Introduction to Uncertainty Analysis and Experimentation

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Module - 08
Reporting and Archiving
Lecture - 28
Validation and verification aspects. Data archiving

Welcome to the course Introduction to Uncertainty Analysis and Experimentation. We are in module 8, looking at Reporting and Archiving. In this lecture, we will look at two aspects, validation and verification and then we will look at the aspects of archiving.

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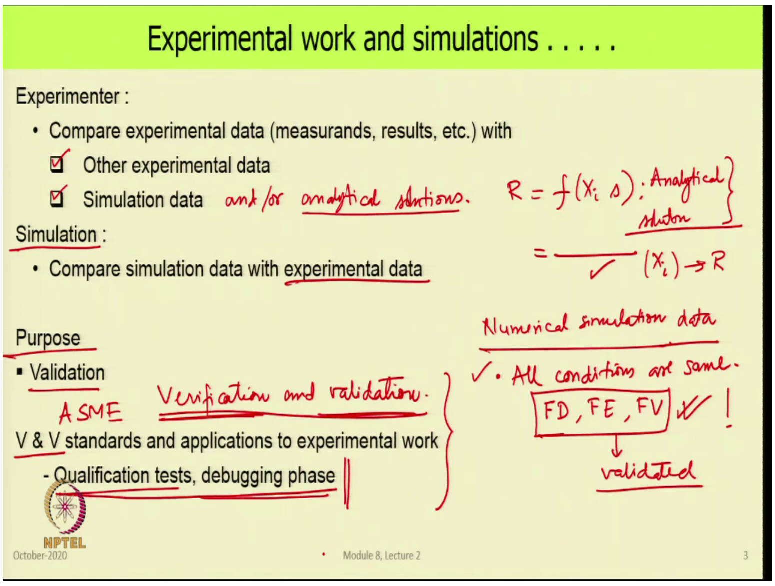

In what we have done so far in this course, we have looked at completely what we do as an experimentalist and after we have got our measurements and computed our results. Some of the things that we do with this data is, we compare our data with experimental data on a similar setup or slightly related setup either from our own previous work or from others work or from work reported in literature.

This helps us benchmark our data and also gives us confidence that what we have done is of good quality and we passed on. There are also many instances where we compare our experimental data with data that is come from numerical simulations and or analytical solutions. We will come to issues related to numerical simulations in a minute.

There are few cases where the data that we are looking for and the relationship between the result and the measurands is such that we already have for certain conditions an analytical solution. What this means is that? We have an explicit formula here which is continuous where we can put in values of X i's and we get the value of the result R.

Depending on the goodness of this analytical solution we can then compare the experimental data. It is possible that the analytical solution is for a simplified case of the experimental condition in which case the analytical solution may or may not match up exactly with the experimental work.

There could be other cases where the analytical solution is much more sophisticated and our experiment is an approximation. So, our data then is to be benchmarked against the solution of the this analytical formula. So, these are integral things one does as a part of the data analysis part of the experimental work.

There is the companion solution aspect that comes up where either we or somebody else has done a simulation and by simulation we mean a numerical simulation and we want to compare the simulation data with experimental data.

So, in once it could be possible that we are the experimenters, we only generate the experimental data and then we are done with; somebody else is doing the numerical simulation they want to do the comparisons then they take ask us for our data for their comparison.

So, whenever we are doing this comparison between the experimental data and numerical simulation data. The first thing to check is whether all the conditions are the same; that means, all the way the hardware was designed in the experimental setup whether exactly the same thing have been taken up for application in the numerical studies.

When that is satisfied then we can say that the two data the output that we get from experiments the output that we get from the numerical simulations they are comparable. Now, numerical simulations could mean solving the governing equations which are generally partial differential equations by the finite difference scheme or the finite element scheme or the finite volume scheme.

We will not of course, going to the details here, this is not a course on that. But, this is now become a very standard way of looking at problem and getting insights into it, but they are limited in that unless that in output is validated against experimental data for similar conditions, until then these results are of limited use. So, that brings us to this issue of the importance of validation.

Over the last 20 years the American Society of Mechanical Engineers ASME has developed standards on V and V which is Verification and Validation. These are broad guidelines that govern that methods by which we assess the goodness of numerical simulations.

So, that it means that if you are doing a computer simulation a numerical simulation, it would be good to look at what these standards say follow that as best as possible and report how the outcome is. For experimental work the process of validation and verification we had come across during a phase of the experimentation which was the qualification tests and the debugging phase.

It was during this time we conducted a series of tests which were we detailed when we were looking at that. Wherein we establish the fact that the experimental setup is doing what we expect it to do. Only then, we have in faith in the data that we generate for conditions about which we do not have full information. That is what we had called qualification tests and this was part of the debugging phase.

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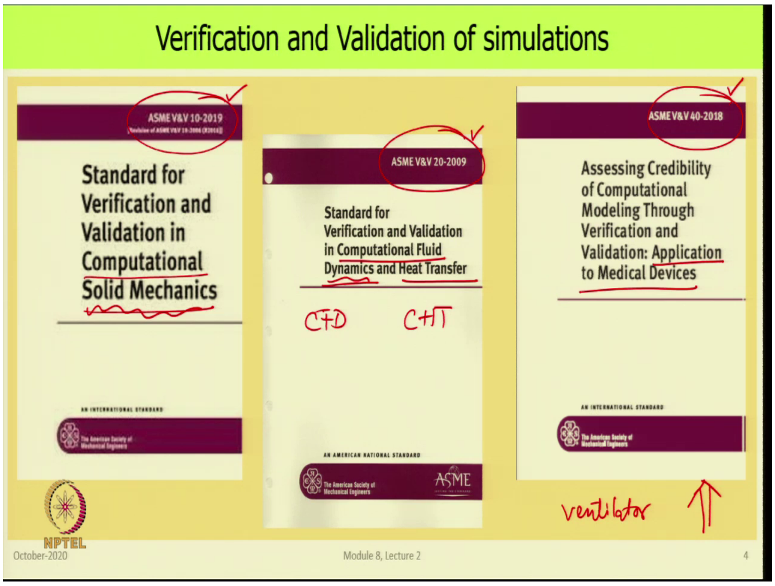

Here are three of the V and V standards from ASME. The first one is V and V 10 which is standard for verification and validation in computational solid mechanics. The second one this is V and V 20, this is standard for verification and validation in computational fluid dynamics and heat transfer.

And the third one I have shown here is V and V 40 which is assessing credibility of computational modeling through verification and validation: application to medical devices. So, in this COVID times, when we look at things like the ventilator this would be our standard by which we have to develop we have to follow the process of computational modeling and verification and validation.

As you can see here this standard is dated 2019, this is 2009, and this one is 2018 which tells us that these are very very recent standards. And this field is a very young and evolving field and we will still see more changes happen maybe in the next 5, 10, definitely 20 years.

These standards came in response to the fact that people began to believe that once you have done a numerical solution using some finite difference or a finite element code, that answer is perfect and correct. And, people started believing in it without having any doubts of the fact that there were uncertainties that there were probably limitations, there were errors introduced at various stages and it is in those light that you should see the goodness of those results.

So, this aspect has become very important now in computational work whether it is solid mechanics, computational fluid dynamics CFD or computational heat transfer CHT. There are few more of these which I am not showing up here. But, I encourage you to have a look at it and see how the full technique where on the one side we do computer analysis or a numerical simulation and say that this is the result. How do we establish the goodness of that that is what these standards do.

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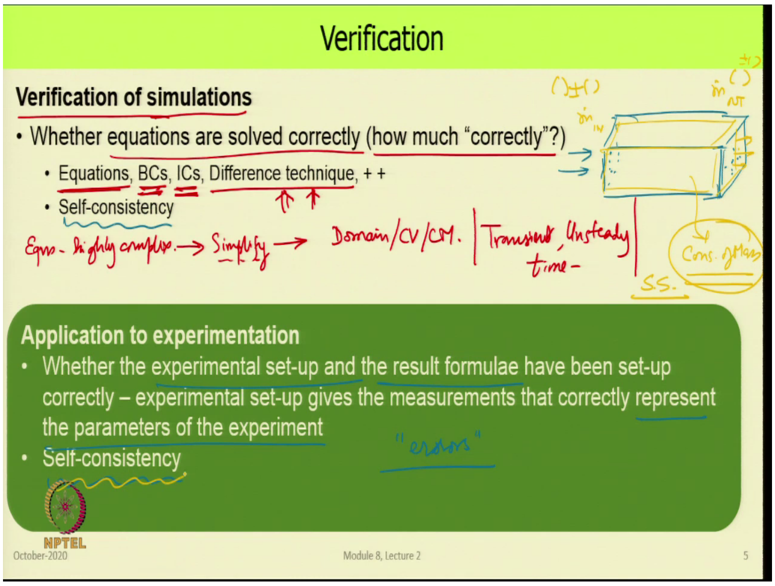

So, let see what it is. First let us look at verification. So, in the V and V standards it says verification of simulations. Basically is whether the equations are solved correctly and in the real world there is no such thing as exactly correct or exactly wrong. But, depending on what assumptions were made what approximations were made the some of the part of the solution would be somewhat good, somewhat accurate and some could be quite off.

So, that is why I put here how do you quantify what is correct correctly and where would the errors come in making a this thing where first whether the equations themselves were correct or not. So, this is typical that in general if you take the full equations that govern the physical phenomena those equations are highly complex and when I say complex it means they are inhomogeneous and non-linear.

Analytical solutions are virtually impossible even if you want to solve the equation full as it is it requires a lot of computing power most of the time we do not have that. And even then we do not get the answer very in a full form the way we want. What we do is we take these complex equations and simplify them.

Simplify based on the assumptions that the problem we are looking at does not there are some terms in the equations which are very small compared to other terms and so, we neglect those. And, in doing so, we have introduced a source of error in the computation. So, that is one part.

Then to solve the equations we need boundary conditions which is that we have to define the domain or the system or the control volume or the control mass. At the boundaries of this domain, we have to define what are the conditions and in many cases there are more than one type of conditions which can be specified neither of them are completely wrong. And so, it is the choice of the person doing the simulations as to which one of these boundary conditions they want to choose.

In some cases we even approximate it and say just to simplify it this might be the boundary condition. In transient problems or in what may call unsteady phenomena, time dependence is an issue and for that we need initial conditions that at time t equal to 0 what is the system like and then we start solving the equation. There also we could have made a some model or an approximation.

Then the big issue is about the difference technique that is used whether it is finite element, finite difference or finite volume we have always got before us a variety of techniques to choose from which one of those we used and how we solved it all of that puts in limitations on the goodness of the result and introduces errors as well. So, that is what the verification of simulations is all about.

And, now let us see if this is in a broad sense what it is all about, how is it applicable to experimentation. And, here we can say that we can argue that whether the equations are solved correctly or not we could say whether the experimental setup its design and the parameters used and the result formula that have been used how good are they for what we are wanting to do.

So, whether the experimental setup gives the measurements that correctly represent the parameters of the experiment. So, in the real world we are limited by various physical constraints. So, we make some simplification. Question is how well that represents what we wanted to study and to what extent we have introduced what we may call approximations or errors in what we wanted to study in the first place.

The second thing we looked at in the debugging phase was self consistency same as what are self consistency over in the verification of simulations which is that whether it is a numerical solution or an experimental solution. There are certain things which are inviolable in both and both outputs have to satisfy that. I will give a small example.

Say, this is a channel through which we have a fluid flowing and we make velocity measurements at the inlet plane which is normal to this and we make velocity measurements at the outlet plane and we want to know various things about it say pressure drop and anything else. The question is this.

The next step of interpretation that we were looking for will be good enough only when we verify that this system which if we draw a control volume like this. Say control volume is all the insides of this whether for this control volume it obeys conservation of mass.

So, there will be two cases the numerical simulation will take all of this solve it and give you how at the exit plane the velocity varies over the phase of the channel. In the experimental case we will get velocity same points or a different points from a measurement. And, in both cases we have no option, but to make sure that the conservation of mass is satisfied.

And, that is very simple that if it is there is steady state operation, then the mass flow rate going at into this face m dot in as to equal m dot out. And, while we will say that theoretically this is always going to be true when the practice I either method will tell you that my inflow rate was this much, outflow rate is this much and there will always be a difference between them whether it is a numerical simulation or whether it is the experimental work.

But, that is where our uncertainty analysis comes in when you say that both of these are plus minus something, then in light of that we should be able to confirm that our measurement technique was such that conservation of mass is obeyed and the case of simulations there also you would have to say what are the uncertainties in these velocities and then say that in light of those whether or not we are able to establish conservation of mass.

Once we have done that only then everything else that we interpret from this experiment or we interpret in the case of the numerical simulation only then it is trustworthy and then it will tell you to what extent it is trustworthy. So, that is an example of self consistency. So, this is about verification.

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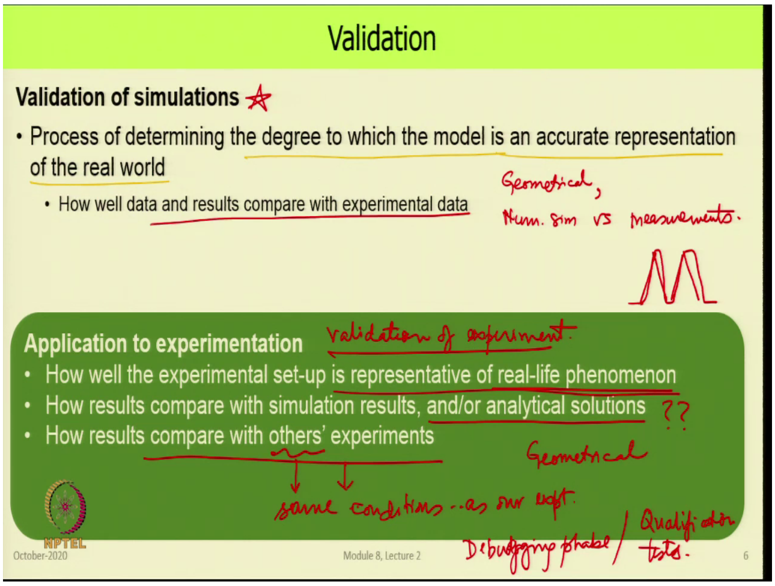

Now, we come to validation. Validation of simulations according to the V and V standards is a process of determining the degree to which the model is an accurate representation of the real world. So, here we make various modifications starting with geometrical model.

The real model may be a complex geometry, we make it simpler just because it may be too complicated to even simulate and the same issue will come up in the experiment. The real apparatus is much complicated it is much bigger, we work with a smaller device or we look at a scaled version of it, so that we can make measurements at all.

Then there is a issue of comparing what we got from in this case the numerical simulation versus what we got from the real world from the world of measurements. So, that is what it is how well the numerical results and the data compare with experimental data. So, this is what would be the case of validation of simulations.

Now, let us see what we mean if at all by anything by saying validation of experiment. So, here are some issues how well does the experimental setup replicate or mimic the real life phenomena. So, it is how well the experimental setup is representative of real life phenomena.

For example, in the real world say you take a motorcycle cylinder fins, they may have nice curves like this. Making exactly the same thing in the lab is going to be tricky we approximate these as may be sharp surfaces. So, we have introduced some uncertainty because of the shape. So, that is one of the examples of this.

Then how well do results compare with simulation results and or analytical solutions. So, we could also say that I would expect this answer to be like this am I getting that. In many cases this might this would be quite difficult to do. Real life is too complicated to get analytical solutions and in many cases simulations would all actually be compared with the experimental work not vice versa.

But, still if you have established numerical simulations already by other means and they are available then we can use that to see how good our experiment is. And the best way we validate our own experiment is to compare it with others experiment. And again the issue here is that the others experiments should be under same conditions parameters everything as our experiment.

This may not always be the case, but we could look at other peoples experiment and there will be certain conditions which are similar to what we do and we can then pick that up for a comparison. So, again here we do have techniques of validation and we have seen that this was all part of what we called our debugging phase and we include this as part of the qualification tests.

This gives us confidence that our setup is doing what we set out to do and now we can go and take the data. So, that was validation.

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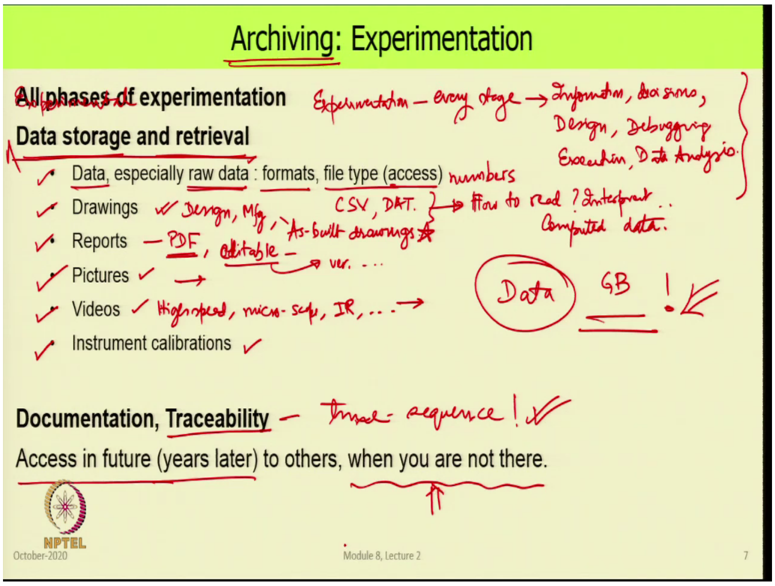

Next, we come to the last stage of the experimentation process which we have named as archiving. In its simplest form we can say archiving is nothing, but storage and retrieval. In our case we are looking at experimental data. So, we can say it is storage and retrieval of experimental data.

What that means, is that during the experimentation process at every stage we not only generated data as numbers, but we also generated a lot of information. We took a lot of decisions some were based on data, some were based on our experience and some we just did because maybe that was practically possible.

Then we did various things about qualification test in the designs of the setup, then we did debugging, then we did the execution and then data analysis. At every stage we generated information in the form of data, sometimes drawings, videos and many other things. We want to store it for future use because all the effort that we have put in this is valuable.

We could have done some things today, there were many things which may be future somebody may would like to do. So, this is very important. Most professionally run organizations have a very well defined way of collecting data and storing and this could even be non-technical stuff which would be related to say marketing or sales or finance things like that, but we are looking at experimental data here.

So, here are the forms in which we create information we can call it information, we call it data. First – as numbers or numericals and data takes two forms as we have seen in the experiment. One is raw data which is data as it came from the experiment without any mathematical operations on it – that is a raw data. These are the values for each measurand, we have to just store it as it is.

Then we do calculations using it interpreted in different ways, then we store that as computed data. So, two things come here raw data and then computed data. So, these are the numbers. We have to think of the format of the number itself and how we put that information together. So, maybe a CSV file or a DAT file all this will have nothing, but millions and millions of numbers.

And, so, we need to find and if put together at the documentation, the what is the file type, its access and how to read that data and then interpret that these numbers are represent this, this, column represents that and so on. That is generally what we may think of all the data that came out of an experiment with the temperature measurement, with the pressure measurement acceleration measurement whatever. So, raw data and then we have the computed data.

Then we have drawings. Drawings of the setup drawings of the instrument, manufacturing drawings, assembled drawings all of that we need to archive later on if you want to replace a part we know what to do, if you want to modify a part we know what to do, if you have to move the setup to somewhere else we know what to do.

The drawings which was the design drawings as they came out of the design stage, then there were manufacturing drawings and then there would be as-built drawings. We may have designed something in mind, at the manufacturing stage we might have modified it, finally, we may have had to make some small modifications so that the whole thing actually fits properly in that case that final drawing that we make this is of importance.

Then we have put together reports a monthly progress reports or weekly progress reports, annual reports, thesis, dissertations all of that. So, this we have to document. One is of course, we can put up a PDF file, but also we put its raw form which is the editable version which could have been made using any word processing package which could be open source or any propriety type.

So, if this is being used we have to be clear – what was the package, what was its version and how to use this. A PDF is of course, a standalone thing and we know this is quite easily portable. We do not have to worry too much about it. Then there could be lots of pictures, pictures of the setup, pictures of the data itself that the experimental process that was done it was a picture itself.

We were wanting to see how an object is moving say a robot arm moving. We may have taken videos from three different cameras. That is our information that is still pictures would be here. And, videos which is pictures in time that would be here. So, this could be normal videos, they could be high speed video, they could be videos that are seen through a microscope or video from an infrared camera or something else.

So, there are many formats in which all these things can be stored. We have to tell what it is only then others can interpret it. Then there are information related to instruments, instrument calibrations, equipment, equipment manufacturer and their data. So, all of that is valuable information for future use and we need to store it so that in future somebody can pick it up, know what it is and take action based on that.

So, pretty quickly we see that in an experiment we are generating lots and lots of data and if you are taking videos the high speed videos or infrared pictures and that too high definition pictures where very quickly you would runs into 10s and 100s of GBs of data per experiment. And this becomes a real challenge of how to store it and then how to use it.

A good example of this is that and the interplanetary explorations spacecraft that say NASA has sent all the data that spacecraft sent has been archived catalogued and is available freely for everybody in the world to use. So, you may see frame by frame pictures of the rings of Saturn or the spot on Jupiter things like that.

And, each one of that image how it was sent, the instrument when it was made by someone how the data is how that information is there and how it is made accessible and readable to the public that is what data archiving and retrieval is all about.

Then we have to provide enough documentation so that this information which is put together just does not happen as say a bunch of reports as a hard copy or a mixture of hard copy and soft or only soft versions and then there should be also traceability as to what is linked to what and then what.

So, this is a time related sequence. So, we have to say that this was data from experiment number 1 then we modified this in this way and then we got experiment number 2, then we modified such and such a thing we got experiment number 3. But, here this thing went wrong so, we have kept the data, but it should not be used, then we went to experiment number 4 – all of that type of a information needs to be preserved.

And we do all of this as we saw in the reporting case, but we want access in future to ourselves and to others especially when you the experimenter who did it initially you are not there. So, this is very valuable in passing information to others and to future generations.

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So, let us see some applications in the real world which is not exactly an experiment, but these are industries where they collect lots of data now and they are storing lot of data and using it in various ways. So, here are some pictures. Here this is a process plant and where various material is flowing.

They have lots of sensors, parameters being recorded, monitored and all of that may be going to some central data acquisition system and for days and months and years it is storing all of that data. So, this is a chemical processing, you can include even bigger things like refineries and petrochemical complexes and other things.

This is a picture from the auto industry where manufacturing is going on. So, for each one of these devices there are various things being done. They are all run through a numerical program. So, there is the various things that have been input to it. Then it does various things and then the product is inspected. So, at all this point you are generating data which is again being stored.

Then we have a manufacturing system lot of these are CNC machines. So, you have one programming them monitoring every component that is coming out and collecting all that data and putting it together. Example of transportation – there it is an aircraft and this aircraft typically has about a hundred-thousand sensors. And data from each one of them is being recorded.

And in the modern plane most of this data is being transmitted to ground computers in real time. So, for every time a plane takes off, all its parameters are being recorded and this is done over the whole life of the aeroplane which would go on for decades. So, there is data about every engine and within the engine there are hundreds of parameters that are being measured.

There are information about parameters that are all over the aircraft whether it is the hydraulics oil, whether it is the inside environment control and fuel amount, velocity all these things are being controlled. So, again plane in flight generates copious amounts of data every time it takes off. Same is now the case with many of the says land based vehicles and even sea based vehicles.

Then there is example of a very sophisticated experiment. This is a facility for testing aircraft engines. This is extremely complex, very expensive to make and a very few of them in the world, but again every time an engine is tested it is equipped with a very large number of sensors in addition to what there would be in the flying aircraft and here you run it and collect lots of data and then see what is happening.

On top of that is not just the one short deal that we make a measurement once and we over with, but after that you would see that over a period of days, hours, months, years what is this aircraft doing the engine doing. This is also used for certification which is a process by which we say that this equipment does this particular thing a parameter this much plus minus this much according to our various standards that we have seen.

This is from the energy sector the coal or a fossil fuel burning power station. It monitors thousands of parameters and you have to keep monitoring them because such a equipment is being run continuously for months and years together and then after servicing for decades together. So, it generates a lot of data from various instruments.

The case where there is video recording taking place and from there we are doing further calculations is in sports and these days there are various ways in which we take this image, do an analysis of it and then draw conclusions. In case of cricket whether somebody got out or in the case of football whether there was a goal or not. So, there are this type of things have become quite you normal now, but they all rely on certain measurements.

All of whom have some uncertainty from which we draw conclusions. Another example of imagery which is working with pictures and drawing conclusions is remote sensing and satellite pictures. So, here we see where there are clouds, what you say the soil moisture the so many things that can be looked at and every one of those analysis which is image analysis will carry with it some uncertainty. So, here our data is pictures.

And, this is a experiment from a college setup. So, we again making some measurements and then what was the learning aspect, but then did we archive it and did we learn from it that is something we can add. So, all these things tell us there is one thing common to all of them. These are all practical physical world systems.

There are sensors, instruments all of them are measuring parameters. So, you have measurements all of this you are either processing in real time or otherwise offline and storing and you get lots and lots of data. All of this data is being archived and in future we go back and look at various trends and take decisions on it. In the past the data was there in many cases data was not there.

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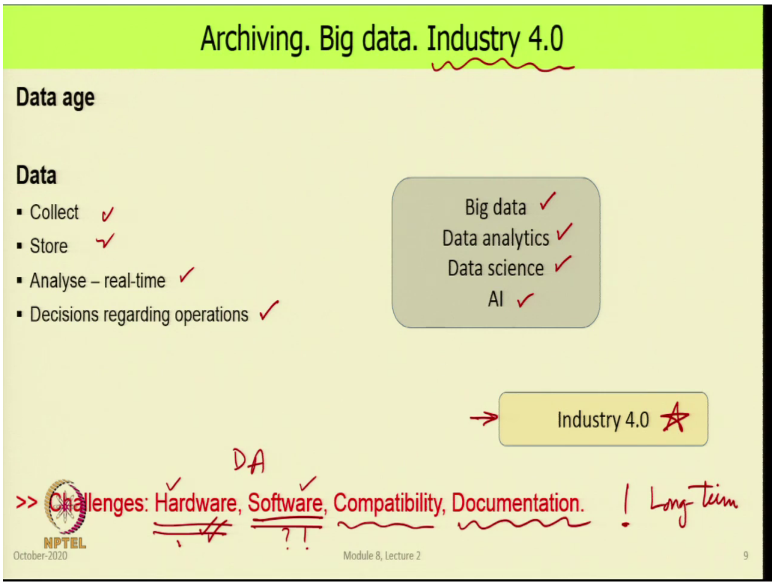

Now, the world has changed and we are looking at issues of industry 4.0 which is largely data driven we are in the world of big data now and the biggest thing going around is big data, data analytics, data science, artificial intelligence and of course, industry 4.0. So, we are looking at numbers that came out of sensors and then drawing conclusions, but as we have learnt in this course, unless we understand the measurement the uncertainties our interpretation in any of these is not going to be accurate.

So, we are in sort of a data age where we collect, store, analyse data some of it in real time and then we take decisions. That is what industry 4.0 is about now. There are many challenges because since this data is coming in digital form, there are issues of what we call software issues. For instance, some data was collected using some propriety software of some manufacturer.

Few years down the line, that may not be there at all how do you access it. Or it could be that some data in an experiment came from a propriety software other came directly in open software. We now have to put these two together to complete our data analysis, that can become a challenge.

Hardware changes and as we have seen even in instruments what used to be purely a mechanical indication instrument gradually started became electronic with electronic indicator and now it has got within it its own storage, its own wireless communication all of that is happened. So, this has also undergone a lot of changes.

Also changes is the software that is used for data acquisition. As hardware changes its many of the software's keep getting upgraded and maybe after a while if some data was collected in certain way, 10 years later or 5 years later that may not be the case. Everything may have changed.

Or it could even happen that for the first few years in ones research we used a certain setup on which there was a certain data acquisition format certain data acquisition system then a new model came and everything change there. But, now as a user you want to compare all these data together in one go that becomes a challenge that is the issues of compatibility. And, finally, we can work with it only when we have adequate documentation.

So, these are the big issues and we all have to be vary about it and take adequate care and make strategies we have fairly long term strategies of managing ones data.

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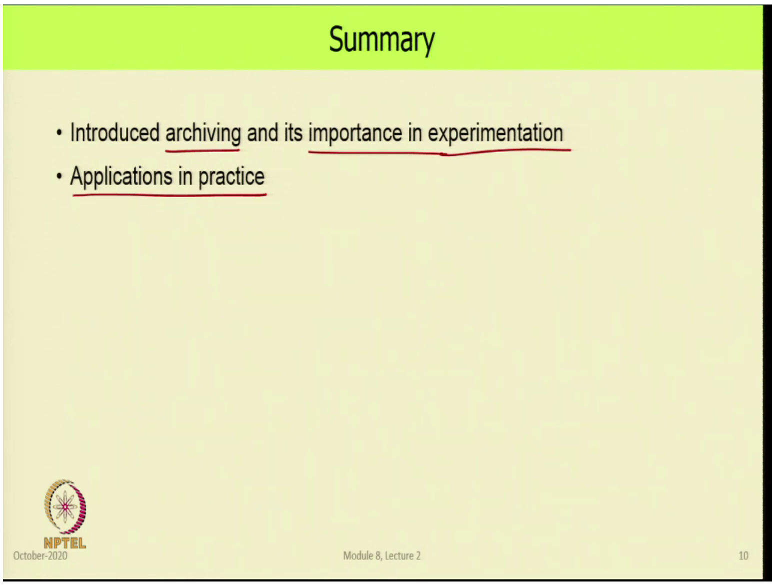

So, we conclude this lecture on this note, where we have seen archiving, what are the issues with it and why it is important in experimentation. And, we also saw it is not just experiment doing an experiment in the laboratory, but in general whenever we are collecting information or data from a measurement in many applications we are basically doing the same thing – collecting data and interpreting it.

So, what we have learnt in this whole course is applicable to many industry applications also. On that note we will conclude this lecture.

Thank you.