Introduction to Research
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Lecture – 13
Experimental Skills

Hello, today's class, we will look at experimental skills as part of our short course on Introduction to Research.

As you are probably aware from, you know, discussion with people around you, in general, research could be, you know, either theoretical - broadly speaking - could be theoretical or it could be experimental. Most often, it gets, you know, separated into these two categories. So, if you want to see,we have basically - you have theory and you have experiments. So, broadly your work depending on wherever you are working on, the kind of area that you are working on, could be of one of these two kinds. There are people who do fair bit of, you know, the combination of these and so on. But, still your activity could be one or the other, most of the cases.

It is important to understand what is the relationship between these two and also to see, as part of today's class, we will look at skills that are associated with the second aspect show here, experiments. But, I would like to point out what is the relationship between them, so that you are aware of what is the broader picture.

So, basically, we have, you know, phenomena in nature and we are trying to investigate this phenomena. So, we are trying to understand why those phenomena are the way they are? What options you have? Can you push the phenomena in one direction or the other direction and so on. In general, to understand the phenomenon we typically run experiments, we run controlled experiments, which means you make sure that certain set of conditions are constant, and then you change one quantity, and then you try to figure out what is the impact of that change on the other quantities that are present in the system. So, those are experiments that we do and we collect a lot of data.

In theory we are writing equations, we are trying to simulate what nature is trying to do. We are trying to say that, you know, may be nature follows some set rules, and if it does follow those set of rules, what can you expect when you change a particular quantity, what can you except in terms of that - the impact of that change on other quantities that are present in the system right. So, here you are doing some calculation to figure out how one change - change in one quantity - impacts another quantity. Here you are running some experiments to understand what is the change - impact of change of one quantity on another quantity. So, in both these cases, you are trying to do may be something similar.

Now, in general, the idea is that the experiments are supreme. Meaning, in general, in theory you are trying to cut out various aspects, and then you say that, you know, maybe the system follows certain set of rules. So, on that basis you make a prediction. So, what theory does is often it makes a prediction. It is the experiment which shows whether or not that prediction is correct. So, therefore, an experiment is very important. Experiments are very important because they are the ones that really validate something that the theory says right. So, it does not matter, how sophisticated the theory looks, how interesting the theory looks, how fascinating the equations are that have come together and so on. At the end of it all, if it makes predictions that are not borne out by experiments, then the theory is not considered good; it is considered, at the very least, it is considered incomplete. It means, either some major aspect that needs to be further incorporated into the theory before it can be considered correct. So, therefore, experiments in the hierarchy of, you know, science it is reasonably fair to say that experiments are supreme. You have to show by experiment that something has actually happening and that is when it is believed.

Now, so that's the basic, you know, relationship between these two. Now, therefore, it is also very important that you run your experiment correctly okay. So, if you run the experiment incorrectly or you have done it in an uncontrolled way, then, naturally, your results will not be appropriate, will not represent the actual phenomenon right. So, it's important to, when you say that experiments are supreme and all that, the underlying statement they have, that the underlying assumption they have, is that you have run the experiment correctly. So, that is a very important aspect associated with experiments.

So, today, that is the reason why we have going to spend some time on this concept or this idea of experimental skills. Because, experimental skills are the kinds of skills that we should have to ensure that our experiments are running correctly, for us to feel confident that the data that we have obtained from the experiments are correct; and therefore, we can now, you know, with great confidence we can say that if the theory does not match that experimental data, then there is some issue with the theory. If you have run the experiment incorrectly, then obviously, this is not going to hold true. So, in that case you cannot confidently say that the theory is not correct or the theory is incomplete. So, it is very important for you to run your experiments correctly and if you are an experimentalist, that is something that will have to put up with all the time. You should feel ready to indicate in what ways you have run your experiment correctly, and your experiment should be open to scrutiny - people should be able to ask you lot of questions on how you ran the experiment. You should be able to defend how you ran your experiments. And learning experimental skills is a very important aspect associated with that right.

So, we have to run our experiments carefully and correctly.So, today that is what we are going to look at - how to do this and, or at least, what I am going do is, you know, if you take the idea of experiments it is a very vast world out there. There are lots of different experiments you can do to probe different phenomena, to demonstrate different phenomena, and so on. In most cases, there are specific experimental quantities or experimental parameters that we tend to control or we tend to measure. And then, based on that we investigate wide range of phenomena. So, I am going take a few common parameters that we tend to control or measure and so on. And then, highlight to you, you know, what are the places where you can make an error, and therefore, you need to be cautious about, when you… you know… or double check or cross check what measurement you are making and how you would go about doing that. So, this is I will small… I mean process that we will go through with few different quantities that I feel, we commonly encounter.

And naturally, if there are other, they are bound to be lot of other quantities which you will measure in your experiments, which you should follow a similar process. So, it is not the intent of this class to, you know, exhaustively look at all possible quantities that you can measure and, you know, figure out what all ways you can get it right or what all ways you can get it wrong. But, representatively, I am going to pick a few, I am going to highlight, where you can go wrong, and then, I am also going to highlight, how you can, you know, correct for it; how you can cross examine it; how you can make it better. And the same philosophy is what you should carry with you to any other experiment that you do where you may be dealing with quantities that are not necessarily shown to you today right.

So, we will take some common quantities and we will start with that. Ones that we often encounter are temperature, there is pressure, humidity, and then, electrical quantities such as current or voltage. So, these are common quantities that you are likely to see in many experiments. You are measuring current, you are measuring voltage, you are applying a current, measuring a voltage, applying a voltage, measuring current, lot of things we do.

There are experiments where we worry about the humidity in the system and we want to quantify it or we want to ensure that it is a certain value or we want to claim that it is a certain value, so that's something we will look at. There is pressure; you have pressure gauges and so on to tell you what is the pressure in the system. I will look a little less on pressure, I will spend more time on temperature, humidity, and current and voltage.

Some of the basic approaches we use will be similar to what you will have to, you know, utilize when you look at pressure, what we will look at for temperature. So, conceptually similar; of course, the gauge used and so on going to be very different right.

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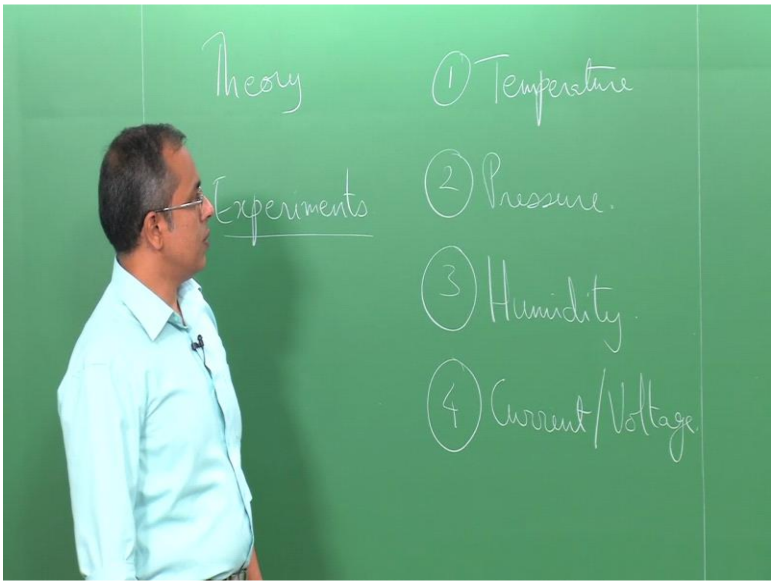

So, we will start with temperature. So now, many experiments that we do, commonly we will start by saying that, you know, the experimental setup was set some temperature. So, this is common statement that we make right. So, how do we know this right ? So, this is something we have to be very careful about it. So, for example, we may be running temperature experiments at say, 200 degrees C; somebody else may run an experiment at 500 degrees C. Or you may have a series of experiments, one of which runs at 200 C, another at 500 degrees C, another at 800 degrees C; at every 300 C increments you may have an experiment. So, you can have experiments over a set of temperatures right.

So, it is important that…so, when you present the data, you are going to say that, this data I have obtained at 200 degrees C; then I changed the temperature of the system to 500 degrees C and I obtained some other data; then I changed it to 800 degrees C, 1100 degrees C; and then you do a trend based on temperature. So, and then, you may get some activation energy values, lot of different things you may get out of this kind of data. So, it very important that your experiment actually when you are claiming it as a 200 degrees C, the experiment should actually be at 200 degrees C. So, that is the important aspect that I want to highlight.

So, one of the common sources of error in many our experiments, where we are dealing with temperature is that we simply look at a display, which will be there on your furnace or your oven - and hot air oven - and it will simply say 200 degrees C, and we assume on faith that is 200 C, and we proceed; many, many first time experimenters do this.

Now, there is a lot of scope of error, scope for error, when you just look at that display, take that value and proceed. And that is something that I want highlight here, because this is… temperature is one of the most common quantities that we encounter in experimental setups. So, therefore, we need to be careful. So, the point that we have to keep in mind is that any experimental setup you buy, if it's a hot air oven or it is a furnace - let us say, it is a tube furnace, could be a box furnace or a tube furnace, in all these cases they have a sensor, which measures temperature. And that is how that sensor, that is how you see a display somewhere outside that says that it is 200 degrees C or whatever. It is very important for you to understand, what is the location of that sensor? That is very important; because you can have a situation where the sensor is located at one location, your sample is located at another location, and therefore, the temperature that the sensor is reporting to you is not that temperature at which your sample is sitting. And, this is an experimental thing that you have to be aware of right.

So, for example, let me just say that I have a box furnace, I am sorry, a tube furnace. So, let's say there is a tube here, and this is inside some, you know, structure that is there which envelopes it. So, this is a tube and inside this you have a boat - a ceramic boat right. So, you have a structure which has all the heating rods, heating elements are there on this, all are around this tube; in the middle there is this tube, it is a ceramic tube; and in that there is a ceramic boat. In this ceramic boat, you have some sample; some sample is sitting here; the sample that you are testing is sitting in this ceramic boat okay. So, now, let's say you are trying to run this at 800 degrees C. You want to say that your sample was at 800 degrees C for 1 hour; that is, let's say, that's the experiment that you are trying to do; that you are going to take the sample, keep it at 800 degrees C for 1 hour, under some atmosphere. So, those are two things you will specify: the temperature and the atmosphere.

So, let's say it is air, in which case you can keep it open or if it is some other gas, let's say it is under nitrogen atmosphere or argon atmosphere, then you have to ensure that there is an inlet that, you know, air cannot freely get in here, there is a controlled way to introduce argon or nitrogen, and there is a control exit for argon or nitrogen, and that you will have a bubbler which will then check. So, for example, you may have something like this, this would be then closed except for this inlet, and you will have a tube coming out which will then go to a bubbler, and you will see bubbles of gas coming out. So, this is the way you can ensure that there is actually gas coming in, there is gas going out, and since there is an inlet and there is an outlet, there is no build up of pressure, just free flow of gas. Even with air you can ensure that you have an air bottle, which is just supplying air, so that it is not… it's some controlled flow of air, and then, you have a gas coming out right. So, this is the typical set up. So, you have heating elements.

So, what normally happens is that the manufacturer of this furnace will now provide you with a thermocouple which would be somewhere here, which will enter from somewhere here, and it will come in contact with the tube here. And from this you will have a display. And let us say, this is now showing you 800 degrees C. So, experimentally, now you have got a set up where you have got a tube, a tube furnace, you have got a boat, you have got a sample, and you have a display, you have got some controller here, you set the temperature to be 800 degrees C, and it shows your display of 800 degrees C right. So, it looks like your experiment is all running fine. Now, the issue is this - when you have… especially when you have gas flowing, some small flow rate of gas and so on, this area is actually being cooled. So, and also, it may be… this region is getting slowly cooled by the flow of gas plus the heaters are at specific locations. So, there are some heating elements here, there are some heating elements here, and so on. And therefore, you may even have a coil around the furnace, around the tube, and so on.

So, the point is not every region in this tube is at 800 degrees C. So, that's a very important piece of information you should be aware of. You are seeing a display of 800 degrees C, but you should be very cautious in understanding what it means, because the entire furnace is not at 800 degrees C. What it specifically implies is that the region that the thermocouple is accessing, that location is at 800 degrees C okay. And that location, if you look at this diagram, if this is the layout of the set up, that location is here, your sample is sitting here, and this could easily be of the order of say 2 or 3 inches, may be about 5 to 10 centimeters; 5 to 10 centimeters can be there between the location of your thermocouple and the location of your sample.

And, in this region you could have gas flowing, you could have lot of different things happening, and therefore, even though this region is marked as 800 degrees C - that your thermocouple is registering 800 degrees C, your actual sample may be sitting at 750-760 degrees C; that's not a big difference in temperature in terms of, you know, that the cooling rate might have caused that, could easily caused that 50 degrees difference. And even…so, vertically there can be a difference in temperature; horizontally also there is a difference in temperature. So, your boat may also not be positioned exactly below this thermocouple. It may be off a little bit; it may be a couple of centimeters ahead or couple centimeters below, behind, because it's a long tube.

Based on the location of your boat, which then contains the sample, the location of your sample may not be at 800 degrees C; it could be easily be at 750 degrees C and that is a big difference, because you have an experiment were you are looking at 200, 500, 800 and 1100, and if each them is off by about 50 degrees C, 70 degrees C, 80 degrees C or even 100 degrees C, then the data is completely wrong; I mean or at least it is not the data that you think it is; it is correct data but it is not what you think it is. It is not data at 800 degrees C, that is data at 750 degrees C; what you thought was 500 degrees C, may not be 500, it may be 475 degrees C. And, the difference may not even be the same, it may be 25 degrees difference here, it may be 50 degrees difference here, it may be 100 degrees difference here. So, you are getting data at 475, 750 and 1000, when you think you are actually getting at 500, 800 and 1100.

So, as part of experimental skills you should be aware of this. That any experiment you set up, where you are trying to measure something, the manner of measuring it you have to really think about it, you have to examine how is that instrument making that measurement, and satisfy yourself that what it is displaying - because all these electronic devices, these days, display something. So, you should satisfy yourself that what it is displaying is correct, is what you think it is or what you feel it should be at the location where your sample is located right. So, in this case, a very common thing that we do, which is measuring temperature, in so many experiments we measured temperature or we try to control temperature, measure temperature, set temperature – it's a very common experimental thing that we do. There is so much room for error. There is so much room for error. So, you have to be aware of this.

Now, this is not an insurmountable problem. This is a problem that you should just be aware of because you can easily handle it, if you know that it is… this is something that you have to address, something that you have to carefully note down, then you can easily address this. The simplest way to address this is to add another thermocouple. So, for example, this is a thermocouple. It is just a thermocouple wire that you see here, it is a K-type thermocouple. So, you can get this in all your labs, in experimental facilities you can always obtain it; most likely it is there in your lab; you can always obtain it. Its a long wire, thermocouple wire. So, all you have to do is, you have to insert it. You have to insert it; you have to make a provision such that it gets inserted and it comes to a halt just above your sample. So, this is something you can visually verify before you start the experiment. You can bring it such that, it is now, you know, barely half a centimeter to or even less above your sample, actual sample. It will come on top of the boat and it will come directly sit there right.

So, this is how you are now looking at the temperature. And this can then be connected to a different display right. So, what we have done now is in addition to whatever display was there on your experimental set up, we have added one more thermocouple, which I am now drawing here. So, we will just say that it is like this and you make sure that it is positioned here. So, this is another thermocouple. I have just drawn it like this because I have written something here, but basically it will be a straight wire, it will come out there, and this then you take to another display. So, as long as your thermocouple is good and there is no problem with it, etcetera, and that you calibrate again some standard setup, if your thermocouple is working right.

Now, this is now giving you the temperature barely millimeters above your sample. So, barely millimeters above your sample. So, this may now show you 760 degrees C. So, now, you know, that your sample is actually sitting at 760 degrees C even though the furnace is showing 800 degrees C. So, you simply have to… So, this is a problem; this is now solved, all you have got to do is you have to raise the set point of that furnace there, you may have to go to… it may not be exactly linear. You may have to go say let just assume it is linear for the moment, you may have to go to 840 degrees C there. So, that your sample start seeing 800 degrees C.

So, now you bump this up to 840 degrees C. So, this will show 840, and that means, the furnace is trying to set it at 840 degrees C and the furnace is measuring 840 degrees C at that location. But, your actual sample this would have reached 800 degrees C and you now know that your sample is sitting at 800 degrees C right. So, this is a simple parameter, simple experimental quantity that we commonly… when I say simple it means very common, rather than simple I should say very common experimental quantity that we all measure, that we all encounter in so many experiments, and there is so much room for error in it, and there is also simple ways to make sure, there are simple ways to make sure that the temperature you are measuring is the temperature that you think it is. Or the temperature you are measuring is a correct measure of the temperature at that location of your sample right.

So, now if I have this additional thing thrown in here, I can actually run - confidently run - my experiment at 200 degrees C, 500 degrees C, 800 degrees C, 1100 degrees C. The margin for error is very minimal now right, and with much greater confidence I can actually see the trend in temperature, a trend in the behavior of some property of that sample as a function of temperature okay. So, I just want to highlight that therefore, like you have just seen now, I am going to show you couple more instances where these are, I mean things that you can think of.

When you see an experiment, when you run an experiment, you start running so when you go to a lab you have learnt some experiments, you learn from your colleagues, you learn from your, you know, seniors in the lab, etcetera, you start running some experiments to familiarize yourself with that experimental setup.

As part of the familiarization process, you should spend some time carefully understanding what are each of the quantities that you are measuring, what are each of the quantities that you are controlling, and try to understand - what is the process, what is that technique that is used to do that measurement, what is the technique that is used to do the control of that value, etcetera. And, when you understand that, you can figure out if there is a scope for error. So, here we figured out that the location of the thermocouple can therefore give you a wrong idea of what is a temperature, because your sample is sitting somewhere else.

So, this idea may not be exactly the same for some other measurement; you may have to think of what is concept which creates the possibility of an error and then compensate for it. So, you compensate for it such that the actual measurement, you know, what is that actual measurement. So that, you have eliminated the error, you have adjusted for the error, compensated for the error. So, in using some standard sample, using some standard test conditions, you figure out what is that error that occurs in your instrument. So, instrument related error can be corrected, and therefore, you are now making a good measurement okay.

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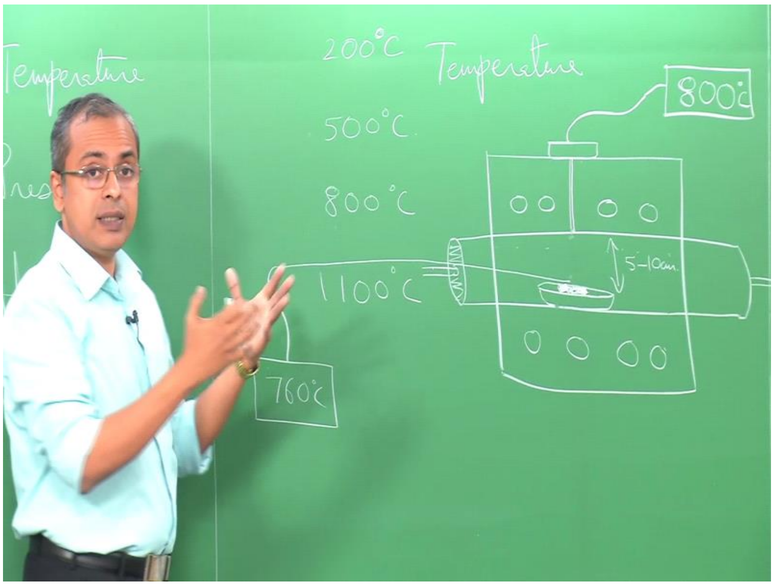

So, this is one example of what can happen and this philosophy you should take with you for any other measurement you make, because the type of errors that may creep into those measurements may be different from what I am just showing you. So, that is something I wanted to highlight. This is with respect to this first quantity here - temperature. And as I said it’s a very common experimental quantity that we all measure.

I wont spend too much time on pressure except, because we do not, I mean we do use it in many places, we do measure pressure in many places except to say that, you know, in similar to temperature you have to be cautious about - where is the sensor located? Where is the sensor located in your experimental setup and does it actually measure the pressure that you think it is measuring okay? And, in both these cases, you should also - both temperature and pressure - you should also make sure that the sensor that is doing the measurement is not, you know, polluted in someway, it is not clogged in someway, it is not, you know, covered by something else that it is getting an error in the measurement and so on. So, you should always check against some standard, so that your sensor is correct, and then, once it is correct, you should make sure the position of the sensor in your experiment is appropriate for the experiment that you are doing okay. So, those are two things.

Now, I will now spend a little bit of time on humidity and try to show you, you know, what is humidity measurement and, you know, what is the possibility of error in it, and so on. So, and I have picked these, because these are all relatively common quantities and they also give you some variety in terms of, you know, what is it that we need to be cautious about. So, in terms of humidity, I will just clear this drawing here. So, there are many experiments where we want to know - what is the relative humidity of the gas that is present in the experiment okay. So, often what is done is, you have something called a humidifier and this could be of various designs. So, in principle, what will happen is, there is a gas inlet, and then, there is some system here in which the gas mixes, in this case with water. So, there is water inside here, gas mixes with water, and then, there is a gas exit. So, the gas outlet. So, the gas that's coming out of this humidifier… this system would then be called a humidifier. The gas that comes out of the humidifier carries with it moisture and then that gets used to various experiments.

Now, the issue is that the amount of moisture that the gas can carry, varies. So, there is always an upper limit and that upper limit is based on temperature. So, at room temperature, for example, air can carry so much of moisture with it; some number of grams per some… so many grams of water - water in the form vapor - it can carry per litre of air. And, if you got to 100 degrees C, it will carry… usually it goes… the amount of carrying capacity of the gas goes up with of moisture, goes up with the temperature.

So, at 100 degrees C, same one liter of air can carry much more moisture. So, if you go from room temperature to 50 degrees C, 70, 80, 90, and 100, as you keep raising the temperature of the gas, it can carry more and more moisture. But, the point is that sets… that can be thermodynamically figured out. So, thermodynamically there is an upper limit for how much it is going to carry. But, the important point is that is only the upper limit. So, there are steam tables which give us these upper limits, but that is the upper limit. If you don’t do this process correctly it may be carrying a lot less water than what it is capable of carrying okay.

So, therefore, you have to, if you are running an experiment where the humidity of your gas is an important quantity, that you want to say that humidity is 100 percent, meaning it is carrying the maximum amount of moisture that it can possibly carry, then you need to be able to measure it and satisfy yourself if that is the case. There may be experiments where you want the humidity to be only 50 percent, we call that relative humidity, relative humidity of 50 percent, which means if the gas can carry x grams of water in the vapor form per litre of gas, you are only running an experiment where it is only carrying half as much, x by 2. So, you can choose to do that; you can control that; you can say that I want 25 percent relative humidity is typically indicated as RH, you can say you want 25 percent, you want 50 percent, you want 75 percent, 100 percent, whatever, you can specify that and your experimental setup should enable you to do that okay.

So, therefore, it is very important for you to know what is the humidity of the gas that is coming out. Again, if you did’nt know better, you would simply have a humidifier, and you will think that you are humidifying, and therefore, it should all be coming out at 100 percent RH. That is not the case. Based on the design of the humidifier, the efficiency with which the moisture is picked up varies, and therefore, often what is coming out is not at 100 percent relative humidity; it is typically lot less then that okay. So, therefore, you need to check, what is the humidity coming out. In other words, you need to calibrate your humidifier. So, what’s the best way to do it? You can actually, you can use sensors to check your humidity, but invariably the sensors also face the same problem because you can have moisture condensing on the sensor, and in which case once again the sensor will give an erroneous reading, and therefore, you need to independently verify what you have got.

So, the simplest thing to do is to setup a system, where in you actually collect the water that is coming out with the gas, and then measure, how much water is coming out per, you know, volume of gas. So, the simple thing to do is therefore, to connect.

So, this is a basically a box, it is a very straight forward experimental setup that you can make and it enables you to check the validity of your humidifying system. So, it is simply a box, it has some holes on the top and a tube. So, the gas, you typically send in humidified gas that you want to check, the gas that you want to, you know, analyze is sent in through a tube, it goes inside this chamber, and then it exits out through the holes that are on top. And, inside this there is a desiccant; the desiccant simply absorbs moisture right. So, what happens is, the gas goes in, it goes through the desiccant, and all the moisture in the gas is absorbed by the desiccant, and then dry gas comes out of the box right. So, you can flow gas for some amount of time, before that basically you weigh this set up, you weigh this setup. So, you know, what is the weight of this box plus the desiccant plus this tube, this entire setup weight you know; you attach this to your humidifier. So, whatever is exiting out of the humidifier will go into this box, it goes inside this box, it releases all the water it has inside this box, and then, exits out dry. And then, when you continue this experiment for sometime at some fixed flow rate, you can know how much volume of gas went through this, and then, you take this bottle and weigh it; you know what is the gain in weight, that gain in weight is all the extra water that got collected in this box which was captured by desiccant, and so you know that many grams of water was carried by that much volume of gas; and therefore, you know, the humidity of that gas; because you know theoretically that same volume should have had how much of, how many grams of water.

So, this is a simple experimental setup, but it’s a very good setup, because it helps you analyze and get a good idea of what is the actual humidity that is there in the gas that you are using right. You can make smaller versions of it and these are all homemade, that is why it looks, you know, simple boxes that you can get; based on the flow rate you can take smaller versions of it which essentially do the same thing. You only see one inlet, but there holes on top which are not visible to you through which the gas exits out. And of course, that you can do if it is air; if it is some other gas which needs to be handled carefully let us say, hydrogen, you have to make sure that the exit is handled properly, you cannot just exhaust into air okay, into the ambient atmosphere.

So, this is a way in which you would check humidity. So, you would take this, exit it out into this bottle that we just had, send it into another bottle, and all the desiccants are here, the desiccant... and then the gas exits out. So, this is one way in which you would quantify what is the humidity that is present in the gas. And, this is very important, because as I said you need to know, you simply said something on the…

Usually these humidifier bottles also come with a temperature control. So, that will show you something; say 70 degrees C it will show. The general assumption is that you are seeing a humidifier set at 70 degrees C, you will assume that the gas is coming out at 100 percent RH, at 70 degrees C. What I am telling you is based on the flow rate that you have, based on the design of your humidifier, that may be completely incorrect assumption to make. You may, instead of getting 100 percent RH at 70 degrees C, you may only be getting 50 percent RH at 70 degrees C or 70 percent RH at 70 degree C; some, some number; it may be 100 percent RH. And, it's again a process that you can easily correct, because now once you know this information, once you know that at 70 degrees C it only captures, carries so many grams of water, you check the same humidifier at 80 degrees C, 90 degrees C and so on. So, you will find out that may be at once… and you do some interpolation between, so you will find out that may be if you set the bottle at 77 degrees C, it carries the correct amount of water which is what would be required for 100 percent RH at 70 degrees C right.

So, I am just saying that if this requires, you know, x grams of water to be carried per litre, x grams of water to be carried per litre of air, it may end up that at 77 degrees C, with a set point of 77 degrees C, it is a actually carrying x grams of water per litre of air. So, it is still inefficient; at 77 degrees C, you again, I mean normally you would think that it should be 100 RH for 77 degrees C. It is actually giving 100 percent RH for 70 degrees C with set point at 77 degrees C. But, if your experimental setup is at 70 degrees C, you can always run your bottle at 77, and then, ensure that it cools down to 70 degrees C before it enters the bottle, enters your experimental setup. And therefore, when it goes into your experimental setup, the gas is now at 70 degrees C and it also contains x grams per litre, and therefore, it is 100 percent RH at 70 degrees C okay.

So, you have to worry about what is your humidifier doing; what is this path doing heading towards your experiment and then your experiment. And, so you can always change this setting here, so that the inlet for your experiment is correct right. So, and also I will add one additional detail. I said, I told you, you have worry about the path, because if this path drops to room temperature, if you don't maintain temperature of this path, if this is not heat traced as they call it, if this drops to room temperature, then the water will completely drop out as liquid water, and then, what you will have is gas entering the experimental setup, where gas will be an independent phase as gas, it will be close to, you know, room temperature relative humidity and independently you will have liquid water going in as liquid water not in vapor phase.

Whereas, in many of these experiments when you are talking of humidity, you don't want water in liquid phase, you want water in vapor phase right. So, in vapor phase, so therefore, it has to stay in vapor phase as it goes in. It does not help if you simply through in x grams of water and one litre of air. You cannot say that it is 100 percent RH at 70 degrees C. You have to have x grams of water in vapor vapor phase, along with one litre of air combined, sitting at 70 degrees C entering your experimental setup. So, that is important. So, therefore, it is necessary to keep this line heated, so that the temperature does not drop below 70 degrees C, and therefore, the correct value of water, correct amount of gas, at the right temperature, in the correct form which is vapor phase, enters the system okay.

So, there is a fair amount of detail here. You will often find many experimental setups are not addressing this level of detail. So, that's an experimental skill, to just look at your experiment carefully, to understand what is the possible sources of error in making a measurement, and then making sure that you have, you know, accommodated for all of them, so that your experiment actually runs correctly, is the experimental skill. So, here I have shown you there is a possible source of error in the bottle, possible source of error in the line, and then, what goes into your setup. And, I have shown you how you can correct for the bottle, you adjust the temperature here. I have shown you how you correct for the line, to adjust temperature here, and how to measure that you have got it right, all of them are possible. All these steps are possible, you just have to be alert to them, think about them and then implement them in your experimental setup.

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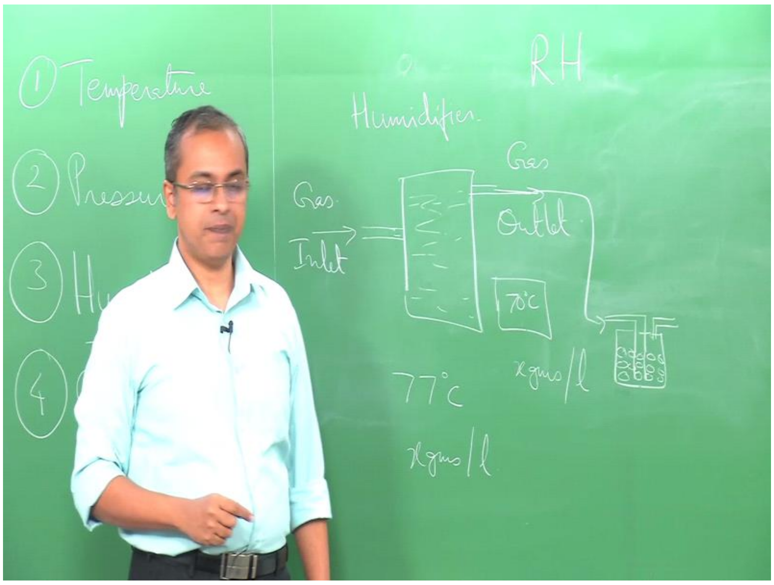

So, that’s the idea. So, we have now seen temperature. I only just said I glossed over pressure, but I just told you that, you know, similar concepts are there. And then, we have discussed humidity because this is significantly different from what you would normally do right. So, these quantities we have looked at.

Finally, I will look at current and voltage and then with that we will, I mean, sum up this discussion. And again, many experimental setups we have, we are measuring current, we are measuring voltage and so on. I would say there are only two major aspects that you have to measure, be alert to in an experimental sense with respect to current and voltage.

The first is that it is always good to cross check your value, because you usually, again, I think the major mistake that most of us make with our experiments is that we simply trust the numbers that the display shows and that is fine, I mean many times the displays are working fine; I am not saying that the display is automatically wrong but it is very important for you to cross check the value that the display shows. So, many times you are drawing current, you may drawing, let us say, you are testing a battery, and you are drawing 50 amps from the battery; 50 amps from the battery; you are drawing 50 amps from the battery; and you simply have a display that says 50 amps. Sometimes the electronics of the system may not be correct, and so, it may be actually be drawing 47 amps or 45 amps or something like that or may be erroneously showing you 50 amps. There are many ways. So, you have a battery here, and then you have two leads coming out of it, and then you have some electronic setup here, which shows you 50 amps right.

What I would suggest to you, is that I mean, of course, you can always use different different meters to run it and so on. There are many facilities that are available these days, many electronic devices that are available these days, and they are all available with varying levels of sensitivity. So, you can buy electronic devices which have a highly sensitive devices, which can help you cross check this, and one of the simple devices that is available is something that are, I will just show you here, this is called a clamp on meter. So, you can always… this… it basically opens like a clock. So, you can put at any, any experimental setup where you have a wire through which current is flowing. So, you have basically a wire that is flowing, you simply have to put this around that wire; when you put this around the wire like that, so there is wire which perpendicular, which is headed towards you, and then you take this clamp on meter or since the circuit is complete you cannot just get in here, you open it, do this, close it, and then you will see a display of current.

So, now you can, of course, get this clamp on meter with varying levels of sensitivity and so on, and it may not be the best kind of technique to look at for, you know, getting very accurate values, but still, it’s a good technique. What happens is… it’s a good instrument; it is a very convenient instrument used because many experimental setups you do not want to disturb the experiment, the experiment is already running, you just want to cross check. Once in a way you want to cross check that the value is correct. So, you simply put a clamp on meter, on any… around anyone of these wires, and it should show you 50 amps. It’s a good way for you to cross check.

So, one of the experimental skills you should have and you should pay attention to, is to have instruments available in your lab, and you should, you know, build up such instruments available with you so that you can cross check values, without interrupting the experiment. So, you know, from your, you know, activities in your lab, what is the kind of experiment you do. It is nice for you to build up a few extra techniques available with you, so that you can cross check at your convenience or as per your necessity you can cross check each of those values. And, I will just show you one of them which a clamp on meter.

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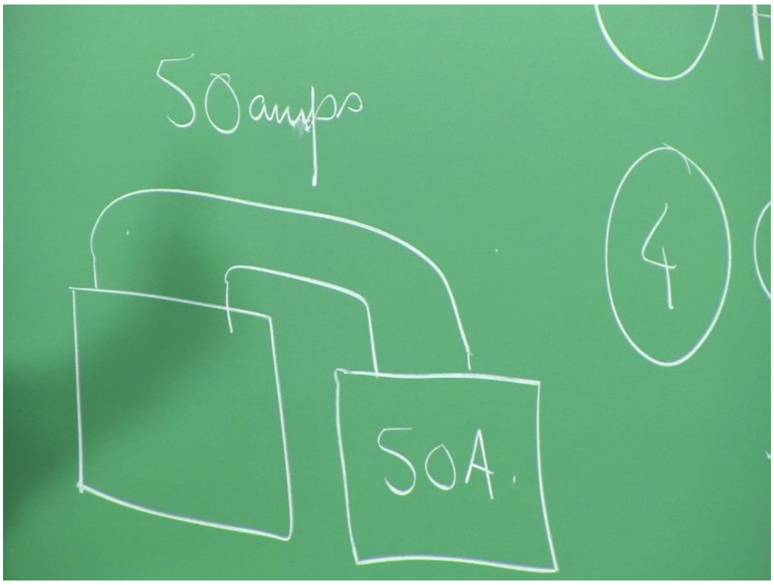

The other thing, I will also tell you about current and voltage, is that at least… So, this is with respect to current; what I just showed you is with respect to current. With respect to voltage, the other major point that you have to remember is the location where you measure the voltage. So, for example, you have a sample; I am just showing you the top view of a sample. So, you looking down on a sample; lets say you simply want to measure the… you want to measure the resistance of the sample okay. So, let's say you want measure resistance of this sample. So, you can simply put, you know, current from this location, draw it out of this location and you also measure the voltage here. So, you measure the voltage drop here and you have a meter here. So, you can send current in, current comes out. So, this is just a lead through which you contact the sample. So, between these two leads current is following coming in here, coming out that way and you are measuring the voltage. And you simply say V equals IR, and therefore, the resistance is simply V by I, if it's a DC measurement and you have got the resistance.

Now, what you often don't realize is that there is a contact resistance. So, there is a resistance associated with the contact of this - of the leads - with this sample and that can be significant. So, actually what you are measuring, this R that you are measuring, is not simply the resistance between this point and this point, that can be attributed entirely to the sample. I will say that there is a contact resistance R, which I will put R subscript C, and we have one here and we have one here. So, actually what you are measurings and lets say the R for the sample is R s, sample s. So, what you are actually measuring is R C plus R s plus R c. So, you are measuring two contact resistance, associated with these two and you are measuring the resistance for the sample.

And, generally you cannot automatically assume that these are very small values; these could be significant values. It could upset your overall measurement, you are measuring this whole thing and that's what you are seeing as R here, and this could be easily, you know, off by 20 percent or 30 percent or something from your… you are assuming that the R is the belonging to the sample, but I am just saying that it could be off by 20, 30 percent from what is actually attributed to the sample.

So, therefore, so, this is called a two probe measurement, wherein both the entire process of connecting to your sample, some power source you are applying here, so through which you are connecting to the sample. The entire process of connecting to the sample occurs only at two locations - this one and this one. The same two locations you are checking the voltage and the current follows to the same two locations; this is called a two probe measurement. And a very simple way to correct for this, to avoid this contact resistance problem is to simply move the voltage lead away from here to two other locations in the sample, and therefore, now you will have voltage from here to here. So, volt meter connects to two locations which are towards the interior of the sample, the current goes from two outward locations. So, you have this situation and when you have situation, you basically avoid this contact resistance problem because the contact resistance is the… actually the amount of current going through the volt meter circuit is negligible, and therefore, technically you can say there is a contact resistance here also, but that contact resistance is extremely tiny relative to the contact resistance that you get here.

But, the way we are running… the current that follows to the circuit is the same. So, the same current goes through the entire circuit. It's just that we no longer bother about the behavior of the sample on this side and the behavior of the sample on this side. We only look at the behavior of the sample here. And in this location, we know the current that is going through and the contact resistances involved with this measurement process is extremely tiny okay. And therefore, you eliminate the contact resistance problem. You still have two contact resistances, but they are now extremely tiny there are, you know, 3, 4 orders of magnitude smaller than what they were, when you were, when you had two probe measurement; this is called a four probe measurement.

And, mainly you are eliminating the IR drop associated with this contact and the IR drop associated with this contact. You are picking up two other IR drops, but these I' s are very small. The I going in this circuit is extremely small, relative to the I that is going through this circuit; and therefore, the IR drop associated with this measurement is extremely tiny. So, there's a way in which when you measure voltage, based on where you will measure the voltage, you can eliminate errors in the overall measurement. If your overall purpose was to get a resistance of the sample or more specifically you want to get resistivity of the sample, because that would then account for the sample dimensions.

I just showed you how the resistivity could be erroneously measured, if you had two probe measurement and can be much more correctly measured if you did a four probe measurement. And therefore, again, the way you run your experiment can give you either a wrong value or a correct value. Always, there are numbers on display and always you can note down those numbers, draw ratios, write up ratios, draw graphs and so on. I am just pointing out that, you know, in straight forward experiments that we commonly do, there are so many sources of error right.

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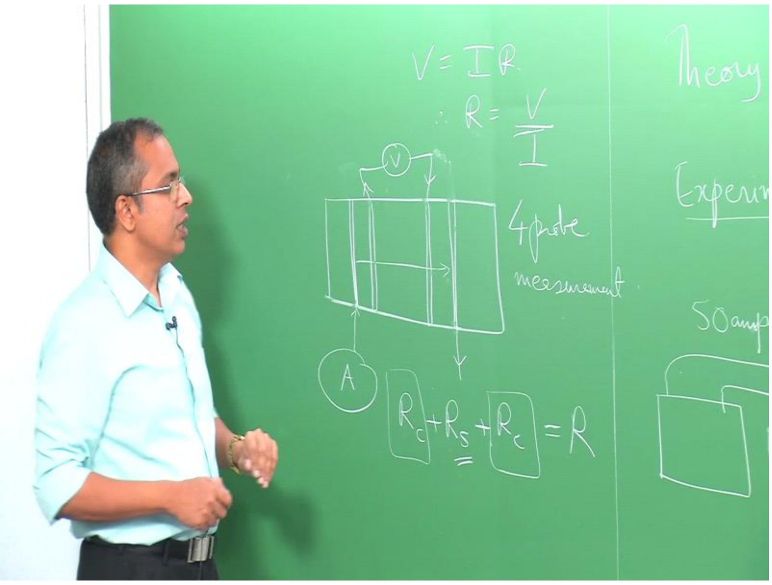

So, to sum up we have seen temperature, not a whole lot on pressure, but humidity, and current and voltage. And, I have just shown you that these are all common quantities that you measure. I just pointed out that, you know, there is so much room for error, based on where you may put your sensor; similarly, where you would put your sensor here for pressure, what kind of, you know, impurity or dirt, for example, covers the sensor; the location of the sensor or any other impurity that is on this temperature sensor also.

The humidity value based on the actual temperature of the system that is humidifying it, the design of the humidifier, the design of the path way between the humidifier and the actual experiment, the humidity value could be wrong.

Based on how you measure your current, you at least need to cross check the value of current, and location where you measure the voltage, could change the voltage and ... could change… may not change the voltage, but it will change the significance of the voltage, because that is different.

So, I just looked at some common quantities here, that we would typically measure. And I think the main thing that I want to convey is this idea that in all experiments there is room for error okay, there is scope for error, and we have to as experimentalists, pay attention to it; first of all, look for it - that is the thing that when we say experimental skills, that is the experimental skill. The experimental skill is to take an experiment, and in your mind you should just, you know, rip it apart, you should look at every stage of that experiment, every step in that experiment and ask yourself - so, what can go wrong in this step okay? If you do a thorough analysis like this, you will feel very confident of your experiment. You go and make a presentation in a conference, you make a presentation in your college, in your university or some international conference or you send a paper for publication, you will feel very confident of the values that you are reporting. If somebody challenges your value, you can defend it; you can say, you know, I measured it like this, I have taken the following steps to account for errors, and therefore, I am confident that the value I am measuring is correct. And therefore, the significance of what I am measuring is also appropriate. I am highlighting it in the correct way.

So, this is the basic idea that I want to highlight and this whole process is something that I would call as, you know, being an experimentalist and as something that we should develop in our process and so that we can say that we have good experimental skills.

So, with this I will conclude and I wish you good luck with all the experiments you do. And, just take this philosophies with you and look at the quantities that you are measuring. I mean again as I said, you know, that many other quantities that I have not even spoken about here - you could be looking at magnetic properties, you could be looking at optical properties, so many other properties you could be looking at. In each measurement, look for that source of error and compensate for it, correct for it and feel confident with your results okay. With that I conclude the class.

Thank you.