, platinum. For a considerable range you can see that for platinum you have almost a linear range and for copper, there is some linear range up to some portion. Similarly, for the nickel also there is some linear range up to some temperature. When the temperature increases the R t increases and that R t resistance measurement is the principle of the resistance temperature detectors. Now, next, let us look at the thermistors.

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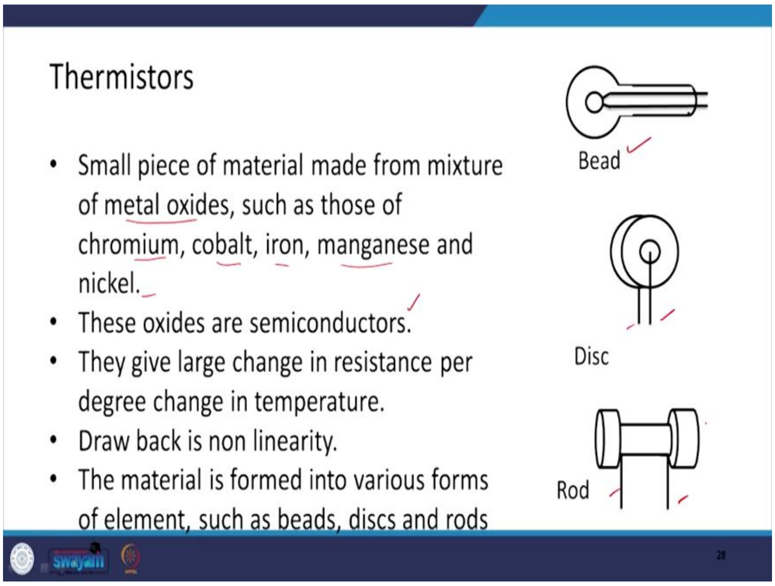

The thermistors are small piece of material, made from mixture of such as metal oxide and metal oxides such as chromium, cobalt, iron, manganese, and nickels. These oxides are semiconductors. Now, they give a large change in resistance per degree change in the temperature. The drawback of these devices is that there is a non-linearity in that. These materials can be formed into shapes say, you have bead is there, you have disc the two terminals; you have the rod the two terminals like this.

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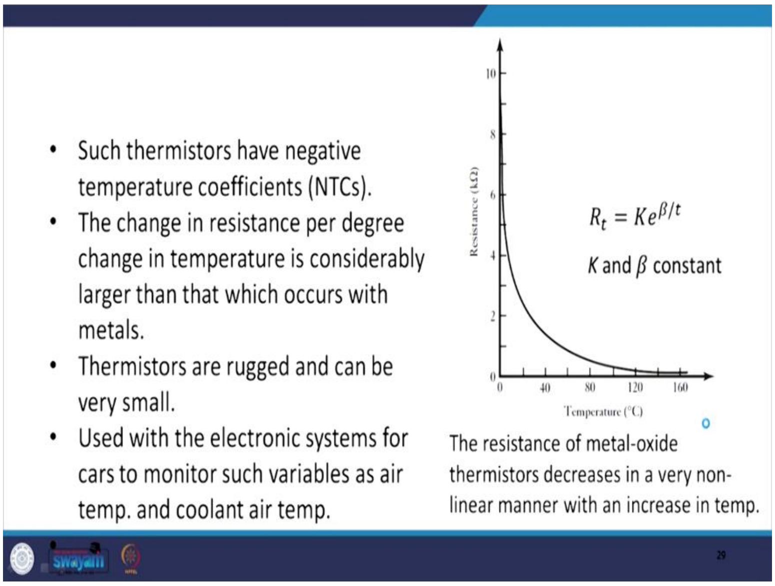

Such thermistors have negative temperature coefficient. The changes in resistance per degree change in temperature are considerably larger than that which occur with metals. So thermistors are rugged and can be very small in size. These are used with the electronic systems for cars, to monitor such variables as air temperature, coolant air temperature.

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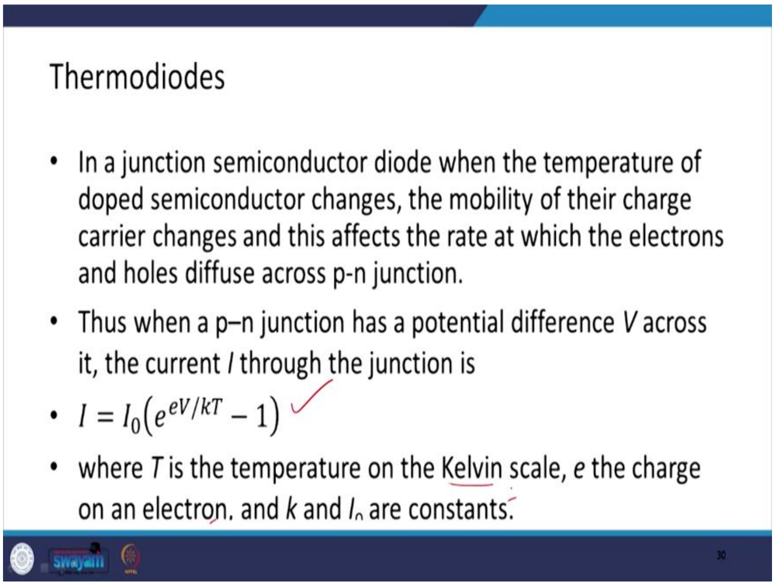

Next let us look at the thermo diodes. Thermo diodes again device for the measurement of temperature. Now, in a junction semiconductor diode when the temperature of a doped semiconductor changes the mobility of its charge carrier changes. This affects the rate at which electrons and holes diffuse across the p n junction. Now, when the p n junction has a potential difference V across it the current through the junction can be given by the popular equation,

$$I = I_o(e^{\frac{ev}{kT}} - 1)$$

Here T is the temperature on the Kelvin scale, e is the charge on an electron, and k and I_o are the constants. By taking the logarithmic equation in terms of the voltage can be obtained here like this.

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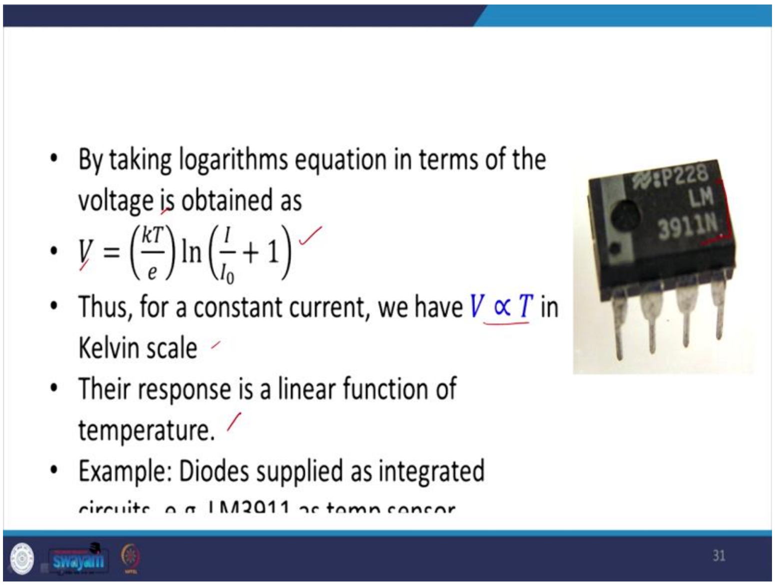

And so, for a constant current we have V proportional to temperature in the Kelvin scale. And their response is a linear function of temperature and the commercially available form is a LM 3911 N. So, this is how commercially they are available.

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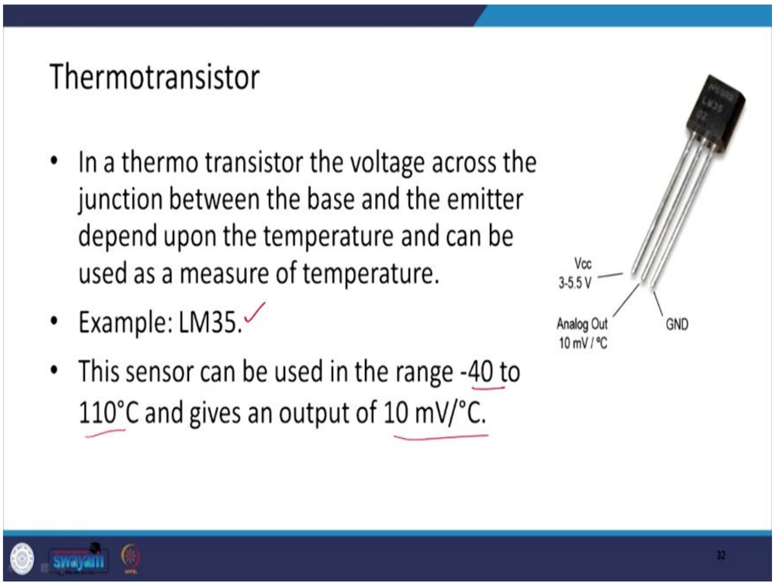

Next, let us look at the thermo transistor. So, in a Thermo transistor, the voltage across the junction between the base and the emitter depends on the temperature and can be used as a measurement of the temperature. And, the best example is LM 35 which is commercially available and this sensor can be used in the range of say minus 40 to 110 degrees. And gives an output say 10 millivolts per degree centigrade.

Then, next, let us see the thermocouple which is being used for the temperature measurement. So, for the thermocouple, all of you must have studied earlier, the basic principle of thermocouple, that if two different metals are joined together a potential difference occurs between the junction.

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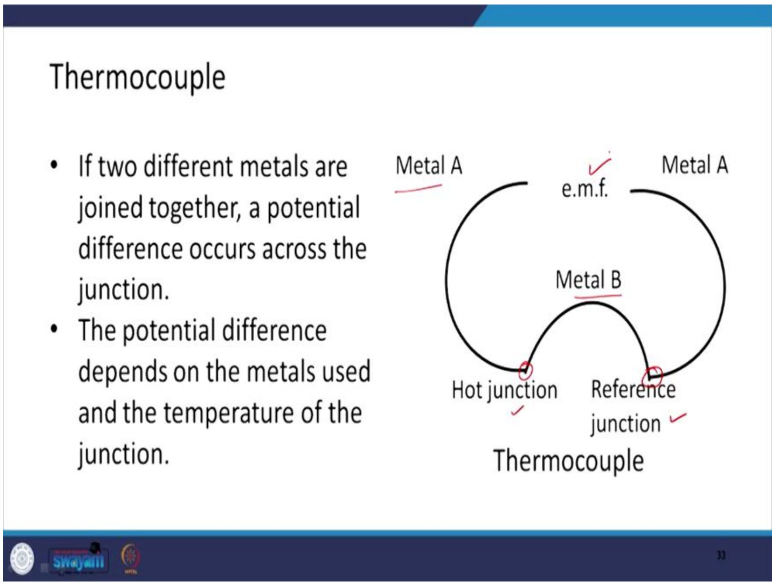

So, if you have to say metal A and metal B and if there are two junctions say, this one is a reference junction and another is a hot junction. If they are placed like this then you get an emf that is the principle of the thermocouple. The potential difference depends on the metal used and the temperature of the junctions.

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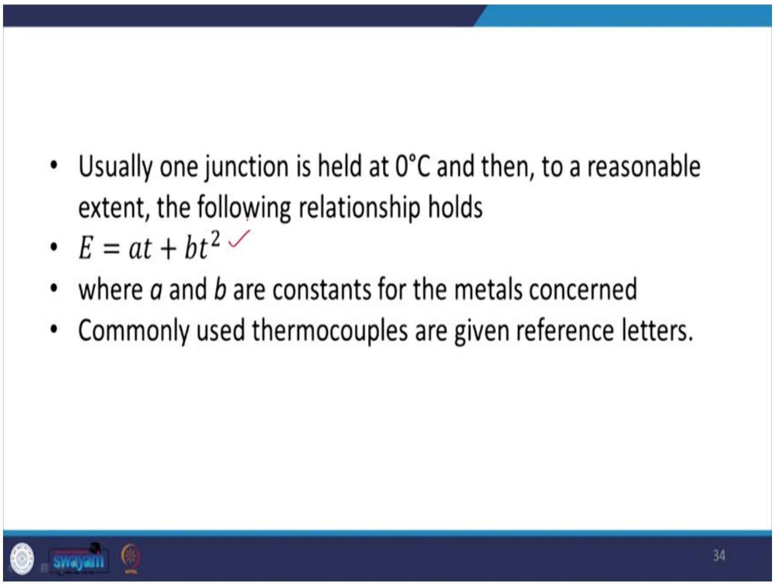

Usually one junction is held at 0 degree centigrade and then to a reasonable extent the following relationship holds,

$$E = at + bt^2$$

where a and b are constant for the metal concerned.

These are commonly used thermocouples are given in the reference letters here.

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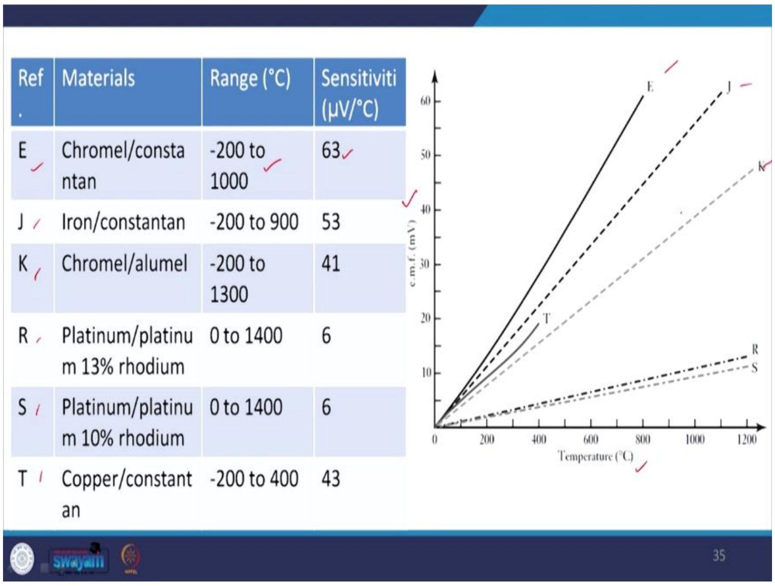

The reference letters E J K R S T and these are the materials for, these thermocouple pair say Chromel for E, it is chromel and constantan and their range is - 200 to 1000 degree centigrade and their sensitivity is 63 microvolt per degree centigrade. Likewise, it can be given and this plot says the e m f versus temperature for various these E J K T R S and on.

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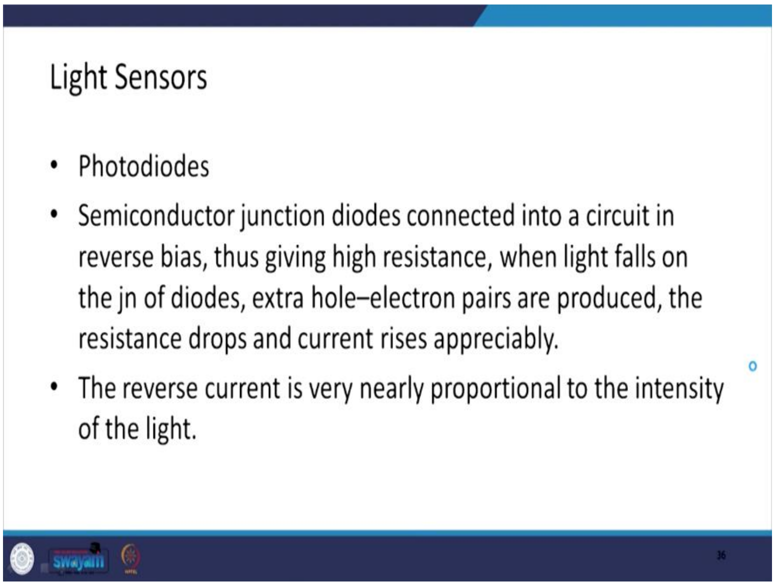

Now, let us look at the light sensors. These light sensors are photodiodes and they are semiconductor junction diodes connected in a circuit in reverse bias. And, thus giving high resistance with light falling on the junction of the diode. Extra hole electron pairs are produced the resistance drop and the current rise appreciably. The reverse current is very nearly proportional to the intensity of the light in this case.

The phototransistors have a light-sensitive collector base, p n junctions, and when no incidence light, is there is a very small collector to emitter current. When light is incident a base current is produced that is directly proportional to the light intensity. And this leads to the production of collector current, which is a measure of the light intensity there are these are often available in what is call it as the Darlington arrangement.

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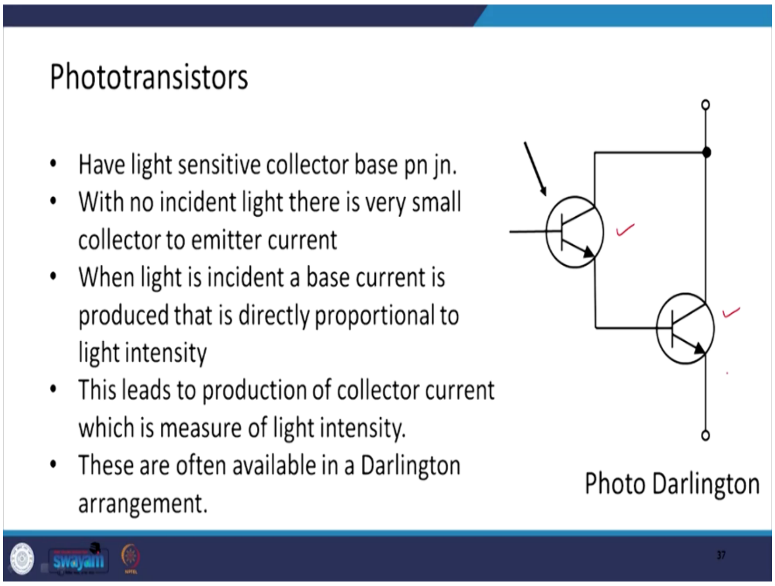

So, this is the Darlington arrangement, in which these are available.

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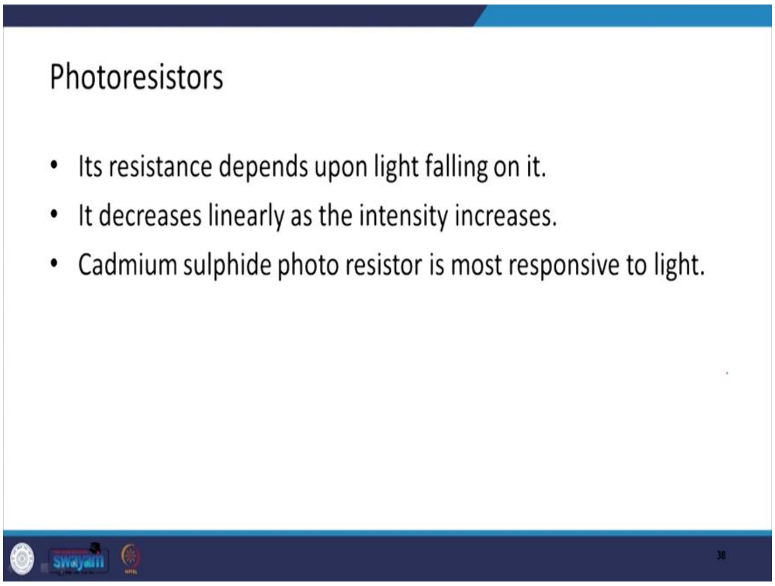

Then, we have the photo resistors, their resistance depends on the light falling on them, and as the name indicates photo resistor and it decreases linearly as the intensity increases. The cadmium sulfide photo resistor is most responsive to the light. These are the references, if you want to have further reading, you can refer the Bolton a very popular book, on the Mechatronics Electronic Systems in Mechanical and Electrical Engineering by Pearson.

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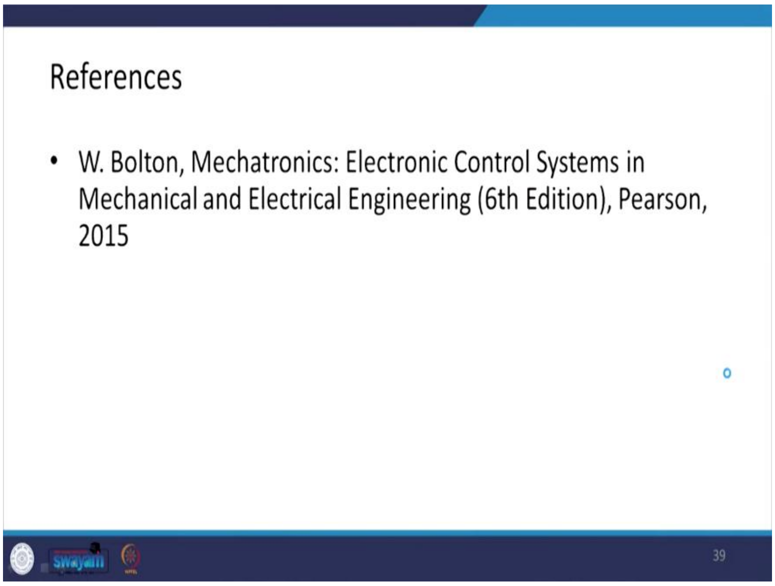

Thank you.