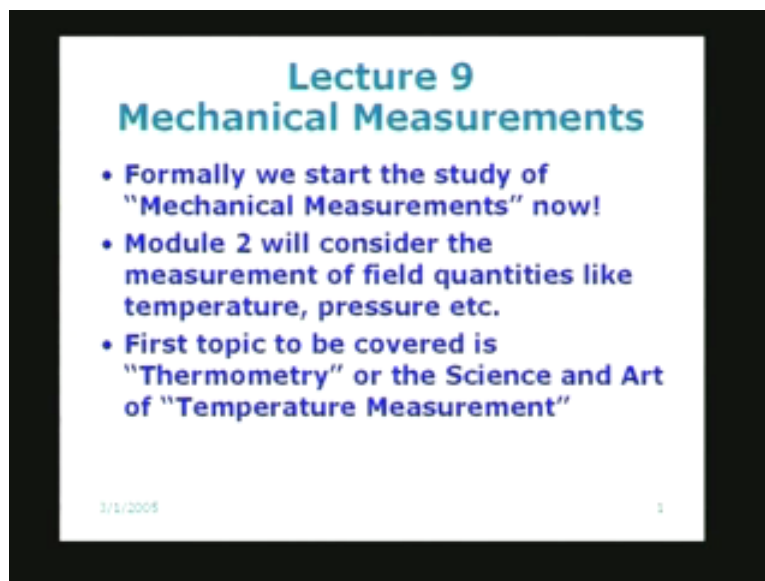


Mechanical Measurements and Metrology
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Module 2
Lecture - 9
Temperature Measurement

This will be lecture number 9 in the series on Mechanical Measurements. In the past 8 lectures, we have given introduction to the broad area of measurements, touching upon various aspects of measurements like the occurrence of errors, both statistical as well as systematic. We have talked about how to model these statistical errors; we also talked about the outcome of experiments in terms of measurable quantities and how to interpret the data in terms of a regression analysis. We also talked about design of experiments, both factorial as well as simple type of experiments. Lecture number 9, that is, the current lecture, is in fact the beginning as far as the topic of mechanical measurements is concerned; because here we are going to discuss in detail the different things we measure and the instruments we use for them, their characteristics and so on and so forth. So in that sense the slide shows that we formally start the study of mechanical measurements at this time.

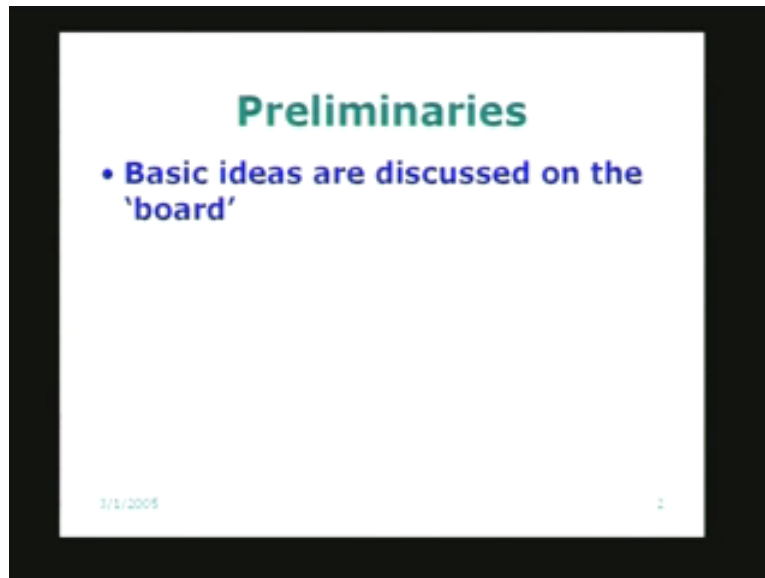
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This is also the beginning of module 2, which will, in general, consider the measurement of field quantities. In fact we have already explained what field quantities are. A few typical examples are temperature pressure and so on. Actually I am going to consider the measurement of various field quantities, and they will come in the order of their preference as far as I am concerned. But if somebody wants to learn, it is not necessary to start with temperature. You can start anywhere and learn about the various measurements of various field quantities. The first topic I am going to cover is thermometry. It's a very

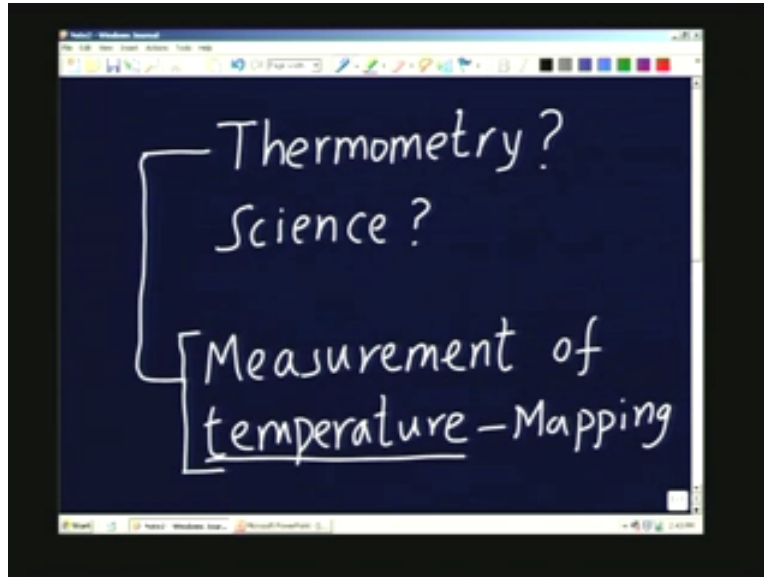
vast subject and what I am trying to do in this set of lectures is to make it very concise and look at the most important aspects of it. And in fact for the science and art temperature measurement; I deliberately use these two terms. Both these—science and art—where art is something which is involved in practice and science is the basic things involved in the measurement of temperature, both are important in the case of temperature measurements.

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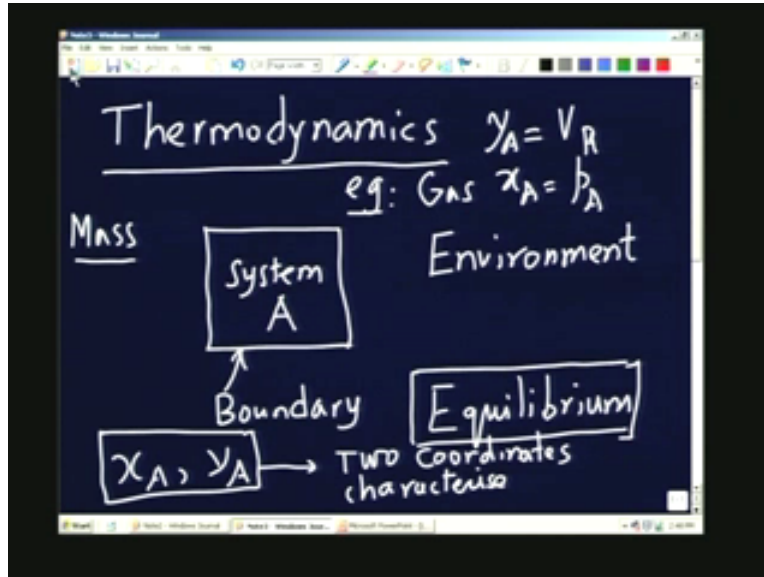
So what I will do is introduce broadly the idea of temperature, and once we identify the basic ideas and discuss them, we can go on to the specific ideas, which are again going to be presented in the form of slides. So I will go to the board now and try to look at the basic ideas of thermometry.

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So what is thermometry and what does it mean in terms of the science of thermometry? What is the science involved in this thermometry? So, broadly speaking, what we are talking about when we talk about thermometry is to talk about measurement of temperature. Of course, measurement of temperature is a simple specific task and it may mean the measurement of temperature of a medium at a localized point; it may mean the measurement of temperature at various points at the same time and so on and so forth. It's a very broad definition—measurement of temperature is very broad and it can encompass different types of situations where temperature is indeed measured. It may be even mapping of the temperature. Nowadays we talk about mapping of temperatures by using thermography; for example, it is just like taking a picture, picture of temperature field. So everything comes under this. So it's a very broad thing and even though it is very broad in terms of its application and also in the type of situations we come across, basic science is simply the same. So we will first look at the basic science of thermometry and once we have understood this very well, we will be able to take a look at all sorts of situations where thermometry is practiced or measurement of temperature is practiced.

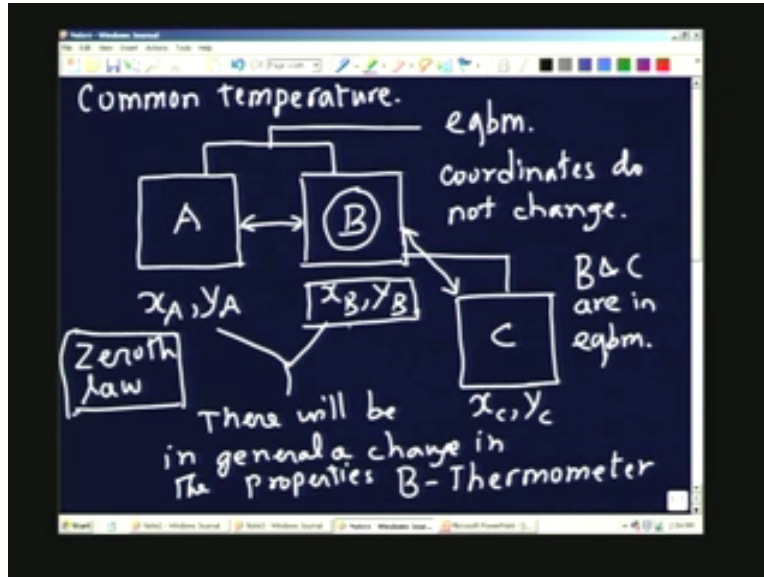
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So, to further clarify, let us look at what we mean by temperature. The concept comes from thermodynamics, where we describe a system. For example, I will just draw a rectangle or a square here. I will call this a system; I will call it system A to identify it and differentiate it from another system, which may be also under consideration. In this case, I will just call it the boundary of the system. In general, different types of interaction can take place between the system and the outside, if we want to call it the environment, or what is outside the system. What I have done is, I have separated a certain domain, which may contain, for example, a mass of material. It may be a liquid, gas or a solid and I am going to focus my attention on this piece of material when I am talking about the thermodynamic properties and the thermodynamic behavior of this system.

In thermodynamics, we talk about equilibrium. These concepts are of course clear to you from your course on thermodynamics. Therefore it will be very briefly discussed here, just enough to understand what we are talking about. So equilibrium of system A means the following. Suppose system A requires some coordinates or some properties that characterize the system. Let us say, I can have x_A, y_A , two coordinates, or may be more, but I am just taking a simple system; 2 coordinates characterize the system. It will become clear as to why I choose 2 coordinates here later on. So if I say that the values of x and y are some particular values, that means the system A is completely defined. I am able to define or describe the system A by using the 2 coordinates x_A and y_A , for example, in the case of a gas, which is a pure substance, let us assume the pure gas has only one species present; x and y may be the pressure and volume.

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So for example, I will write here that gas x_A stands for the pressure of the system A and y_A may stand for the volume of the system A. If x and y are given, that means the state of the system is fixed. Now what is this equilibrium? In order to describe or define equilibrium, let me talk in terms of 2 systems. Suppose I think in terms of 2 systems. We have just described system A and let me have another system, system B, and for the present we can assume that just like A, B is also described by some coordinates. For example I can say x_B, y_B are the coordinates for system B. In other words, those are the properties, which characterize system B.

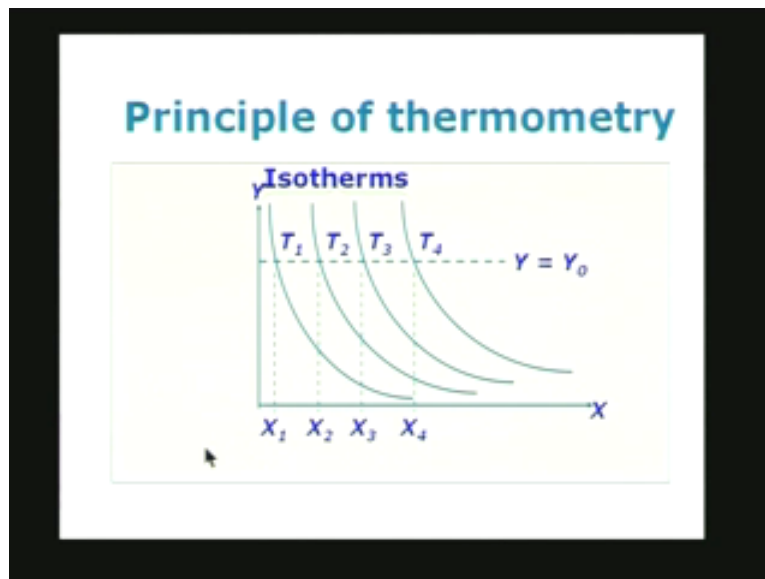
If I bring a contact between system A and system B, we can have some kind of interaction. If the systems A and B are not in equilibrium with each other, to start with, changes will take place in the properties. That means if I had x_A, y_A and x_B, y_B , if I bring them together, there will be in general a change in all these quantities: in the coordinates, in the properties. It looks like we haven't said much really. All we are saying is that if the 2 are not in equilibrium with each other, then we will observe that x_A, y_A, x_B, y_B will keep changing; so we can go back now and say that if they are in equilibrium, that is, if these 2 are in equilibrium, the coordinates do not change. This is one idea we should keep in mind. Actually I may have a system with x_A, y_A in equilibrium with B. It can also be in equilibrium with another system C and so on.

For example; I can now say that or in fact if you take system B, it may also be in equilibrium with a system C. That means I am going to say that B and C are also in equilibrium. That means if I bring them together and allow interactions to take place, excepting transfer of mass, we assume that other interactions take place; the interaction possible is heat interaction between the 2. Then if B and C are in equilibrium you will again make the statement x_B, y_B, x_C, y_C will not change when you bring them into contact with each other. That means B and C, when they are together, are allowed to interact, if x_B, y_B, x_C, y_C do not change, that means these 2 are in equilibrium. The proposition we are

going to make is that if B and C are in equilibrium with each other and A and B are in equilibrium with each other, A and C are also expected to be in equilibrium with each other. So this is one important result I am not going to prove. I am just going to say this is like axiomatic development of what we are talking about. Actually what is the connection between this and what we are going to talk about—thermometry? I will say system B is the thermometer, whatever it may mean; right now we don't know. But soon we will find out what thermometer means and what is thermometry; what is temperature measurement. So if B is the thermometer and it is in equilibrium with A and in equilibrium with C, then we can infer that something is the same, something is common to all of these—the thermometer and A and the thermometer and C—and this common thing would correspond to a common temperature. We will say they are common or are characterized by common temperature.

The germ of what we described now is actually contained in the zeroth law of thermodynamics. Because the first and second laws came earlier or at least they were enunciated earlier, the people had no other go than to call this the zeroth law and that is how we are going to call this—zeroth law of thermodynamics—and what is common between all these things is actually the temperature. Actually, it is very interesting to see that we talked about 2 coordinates x_B and y_B , and let me go back to the slide show.

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Remember x_B y_B ? We were talking about 2 coordinates of that system B, which I called as a thermometer, or I would like to call it a thermometer. What I have done here is I have shown the performance of the system, the parameters which characterize the system. Suppose the system with x_B and y_B as the coordinates is in equilibrium with a system whose coordinates are given some 2 numbers, which means that its temperature is practically fixed; in which case, x_1 and y_1 , x_1 here and the corresponding y value, x and y values, may have a multiplicity of numbers, which will be having the same state. That means they all will be in equilibrium with the system whose temperature is shown as T_1 .

That means I have more than one set of values for x and y for the thermometer, which will have the same or which will be in equilibrium with the same state. Therefore they are all possible coordinates for a system having the same temperature. So I will call this isotherm and in this case I have shown 1 isotherm as T equal to T_1 . The exact numerical value of T_1 is going to come later and what I have done is I have fixed values of y for the thermometer y_B as equal to y_0 . So when I hold this y equal to y_0 there is only one value of x corresponding to the temperature T_1 . There is a unique relationship between x and T . So what does it really mean? Suppose I bring the system with coordinates x_B, y_B , which is the thermometer, into equilibrium with different systems at different temperatures, what I will observe is that one of the coordinates being fixed at y_0, x will of course vary. The change in x is because it's going to change, to match with equilibrium common to the system, whose state is now different from the initial state of the thermometer. Therefore it will change till such a time that it is going to be in equilibrium with the system at T_2 and therefore x_1 will change to x_2 and similarly, if I bring it in contact with another reference state whose temperature is given as T_3 , then x_2 will change to x_3 and so on. Therefore I will have a unique relationship between x_1 , which is shown here, x_1, x_2, x_3, x_4 , and so on and the isotherms, T_1, T_2, T_3, T_4 .

Once I fix the value of y equal to y_0 , y will be equal to y_0 ; then x_A, x_B will change from x_1, x_2, x_3, x_4 to reflect the change in the state from T_1 to T_2 to T_3 and so on. Now the question is if I have kept one of the coordinates fixed, and I am going to use the other coordinates as the measure of the temperature, I will refer to this x as the thermometric property and for a given value of y , which is held fixed, there is a definite relation between x and T , and that is what we are going to use for the measurement of temperature.

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Thermometer	Thermometric property	Symbol
Gas at constant volume	Pressure	P
Electric resistance under constant tension	Electrical resistance	R
Thermocouple	Thermal electromotive force	E
Saturated vapour	Pressure	P
Blackbody radiation	Emissive power	$E_{b,\lambda}$
Acoustic thermometer	Speed of sound	a

So let me amplify this further and look at some of the possibilities. So I can construct for thermometers with different substances or I can make different thermometers using a

specific thermometric property, which has a direct relationship with the temperature. So in this case, I will label the thermometer using its thermometric property and the symbol, which will characterize the thermometric property, is given in the last column. One of the most important ones in this is the constant volume gas thermometer. In fact the assumption is that we have an ideal gas and we will later come to look at it in more in detail. We have an ideal gas at constant volume and if the temperature varies, the pressure will also vary. In fact the pressure and temperature have a direct relationship, and that is what we are going to use as the thermometric properties.

Pressure is actually measured; it's a measurable quantity and temperature is inferred, corresponding to a given pressure. The second type of thermometer I can construct is an electrical resistance, which is under constant tension or even 0 tension. The electrical resistance is the thermometric property, which will systematically vary with temperature and the symbol is R ; resistance of the element, which is a function of the temperature, is the thermometric property which is measured. Electrical resistance is measured by using an electrical circuit in which resistance can be measured. For example, Wheatstone bridge circuit can be used.

Once I know the resistance, I can find out what is the corresponding temperature by having a definite relationship between R and the temperature. Just like in the case of gas, I have P or pressure related to the temperature in a direct way. Here R is related to temperature, may be linear may be not linear, that is not of importance to us. There must be a unique relationship; as long as such relationship is there, we can use the resistance as the thermometric property and this is the resistance thermometer.

The third one, which is also equally important and very commonly used in practice by engineers, is the thermocouple, which generates the thermal electromotive force or electromotive force because of thermal reason. It essentially consists of 2 wires forming a junction. And the junction temperature is different from the referenced junction temperature—we will see it later in more —the electromotive force, which is generated, is a measure of the junction temperature. So E is the electromotive force; it is a measure of the temperature because there is a relationship, which is the direct relationship between E and the temperature.

A fourth kind of thermometer uses the relationship between the saturation vapor pressure and the temperature. That means the boiling point is pressure dependent; there is a direct relationship between the pressure and the temperature and this pressure is vapor pressure. I am going to measure the vapor pressure as measurable quantity by using a pressure measuring device. Just as in the case of gas at constant volume, here I am going to use the pressure as the measurable property here, and I am going to relate it to the temperature through a relationship between the pressure and the boiling point or the vapor temperature corresponding with that. If you have a saturated vapor, it has got a saturation temperature, which has a definite relationship with the pressure. These are all things which we can directly understand.

The next one is somewhat more difficult to see; it is easy to see that a relationship exists. What we want in a thermometer is a definite relationship between a measurable quantity and the temperature; that's what is required. So if I use black body radiation we know that black body radiation is electromagnetic radiation, which spans the entire spectrum from 0 to infinity in wavelength or frequency and the emissive power of a black body or a body which is at a temperature equal to T , emissive power has a definite relationship with the temperature. It is given by the Planck's distribution function, which is derived from the first principles.

Therefore this relationship—because it is a direct, unequivocal, unique relationship between the emissive power of the black body which is in watts per square meter, micro meter, because I am talking about the spectral emissive power—is a given function of temperature and therefore this unique temperature emissive power relationship can be used by using the emissive power for finding out the corresponding temperature. The last one I have shown here is an acoustic thermometer. The speed of sound in a medium depends on the temperature.

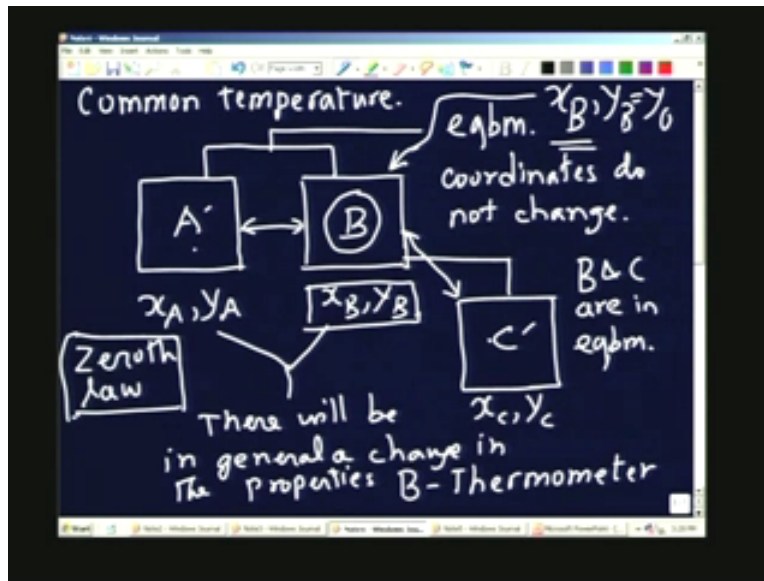
For example, if we have a gas whose composition is known or given, fixed composition, I fix the composition of the gas and I find out if there is a relationship between the temperature and the speed of sound. Speed of sound can be measured by measuring the velocity of propagation of the waves, the pressure pulse, which can be in fact be measured by measuring in principle the ratio of the length and the time taken. I can measure the velocity, and once I measure the velocity, by having a definite relationship between the speed of sound and the temperature, I can infer the temperature. Therefore you will see from this table and the discussion we had that in all the cases there is no effort to measure temperature directly.

Temperature is not directly measured; we are measuring something else. In the first case we measured the pressure of a gas whose volume is held fixed; in the second case we measured the electrical resistance of a resisting element. The resistor element may be made of metal. In the third case I measured the thermoelectric potential developed in a thermocouple, which is related to temperature. Then I measured the saturation pressure of a saturated vapor and related it to the temperature.

In the case of black body I am measuring the emissive power of a black body at certain frequency and then relating temperature and with the acoustic thermometer I am measuring the velocity of sound and I am inferring the temperature in all the cases. The measured quantity is different from what we want to measure; we want to measure the temperature but we cannot directly measure. Therefore it is inferred from a direct, definite relationship existing between the thermometric properties. The last column actually shows the symbol used for thermometric property.

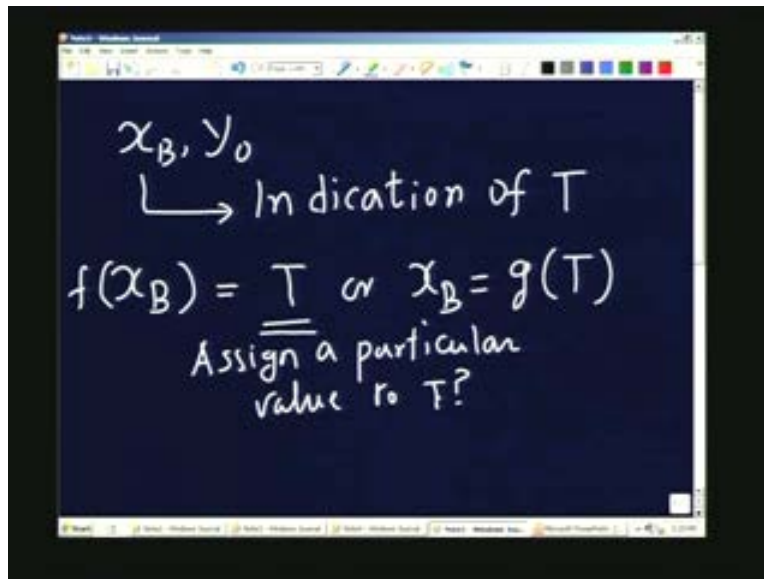
The second column shows the thermometric property, which is being used, and therefore a relationship exists between what is shown in the second column and the temperature of the thermometer; or the temperature at which the thermometer is maintained. Therefore there is an indirect way of measuring the temperature by looking at some measurable

property, which is a definite function of the temperature. So let me just recapitulate little bit of what we did so we consider the box shown here as B.
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This is what I call the thermometer and I am going to bring this thermometer in contact with system A, whose temperature I want to measure, or system C, whose temperature I want to measure. I look for the value of the thermometric property x_B with y_B equal to y_0 . This is what we did on the slide. I am going to keep y_B at y_0 . I look for the value of x_B and this x_B is a function of the temperature; therefore when I bring these different objects or different systems into contact, if they are at the same temperature, this is not going to change. If I bring this into contact with this and allow the interaction to take place, it will show the value of x equal to x_B . I do the same thing between B and C; if I obtain the same value x_B in this case also, then I infer that A and C are at the same temperature. That means if x_B does not change when I do this and this, then the temperature is the same. With this background, let us look at what else we can look for.

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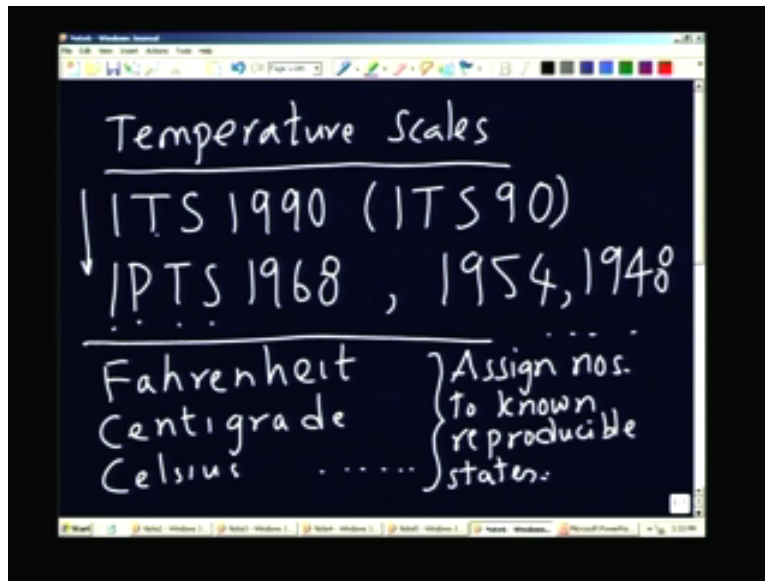
So I will use the same symbol x_B, y_B here. y_0 is fixed. This is an indication of the temperature; for temperature, I will use symbol the T . So what we are saying is x_B is definitely equal to temperature or x_B equal to some function of temperature. The relationship between x_B and T can be written in both these forms; in fact, we are going to use both these forms in the discussion which is going to follow later. The point is how do we give or assign a number to T . This is the only problem which you have not answered as of now. Assign a particular numerical value to T . Actually it's a question: how do we assign a particular value for T ? For this let us digress a little bit and look at what has been done by various people.

In fact we have several temperature scales; may be my discussion is slightly haphazard in the sense that it is not going in the way it probably should go. If one wants to be cosmetically clean and neat, what I am trying to do is to go back and forth and introduce ideas so that we understand what we are doing. This is a more important consideration here. I am not very particular about niceties. I want to see whether we can grasp what the underlying principles are. So temperature scales actually were there even before thermometry was codified the way we know it today.

Today we use what is called the international temperature scales 1990, or in short, we will write it as ITS 90. I am going back in time; in fact, there is IPTS 1968. These are all important dates in thermometry and development thermometry. IPTS stands for international practical temperature scale 1968; of course this practical has been jettisoned; now we simply call it international temperature scale 1990. Before that there was 1954, before that 1948, 1927 and so on. These were all meetings of like-minded people, who were involved in the measurement of temperature. They wanted to make everything as unique as possible within the means available at the time of those meetings

to bring some kind of order to the chaotic system. Earlier, if we go back in history, there were many different scales of temperature, for example the Fahrenheit, and then we had the centigrade, now of course, we also have the Celsius and many more. What these scales did was to assign numbers to the known reproducible states. Everybody knew what should be done; only thing was there was no unanimity in assigning the numbers.

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So let us look at these reproducible states, at least those we can easily immediately recognize. For example we have the ice point. This is the temperature of the ice or melting ice and if we specify the pressure exactly equal to the 1 atmospheric pressure, it has got some definite value. So ice point is nothing but temperature of melting ice at 1 atmospheric pressure. It's also called the ice point as I have written here, and the next one, which is also very familiar to us, is called the steam point. This is the temperature of boiling water at 1 atmospheric pressure; so what centigrade scale did was, centigrade scale assigned 0 for the ice point and 100 for the steam point.

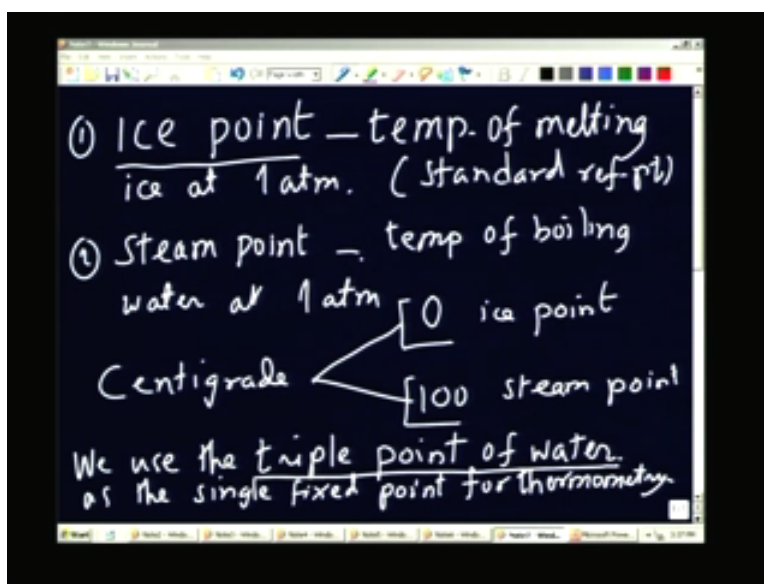
Of course these assigning these values as 0 is quite arbitrary but to be in conformity with historical facts, what we have tried to do or what the modern temperature scales have tried to do is retain this 100 between the 2 points. Of course we don't finally we say we don't care about it. But it somehow turns out to be 100 divisions between 0 and the ice point and the steam point. So let me just go back to the previous slide (Refer Slide Time 33:39). So we talked about different Fahrenheit, centigrade, Celsius, and so on. These are also common.

In fact there is no difference between Celsius and centigrade now—they are the same thing. Fahrenheit scale is used only in USA and all other people have decided to or opted to not use it. So what ITS and IPTS international temperature scales try to do is they try to define the temperature scale and assign one unique temperature to one particular state,

which is again reproducible. In fact, earlier on, we used to have ice point as the standard reference. So this used to be the standard reference point.

However, now we use the triple point of water. I will give more complete description of triple point of water in one of the slides a little later on. We use the triple point of water as a single fixed point for thermometer. It is quite arbitrary; in fact, one can use another well known fixed point as a single fixed point. It is up to one to do that but in common understanding with people working in this area, we use the triple point of water as the single fixed point for thermometry and then define the temperature scale such that it agrees with some facts which are known to us.

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So that is how you try to do that. But before we do that let me just look at the ideal gas or the constant volume gas thermometer and just briefly talk about what it is—constant volume gas thermometer. It is well known that when the pressure is low enough most gases will behave as ideal gas. That means, pV equal to RT , where p is the pressure, V is the volume, T is the temperature. Of course this is absolute temperature; later we will see more about this absolute temperature. And this is the constant, and in the constant volume gas thermometer, this is held fixed. I am going to hold the volume fixed and therefore we can say that p is proportional to T or I can replace this by p_1 by p_2 is equal to T_1 by T_2 . This relationship is behind the use of thermometer, thermometry.

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Constant Volume gas Thermometer.

Ideal gas. $pV = RT$

\uparrow
Held fixed.

$\underbrace{T}_{\text{Absolute temp.}}$

$\therefore p \propto T$

$\boxed{\frac{p_1}{p_2} = \frac{T_1}{T_2}}$

So let us reframe this relationship. So we are saying that, p_1 by p_2 equal to T_1 by T_2 . The way I am going to do that is the following: I will say that p at any temperature T divided by p at the triple point of water is equal to T divided by T of the triple point: this is the defining equation. As long as the ideal gas relation is valid—we will see later when it becomes valid—it should be independent of the gas. So this relationship is the background for the temperature scale, which we are going to define and use. So the ratio of p to the p of the gas, of fixed volume, divided by the pressure of the same gas, if it were maintained at exactly equal to triple point of water—which is a reproducible, fixed temperature—is equal to the ratio of temperatures.

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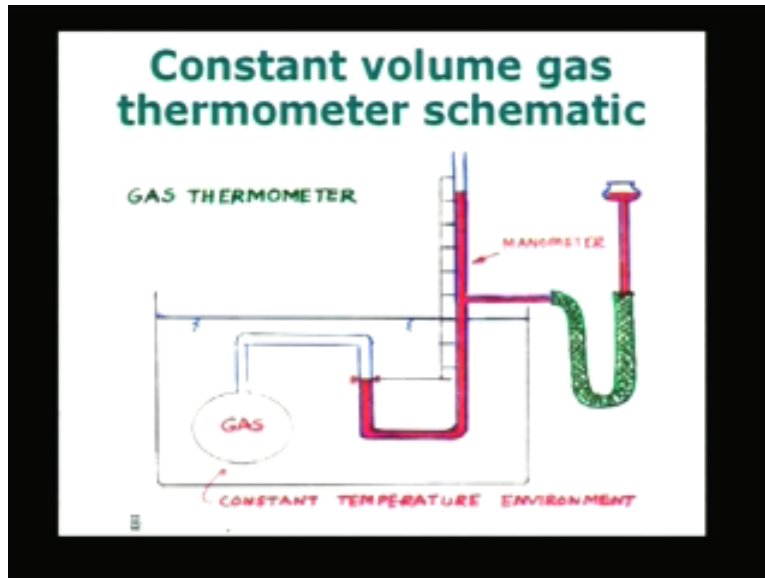
$$\frac{p_1}{p_2} = \frac{T_1}{T_2}$$

$$\boxed{\frac{p(T)}{p_{tp}} = \frac{T}{T_{tp}}} \quad \checkmark \text{ Background for the Temp. scale.}$$

This is what embodies the use of constant volume gas temperature. So with this background, let me go back to the slide show and look at how we are going to construct schematically a constant volume gas thermometer. So what I have done here is to show schematically; it is not such a simple thing. So we have a gas which is confined within a rigid vessel. It is connected to a u tube manometer, which is shown here and there is a scale next to the limb of the manometer. This manometer is in communication with a flexible host and we have a small reservoir, which contains the manometric fluid. So the use of this is that I can raise it up and down. This portion can go up and down; so let us see how we are going to use it. There is also a mark made here and of course, I said this is a rigid vessel; therefore the vessel volume is going to remain fixed and if I confine the gas to within this volume given by this mark on the tube here, it means the volume of the gas is held fixed. That means the constant volume gas thermometer, means the volume, is held fixed as I just mentioned.

Let us suppose that the gas containing vessel here, is in contact or is surrounded by a medium whose temperature is fixed at a particular value. So if it is exposed to this temperature, if I hold the volume of the gas constant, how do I hold the gas volume constant? I have to move up and down the manometer such that at the particular pressure, the temperature of the constant temperature environment, the gas pressure, takes on such a value that the volume is brought to this value. Then the pressure will change; that means this limb is going to move up and down in tune with the variation of the temperature of the gas inside the rigid vessel. In fact I am going to put a scale right here and measure the pressure difference between this meniscus here and the meniscus here. That is the pressure of the gas.

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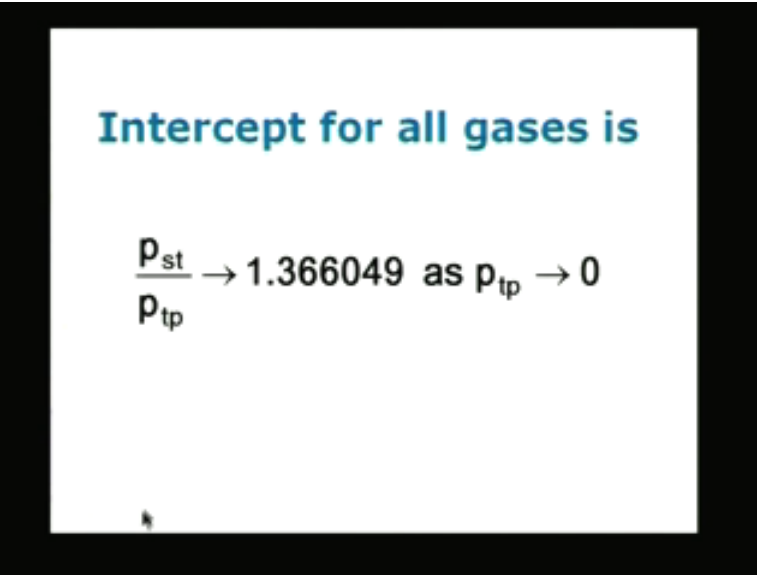


So the thing is not as simple as that. We will see why it is so. Suppose I take a gas A if I had shown 3 gases; it could be any number of gases. I have taken gas A. Initially the temperature at the triple point of water, that means when the gas is exposed to an environment at the triple point of water, the value of the pressure ratio, p , steam point to p triple point. In this case I am taking the steam point to triple point of water ratio is giving some value here, and what I do is, I systematically reduce the pressure corresponding to the pressure at the triple point and then note down the ratio of the pressure at the steam point to the triple point of water. So if I cannot do at the triple point of water pressure equal to 0, I can only do it to some pressure low enough and then I will extrapolate.

So I am going to extrapolate this curve and this is going to hit the axis here. This intercept has some value, let us say. Suppose I do the same experiment with a different gas and again I do that, it also goes through the same point and if I take a gas C, same thing is observed. That means as the pressure at the beginning, when the volume of the gas is at the triple point of water, is reduced systematically, it will reach a stage when all gases will behave in an ideal way and the ratio is unique. In this case, the pressure ratio between the steam point and the triple point, is given by the value which is shown in the slide. p is steam point divided by p triple point of water for all gases, which is 1.366049, which is a unique number. This will happen as p_{tp} tends to 0 but not equal to 0, but tending to 0. We cannot have that equal to 0 because then there is no gas inside.

Now, just remember what we did before we came to this slide, instead, of p steam point divided by p triple point; I can have p at some temperature divided by p triple point. That will also have a unique number. Corresponding to any particular temperature also there is a unique number, which will be independent of gas. Therefore I use the gas thermometer. Actually it defines the temperature scale in terms of ratios and this is what we did on the board.

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Intercept for all gases is

$$\frac{p_{st}}{p_{tp}} \rightarrow 1.366049 \text{ as } p_{tp} \rightarrow 0$$

So with this background, we can see that the temperature scale is uniquely defined because there is a ratio p divided by p_{tp} , as p_{tp} tends to 0, is a unique function of temperature. There are some practical issues, like whether the gas will remain at low enough temperature and so on and those we need not worry about now. Just to recapitulate, we have a single fixed point of thermometry or the primary fixed point, which is called the triple point of water. It is a highly reproducible result and at the triple point of water, the solid water—that is, ice, liquid water—and vapor—that is, steam—all of them coexist in equilibrium and the triple point of water is given by exactly equal to 0.01 degree Celsius equal to 273.16 Kelvin and the corresponding pressure inside the triple point cell is 4.58 millimeters of mercury or 610.65 Pascals. This is just to describe the triple point cell.

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**Single fixed point of thermometry
or the primary fixed point**

TRIPLE POINT OF WATER

**Solid, liquid and vapour of water
coexist in equilibrium.**

$$T_{tp} = 0.01^{\circ}\text{C} = 273.16\text{K}$$

The corresponding pressure is

$$p_{tp} = 4.58 \text{ mmHg} = 610.65 \text{ Pa}$$

So let me go back to the board and digress a little bit, and describe something. So what we are going to do is, we are going to define the temperature scale using the result shown here: p divided by p_{tp} . So let me just rewrite this slightly by indicating that the value is limit p_{tp} tending to 0, limit p_{tp} tending to 0, p by p_{tp} equal to T by T_{tp} . This is the defining equation or this is called the gas temperature scale. In order to give numerical values, I must construct other secondary fixed points. Why do we require secondary fixed point? Let me just briefly explain. We are going to think in terms of secondary fixed points; the reason we have to do that is explained briefly.

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$$\frac{p_1}{p_2} = \frac{T_1}{T_2}$$

$$\lim_{p \rightarrow 0} \frac{p(T)}{p_{tp}} = \frac{T}{T_{tp}}$$
 ✓ Background for the temp. scale.
 Gas temp. scale
 Secondary fixed point

Note that the temperatures of interest to us range from 0.01 degree Kelvin to about 100,000 Kelvin, let us just say that this is our range. I want to measure temperature from the low value to a very high value. The point is one single thermometer cannot cover this entire range. Therefore I can achieve the measurement of temperature in this range with a multiplicity of thermometers, probably covering different ranges. That is the important thing to recognize.

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Range: 0.01 K - 100,000 K
 One single thermometer cannot cover this entire range.
 With a multiplicity of thermometers covering different ranges!

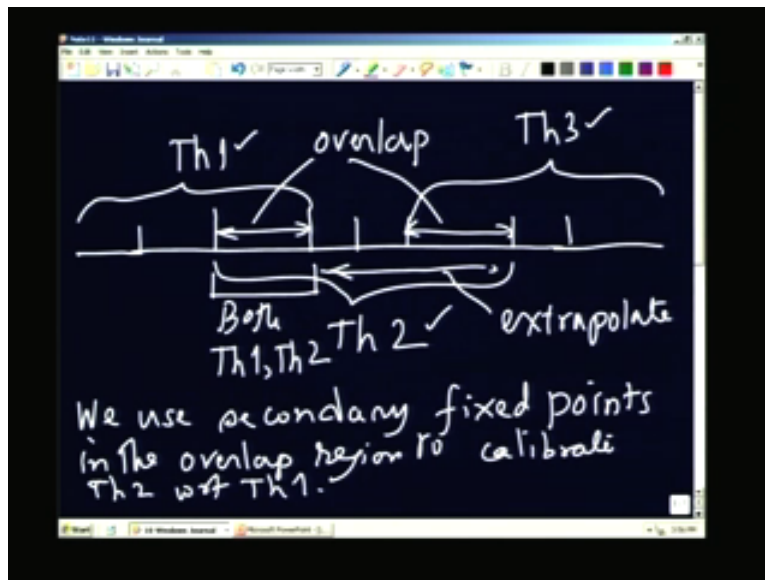
I can measure or cover this range not with a single thermometer but I may have to use different thermometers. That means I cannot calibrate, by using one single calibration but I need to calibrate each one of these thermometers by making sure that they are all going to indicate the same temperature, wherever there is an overlap between 2 thermometer

ranges. So let me just explain it slightly more figuratively. Suppose, I have this, this is just a scale of temperature. So let me say that thermometer 1 covers that range, let me say that thermometer 2 covers this range. Then I will have a thermometer 3 covering this range and so on. There is a certain overlap; there is another overlap here, these are all overlaps.

Let us for the moment assume that thermometer number 1 is the constant volume gas thermometer. I am able to use it up to a particular value; for some reason I am able to go beyond that. Then I have, let us say, thermocouple or a resistance thermometer, which can go from here to this place. By that time, of course, this material will melt or the resistance thermometer may become useless; it may become useless at that temperature. So we are going to now have 2 thermometers, thermometer 1 and thermometer 2, both of which are going to be useful in this range, both Th_1 and Th_2 . So what I must do is, within this gap or overlap where both the thermometers can be used, I should find some fixed points or I should find some definite temperatures, which can be used to calibrate one against the other. So we use secondary fixed points in the overlap region to calibrate Th_2 with respect to Th_1 .

What is this calibration? It simply means that at a particular temperature indicated by thermometer 1 for which I am going to give a certain number, the same number must be assigned for the temperature indicated by the thermometer 2.

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That means that thermometer 1 and thermometer 2 are going to be in agreement with each other in this overlap region. Now by extrapolation, I am going to assume that because they are calibrated in this region and I have found a certain relationship between the temperature and the thermometric property. I am going to extrapolate it here in this region; this is the region of extrapolation; we will call it the extrapolate region. In this extrapolate region, I have another thermometer 3, which has got some amount of overlap

and therefore I will calibrate thermometer 3 with respect to thermometer 2, using some secondary fixed points in this region. Therefore, if I continue this argument, in principle, I will be able to cover the entire region of temperature from 0.01 to 100,000. The idea is to look for secondary fixed points, look for different thermometers which can be used over different ranges and everything must give us some unique temperature scale on which everybody agrees.

Therefore what we are going to do in the next lecture is to look at how this exercise is done. ITS 90 is a result of such deliberation, using different thermometers, using different techniques spanning the entire region and arriving at some definite fixed points, which are reproducible with great finishing and then looking for interpolating functions for different thermometers in different ranges and then completely covering the entire range of temperatures and then completely covering from the highest to the lowest, which is measured in the laboratory. So we will take it up in the next lecture and of course will continue after that with a discussion of different thermometers and their characteristics and so on. This idea about thermometry culminating in a temperature scale of ITS 90 is a very important background and prelude to the understanding of different thermometers and their characteristics. Thank you.