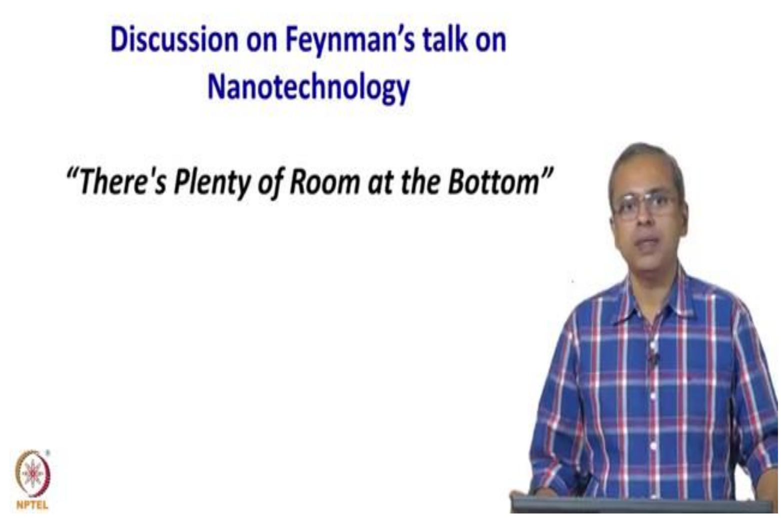
Nanotechnology Science and Applications

Prof. Prathap Haridoss
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture - 03

Discussion on Feynman's talk on Nanotechnology

(Refer Slide Time: 00:15)



Hello, in this class on as part of this course on Nanotechnology, we will have a discussion on Feynman's talk on Nanotechnology. He had titled this talk as "There is Plenty of Room at the Bottom" and if you look at any literature that looks at the history of nanotechnology. Everybody credits Feynman's for this particular talk, which was given I think a lot quite some time back we will see some dates on it and where he put many of these ideas of Nanotechnology together in a very nice manner.

(Refer Slide Time: 00:53)

So, if you see here it was in 1959 that this talk was delivered. And in, through this talk, Feynman described various ideas as well as issues related to the concept of "nanotechnology". He does not necessarily use the term nanotechnology there, but as you will see through our discussion you will see that his foresight into what might happen? What is the level of interest that is there in that field? What issues that may exist when you get into this field?

Were all very nice, very I mean profound. And even today if you look at the time scale now, 1959 is you are looking at something that is 60 years ago, from at this point in time. To look at a time frame 60 years into the future and make some prediction on what might be very important as an area of science going forward, it takes a remarkable amount of intuition and foresight and knowledge and a lot of things coming together in the mind for you to be able to do that.

I mean sitting where we are today if you want to make a prediction of what will be, I mean very significant activity for the scientific community 50 years from now that is not an easy thing to do. I mean so many things have changed in short periods of time that it is not so, easy to predict what is coming up in the future in terms of technology, in terms of scientific thrust and so on.

I mean even if you take normal application like a mobile phone that we take for granted these days, even 20 years ago it was almost not there in common usage even as a word. So, if you look at 1990s, early 1990s nobody even referred to a term like a mobile phone.

And then suddenly around the year 2000-2010 in that timeframe everybody started getting a mobile phone and those were also by today's standard source were considered primitive phones.

Although during the year 2000 to 2010 that still made such a revolution to the general community, general world community that people could actually speak when they were moving around and still be in touch. Since 2010 or a little past that you also had this evolution of smartphones which made even these phones in the first decade of the 21st century also look outdated and obsolete. So, today virtually everybody seems to have a smartphone and it is no longer just a phone, it does so many different things.

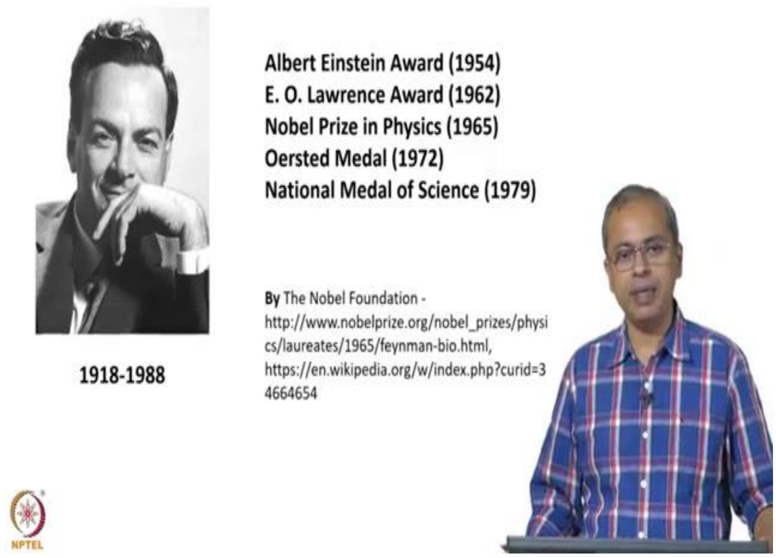
So, if it is just step back in time in 1990, we would not have predicted in 2000, 20 we would all be almost everybody would be having a mobile phone it would be a smartphone that there would be even a concept called a smartphone. And that phone would do almost anything that you wanted it to do. I mean it tells you everything from how much you walked, where you are located, it sends messages for you, receives messages for you, it sets up calendar for you, all sorts of things are available through your phone and that was not something that you could have predicted even 30 years ago.

So, our ability to predict into the future it is actually very limited simply because so many new things come. So, invariably when we are extending ourselves into the future, we are using various frames of reference that we have at our, time frame. So, you look around you see things around you, you have some framework. Invariably when we project into the future, we are looking at little bit more advanced versions of what we are seeing today around us.

So, therefore, we are limiting ourselves in that sense because simply because we do not know what is ahead this is all that we have around us. This is all the knowledge that we have and we are using that knowledge to project into the future therefore, there is a tendency to get ourselves limited into a certain channel. Whereas a completely different channel may appear 5 years down the road which we have not even considered and therefore, we have not used that in any of our predictions.

Therefore, when you look at Feynman's talk which you can I mean there are many sources in the internet, where you can see his talk, I mean you can get a download, you can download the text version of his talk completely. There is also I think a recording of a talk much later where he revisited his talk so to speak, so these are all available to you. But when you look at that not only should you, I think look at individual predictions that he made which is sort of what we would look at through our class today and our next class. You should also look at the significance of the fact that he was able to project, so far into the future.

(Refer Slide Time: 05:55)

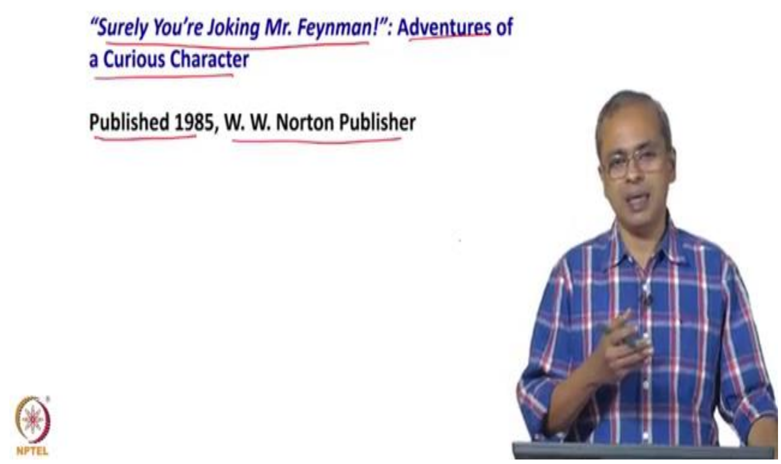


So, we go back to this talk 1959 Feynman delivered his talk describing ideas and issues related to nanotechnology. Before we proceed further let us also get a sense of, who this person is? So, this is Richard Feynman. He is he was a famous physicist and he lived between 1918 and 1988. Very well-known physicist, very popular physicist, because he was able to relate to the public very well, communicate very well with the public which is, by the way, a very important thing if you are in the field of science your ability to reach out to the public.

Because the public often seeks that knowledge from us as scientists and number of times, we find that there are scientists were very good in communicating within their community, but may have difficulty communicating with the public and he was very good at that. You can see here a wide range of awards that he won through his lifetime. Of course, prominent one being I mean each of these is prominent. But from our general public's perspective, he also received the Nobel Prize in physics in 1965.

He I mean, he is like I said, been very good at his communication skills. He also was part of the Manhattan Project which was later there, later then situated in Los Alamos in the United States. So, he was part of the team that looked at the creation of the very first atomic weapon. So, that is something that he has been part of the entire field of nuclear weapons, he is played a very significant role in the early 1940 when the atom bomb project was in progress. So, very well decorated scientist and of course, he is no longer with us anymore.

(Refer Slide Time: 07:42)



There is a very interesting book he has written you can sort of like an autobiography you can think of it that way it is called "Surely You are Joking Mr. Feynman" and this is something you can get, you can purchase I think many online sources have it. It was originally published in 1985 by this particular publisher. If you, I think now if you check maybe it has been republished by others, I think I am not you will have to look and see what is available there.

But the book is available you should be able to get it" Surely You Are Joking Mr. Feynman", adventures of a title as adventures of a curious character. It very nicely lays out many things that he has done through his life in the area of science, in the area of connecting with the public and so on. And interesting ways that the public have reacted with sort of predictions of science or activities of science and so on.

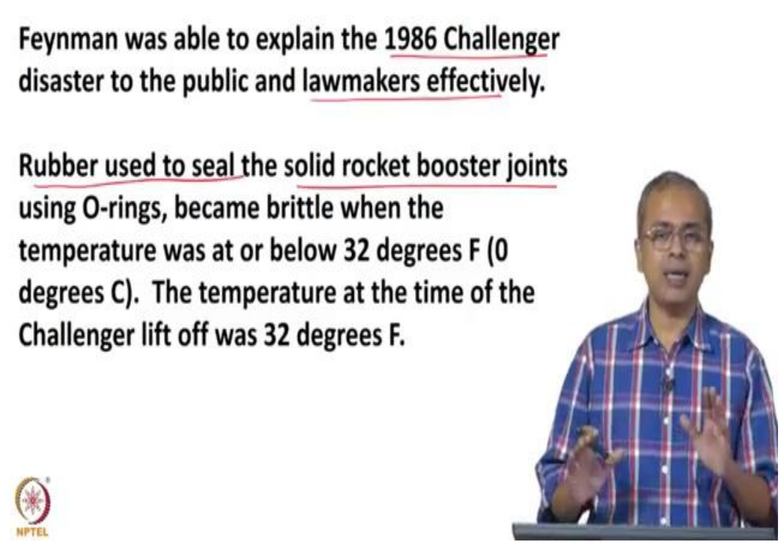
And hence the title "Surely You Are Joking Mr. Feynman" because I think in that book if I remember one lady tells this to him because he gives some, he says something about something scientific and she is quite taken aback because of other information that she has gathered from not non scientific sources which are in conflict with what he was saying.

But in any case, that is the book, it is a very nice book to read. It is a book that anybody in the public can read and appreciate and enjoy. And it shows that as the scientist, as a Nobel Prize-winning scientist he was very much a warm nice human being that people could interact with. So, that is the thing. He also I think was very particular that he should understand something very well before; I mean if he was trying to participate in some activity, he was very keen that he should understand it very well.

And that is something I think again it is a nice trait for a scientist to have. Because he himself says that he comes across a lot of people who are involved in some activity but do not seem to actually a whole lot about the activity and that hampers them.

So, I think that is his general advice that you should get to know things really well you, should really question, question, question and satisfy yourself that you understand every term, every usage of that term and the context in which it is being used and everything. So, that you really get a full internal feel for that activity before you can start contributing to it. So, this is a nice book I recommend it is a very nice book to read.

(Refer Slide Time: 10:17)



I mentioned that he had very good communication skills and his ability, again both those things are I think quite clear in this particular example, somewhat unfortunate example that we have to share here. He was both very particular about communicating things clearly. And also, like I said very particular that he should really understand something very well before so, that he could actually do something contribute something meaningful to it. So, in 1986 the space shuttle Challenger took off heading out to space and about 73 seconds after take-off very, unfortunately, it exploded in space and all the crew were killed.

So, naturally, after the event, there was a formal enquiry to understand why that happened? All astronauts were killed major accident had happened; a formal enquiry was held. And Feynman was one of the scientists involved in that enquiry. And he again as he had this thing that he would keep on hunting down the information and then trying to understand everything to it is complete detail.

So, he was able to explain he was able to pin it down to this fact and explain that it all came down to a rubber-based seal. That the solid rocket booster joints had which were basically O-rings kind of thing which would seal the booster so, that things in the fuel inside would not leak out. And it turned out that those rubber rings were rated for above 0^{o} C operation or 32^{o} F operation.

And during the night leading up to the launch, the temperatures in that area had dropped below 0^{o}C. As a result, that rubber had become brittle and so, as it took off and heat was getting generated, it did not expand properly it was still brittle and it broke. And once it broke contents inside started leaking out and slowly the spacecraft lost control, there was a flame outside and eventually it all exploded.

So, his ability to find it was very useful and he also explained it quite nicely to the lawmakers, who are basically with political background may not have scientific background. He was able to sit in front of them and explain to them how a piece of rubber which is otherwise flexible that we normally assume as flexible can become brittle if make it extremely cold and then it just breaks and that is basically what he demonstrated.

So, his ability to hunt down information and it is ability to explain it very well came together in this in this occasion which of course, as I said is a rather unfortunate occasion where it happened. But nevertheless, that was his duty at that point in time and he was able to do it very effectively because of his abilities.

(Refer Slide Time: 13:12)

So, his paper on nanotechnology, not paper his talk on nanotechnology is something that where he explores the idea that we are all doing research in all sorts of different fields. This is 1959 that he gave this talk that people are doing research in all sorts of fields. But he feels that there is this field that people have not explored too much, where looks like there is a lot of things that you can do and that is why he started talking about it. So, he starts off his talk by talking about something called the Encyclopaedia Britannica. So, before we jump into what his first description is with relative to this idea of know going down in scale.

Let us understand what Encyclopaedia Britannica is? So, that you can get a sense of what he is talking about. So, it was today you we just if you need information, we just go to a search engine such as Google and then you look up information at various sources and one of the most common sources that many of us seem to access is Wikipedia.

So, in olden days for almost 240 years, there was a particular book called Encyclopaedia Britannica, it was not a single book, but it was a set of volumes. And you can see here an image which shows you the volumes the source of that image is listed down here. And it was you can see here, there are about 29 volumes plus 2 other I think like appendix or series of no 3 more out here which sort of list the like index, so to speak of the book.

And so, you have about 26 to plus book, so maybe about 30 odd books of this Encyclopaedia. And for a very long time, these were extremely useful and prestigious additions to any library. So, if you go to any library even if you go to 1990 if you had I mean if your parents had we have been to school if you check with them in any library, they would have one complete set of Encyclopaedia Britannica. It is a very, it used to be a very lovely book to look at because they would look at all sorts of topics it could be history, it could be geography, it could be science, space anything.

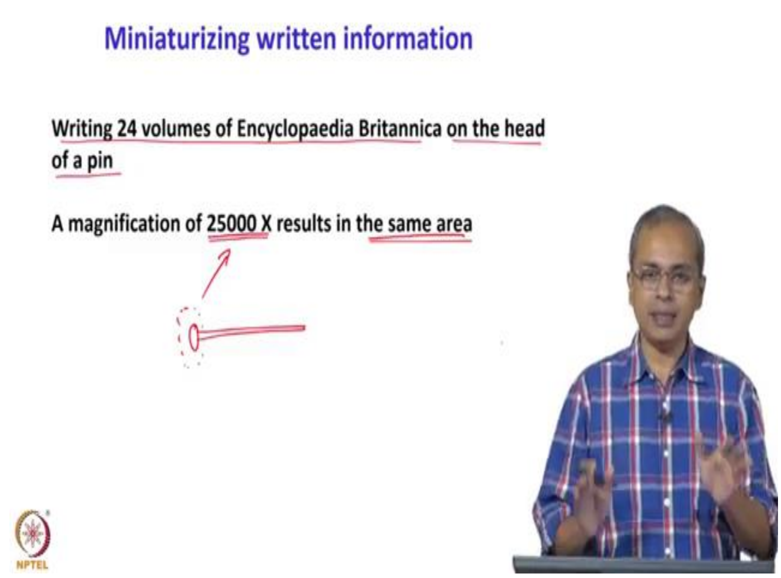
And there would be they had a systematic format in which they would have information on every topic that you could search, you could locate, you can read and you can you could be very well informed on any topic you like it was a lovely set of books to browse through and almost every library had a copy of it.

And people who were rich enough would always love to have a copy of it in their shelf. And that is sort of the example that you see here in this image here it was a very well sought-after book and indeed a very lovely collection of books to have. It used to be there for I think from 1768, I think it is when they started it. So, that is how you get these 244 years that it existed. And of course, once the internet came on and you could start getting resources on the internet, slowly this the popularity of the print edition went away and they eventually stopped the print edition.

So, after 244 years they finally, stopped the print edition and 2012, but still, this was the standard. So, Feynman in a talk says that this is such a lovely book and people are interested in it, is there a way in which you can take all of the contents of this book of these volumes of book, some 30 volumes are out here for example.

All the contents people of this book and put it on the head of a pin ok, on the head of a single pin. So, that is the you can immediately imagine this is a huge amount of information. Technically this book is trying to give you all the information in the world sort of, in some kind of a summary. Because it looks at all the topics that people are looking at or interested in looking at and then tries to keep it all in this collection. Can you put this entire content on the head of a pin? That was the first example that Feynman sort of examined insignificant detail in his talk.

(Refer Slide Time: 17:39)



So, he looks at the possibility of taking 24 volumes of Encyclopaedia Britannica and then writing the contents on the head of a pin. So, it is very nice to read his talk for a number of different reasons.

So, one of the reasons is this the whole idea of nanotechnology that he has presented in his talk. But the other reason why it is worth looking at his talk is also about how he goes about thinking about things. So, how do you extrapolate, how do you extend some knowledge that you have some thought process that you have?

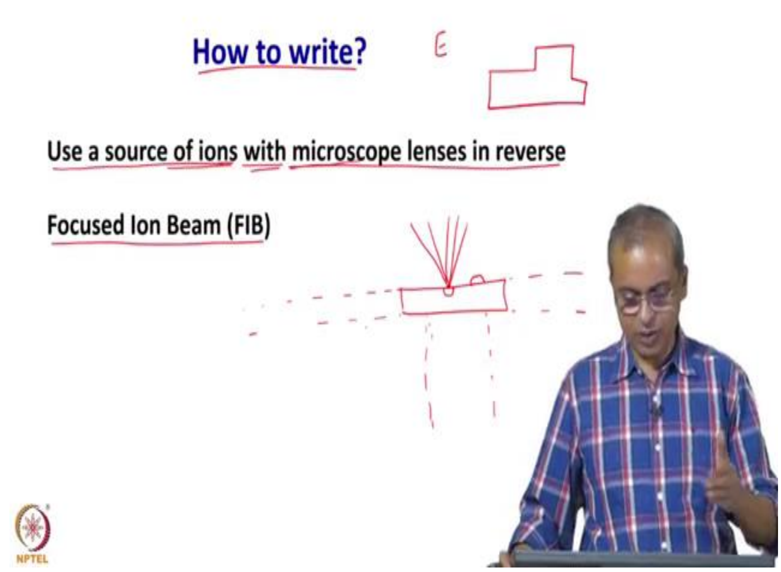
And very important to this whole process in his talk as well as in I think many scientific activities that we get involved in, is the idea of estimation, where you do not necessarily have to have exact numbers, but you can get pretty close, if you do some reasonable estimation and that gives you a very good idea of what is possible, what is not possible, where do you think you would hit a you will hit a problem that you need to address. So, this estimation thing is very nice and you will see through our discussions of his talk and the examples that he looks at, that he keeps using this estimation process in many places.

So, for example, the first thing he does used to compare the area of the head of a pin to the area of all the pages of Encyclopaedia Britannica. So, he looks at 24 volumes of Encyclopaedia Britannica takes average number of pages that are there in each volume. So, 24 × the average number of pages is the total number of pages that is there in Encyclopaedia Britannica. Then the area of each page so, you multiply by the area of each page, you get the total area of all the pages of Encyclopaedia Britannica.

Then he looks at the area of the head of a pin. So, those are the two areas that you have, he says that if you do that estimation you find that if you magnify if you take the head of a pin. So, you have a pin and you take this head of a pin and if you magnify these 25000 times you look at the area of this head of the pin. And if you magnify it 25000 times you get the same area as the as all of the area that is present in the Encyclopaedia Britannica.

So, therefore, our goal is to see how you can miniaturized Encyclopaedia Britannica by a factor of 25000. So, if you can miniaturize Encyclopaedia Britannica by a factor of 25000 the areas match and therefore, that you can actually place it on the head of a pin. So, that is the idea that he looks at.

(Refer Slide Time: 20:27)



So, the question is how do you write this information onto the head of a pin. So, there are multiple approaches here, so the first approach that Feynman looks at in this idea of miniaturization with respect to data. So, this is data you have data on pages of the book. So, in this particular class we are looking at the data and computational aspect of miniaturization. So, data is there in the book. So, what is the data? You have some image you have some written matter below it something describing the image some numbers are there, alphabets are there, etcetera.

We will make the assumption that it is all in black and white or at least they will remove the colour aspect of it, for the moment we just make the assumption that it is all black and white. So, where you have text you have black and where you have no text you have white. Where you have an image, you have something in black a black line or something of that nature, where you do not have an image you have the white background. So, basically you have black and white and this black and white is the information that you have.

Now, in general, you can save information by first encoding it in some way and then storing it, which is sort of what we do these days in computers we and that is something that we will look at. But there is also a much more in some sense a much more basic or primitive way in which you can store the information which is simply to miniaturize it without doing any encoding. In other words if you write the word Encyclopaedia Britannica as the title of the book you miniaturize it 25000 times and essentially you have written the same Encyclopaedia Britannica in extremely tiny font, which is now there in the in some location it so, happens we are trying to put it on the head of a pin.

So, the first example that he looks at is a situation where miniaturization is happening without any encoding. So, as is the image will show up as a small image, the text will show up a small font text, everything will be shrunk by 25000 times it is just the way today when you do photocopying you can shrink it by to half the size or quarter the size, you shrink it 25000 times. So, content is maintained as is without any change and then put on the head of a pin. So, the question then arises how to write it? So, that is this is the nice thing about his talk, he does not simply use his imagination to tell you interesting imaginary scenarios, he is also trying to tell us what is the path to enable that to happen.

And this was at a time when those specific paths that he was referring to, were actually not there and that is why there is, so much of appreciation for his talk. Because all these paths were not there at that time or were in extremely rudimentary level available, he was able to project where they may all end up going in future. So, how do you write? So, in other words, I want to write the letter E, on the head of a pin. How do I do this, how do I write the letter E? Because it is the first letter of Encyclopaedia Britannica, so I want to write the letter E on the head of the pin.

So, I should have a way of doing it. So, he simply says you should use a source of ions, where basically you are using the microscope lenses in reverse. At that time by 1959 electron microscopes had already been out in commercial usage for about 20 years. So, from 1939 onwards there were some commercial versions available. So, by 1959 for 20 years they had been around. So, the basic idea of an electron microscope was understood.

So, you had this electron beam going through and then after going through the sample, you would diverge the beam you would get a basically a magnified image of the sample. So, what he says is you have to do the reverse, you take electrons from some larger source you focus it down to a single point and with that focused point you can etch away, even it is coming with high energy. So, either the electron beam or the ions. So, they are coming from various directions and they all converge to this point. So, this is a focused it is a series of ions. So, it is just like an ion is also a charged particle just like an electron.

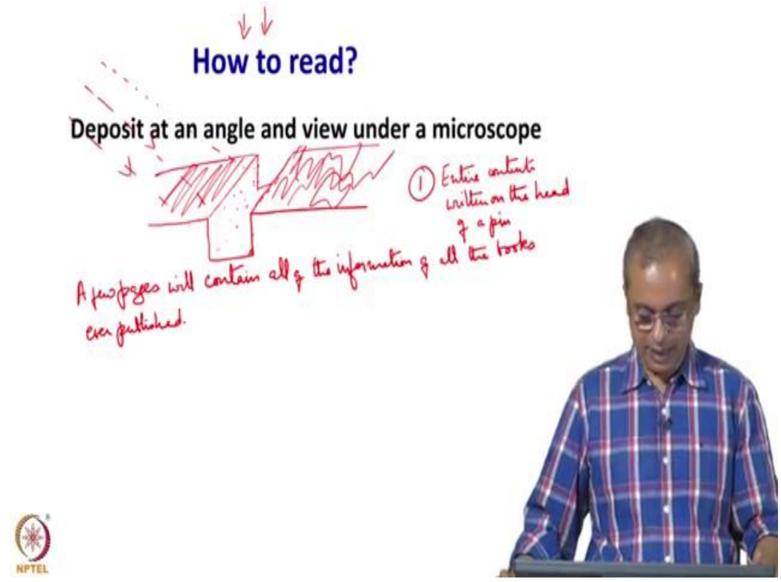
And so, if you have electrostatic fields you can or electromagnetic fields you can actually pull this the ions down to a point and then they would all hit that point. If they hit the point based on how we have got the system set up, you could actually get ions to settle on the point or you can also get ions to etch away at the point. So, you can get that etching action to happen.

So, what happens is? When you do that if you have a surface you can remove some material or at another location you can add some material. So, this process we can do and this is the thing that he sorts of predicted that using an electron microscope with lenses in reverse you can actually do this. Today that is exactly what we do, there is something called a focused ion beam and it is available, they are called FIB systems.

And with that, you can actually send an ion beam down and that is exactly this you can etch away at a sample at a given location or you can add material to a sample at that given location. So, by doing this on the sample, which is now a magnified version of the pin, so this is the huge pin now because you are magnified it dramatically and that is your base of the pin and we magnified these 25000 times.

So, you have a huge amount of area that is available. And on this, you can use this etching process to start etching away. And then you write whatever Encyclopaedia Britannica you want to draw some figure, so you want to draw a box or something of that shape then you etch along those lines and you get that shape. So, everything that is there in the book, can now be done on this surface. So, that is how you write. So, he thinks about this idea and then he sees how it can be done. So, this is how we write. So, that is the first step.

(Refer Slide Time: 26:30)



Then the next question we have is how do you read it? You have to read this information that you have written. So, for that also he suggests the possibility. So, you have done this etching. So, that you have this surface that is like this. So, you have etched something. So, this is the E that you have created. So, this is how that E is going in some direction. So, you basically have some kind of a canal that you have put together there.

Part of the E, say this is all part of the E. So, this is how you etch the surface. So, there is a channel, this is please remember this is an extremely tiny channel inside a that you have created inside a microscope. You want to read this, so, how do you read this? So, he says you deposit at an angle deposit, some material at an angle which has then a different kind of shading associated with it, some darkness, some contrast it gives you. So, you deposit at an angle.

If you deposit at an angle it will deposit only in regions that are exposed. So, it will deposit here, it will deposit maybe in some small regions here underneath there will be a region that I am putting here, marking here with dots which where there will be no deposit because it is in the shadow of the deposit. So, you have this wall the deposit comes from the side. So, it will not fall very close to the wall, it will fall away from the wall. So, there will be a region here where the deposit has not happened.

So, there is a region here where deposit has not happened here and all there is a deposit. So, there is all deposit here, but inside this channel then we region that the deposit is not there. If you do this and then you look at it the same channel using a microscope from the top if you use an electron microscope from the top and look at it. Then you will see that because the deposit has happened only in some places are not happened in some places.

You see a contrast and that contrast will follow the channel that you have dug into that sample, which is the channel that ends up reading the letter E. So, for in this case the letter E alphabet E, so you see the alphabet E because you can see the shading along the edges of that E where the deposit did not have. So, there is a way to write at this small scale, there is a way to read at the small scale both of which are predictions that Feynman was saying in his talk.

So, if you do this you can basically write all of the text that is available in the Encyclopaedia Britannica onto the head of a pin. By just following these things where he compares the relative sizes of the pin and the Encyclopaedia Britannica, he says that level of miniaturization is completely possible, where you go from the size of encyclopedia Britannica to something that is 25000 times smaller, so, that is possible. And then the process he tells you how to etch away. So, that you can for every alphabet on the page you create an exact small alphabet in the on in the head of the on the head of the pin.

And then, therefore, everything that is written without any encoding, so, every sentence that is written, it is also a sentence that is written on the head of the pin, no encoding you can actually read it. You put it under the microscope just the way you are reading a book, you could start reading that book on the head of the pin. Every sentence that is written there, every drawing that is made there all of it would be visible on the head of a pin. So, he gives you this nice way in which the entire contents of Encyclopaedia Britannica can be written on the head of a pin.

So, that is one part. So, entire contents written on the head of a pin entire contents of the Encyclopaedia Britannica. So, is written on the head of a pin. Then he extrapolates that some more he says that is Encyclopaedia Britannica. How about all the books in the world? So, all the books in the world he estimates million times the Encyclopaedia Britannica. So, we have million times the number of books that are there in

Encyclopaedia Britannica. So, he says there are 24 million such books or some such thing some very large number and what would it take to miniaturized that.

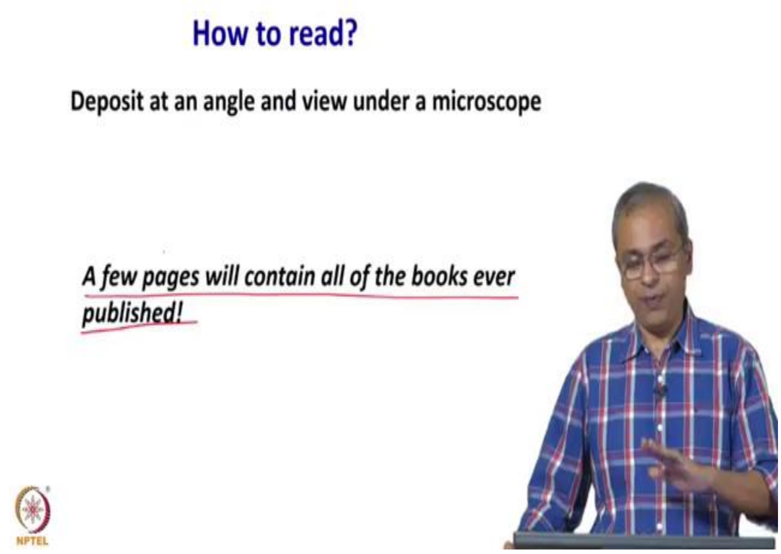
If you followed this exact same process that he has followed for miniaturizing Encyclopaedia Britannica to the head of a pin and you take million times as many books and do the same miniaturization. Then it is a very straight forward extension of area and it turns out that with just a few pages will contain all of the information of all of the books ever published. So, he predicts that if we just follow the same process with just a few pages of material or area equivalent of just a few pages you can take the entire content of all the books ever published and keep it in those few pages using the same process.

So, the nice thing is when you want to make copies of all the books and pass it on to other libraries you simply have to make a copy of those pages. You simply have to follow a system by which you deposit something on those pages and then peel off that deposit. And then pass that on to any other place that requires a copy.

And you can copy the entire content and you have to understand the significance the phenomenal accomplishment here as just an experiment of thought that he had put together. A phenomenal accomplishment here in the sense that he says that all of human knowledge which is there in all of the books that we have ever published it is now present in just a few pages and those few pages you can give to anybody.

And so, this is a nice way in which you could carry all the information you could ever want on any book ever published in just a few pages. And that is a phenomenal nice experiment of thought that he was able to put together and convey to us in his talk.

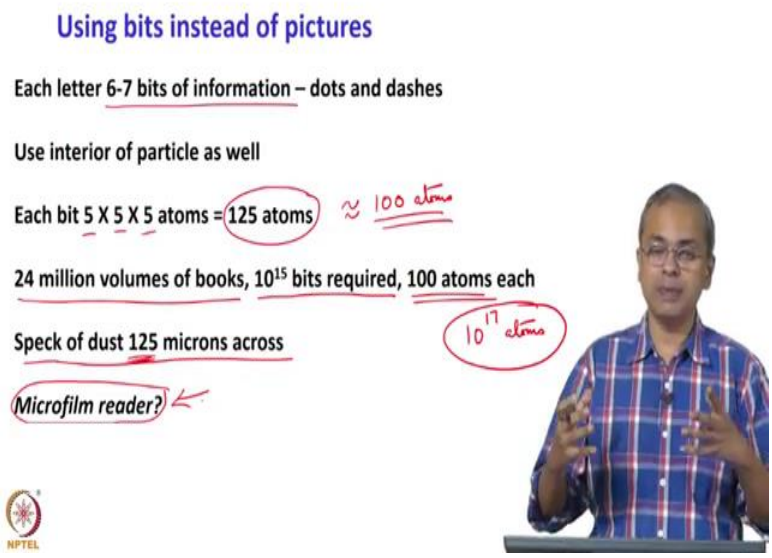
(Refer Slide Time: 33:03)



So, that is what I am indicating here his observation that a few pages will contain all of the books ever published. All of human knowledge would just be available in just a few pages and security of the information is very easy. So, you just have to even if there are a few copies of this anybody could be carrying these few pages and you would always have copies of it readily available.

So, that was the first experiment that he discussed then he goes one step further. So, this is one way in which you could do this encoding and one way in which you could collect all of this information and keep it, but he says let us now consider another way. So, he says let us consider another way where instead of actually writing each alphabet the way it is written in the book. let us use some coding.

(Refer Slide Time: 33:40)



So, that is the other way in which we would store the information. Today in computers that is exactly what we do we use bits of information. So, for every alphabet we do not; we do not write E inside the computer. So, if you have an SD card or whatever reader you are not writing ABCDE inside that you are sort of storing it in some bits and pieces, bits of information which you can then convert back to the alphabets that you want on your screen.

So, for each letter, he has 6 to 7 bits of information in the form of dots and dashes. So, that is what he says. And he says let us consider another thought experiment. Whereas in previously in the experiment with respect to the pin you are only looking at the surface of the pin and because you were writing on the surface of the pin. So, he says let us just consider a possibility that you can get into the interior of the pin also or interior of some particle.

So, and that you can store information inside the particle also incidentally even that is something that we are sort of doing these days we have multilayer storage where you store something on the top layer and we store something at a layer below it. So, that is also something that we have moved towards in modern era.

So, two things he has made changes with respect to his first experiment. Whereas, previously it was only the surface of the pin now he uses the interior of the material. In this case not necessarily a pin he looks at some other possibility and he also says instead of writing ABCDE in just that same manner you write it as dots and dashes which represent ABCD and e. So, he says for each bit let us assume that you have something that you can actually handle in a reasonable sort of way we have small cubes which are 5×5×5 atoms. So, 125 atoms approximately 100 atoms he says.

So, if you have 100 atoms you can safely secure a bit of information. You can have that bit and it will stay that way because you have 100 atoms there that is the reasonable amount of atoms. And so, then he looks at the 24 million volumes of books each the size of each individual volume being equal to a volume of Encyclopaedia Britannica.

So, if you look at 24 million volumes of books. And you look at all the alphabets that are present there and all the diagrams that are present there he again makes an estimate. So, again as I said that is very important for these kinds of experiments to be able to make estimates. He says you need about 10^{15} bits required. 10^{15} seems like a large number, but it is 10^{15} bits that is not, it is not a large number at all. It is a very small number 10^{15} dots is what you dots and dashes you need.

And we just saw that you need about 100 atoms. So, you add for I mean put 100 atoms for each of this. So, you basically need 10^{17} atoms. And if you look at one mole of a substance that is way more than this one mole of any substance is significant Avogadro number of atoms is more than this. So, if you it is more than the 10^{17}. So, you are actually looking at a very small number of atoms.

And he predicts that a speck of dust which is only about 100 and 25 microns across, just 125 microns across that speck of dust has these many atoms. So, that is all that you will require if you use this two-step process of encoding using bits and also using the interior of the material. These two things you add then you can store all the information ever gathered in human history at that point in time in 1959 all the information ever gathered at human history could be stored in a speck of dust.

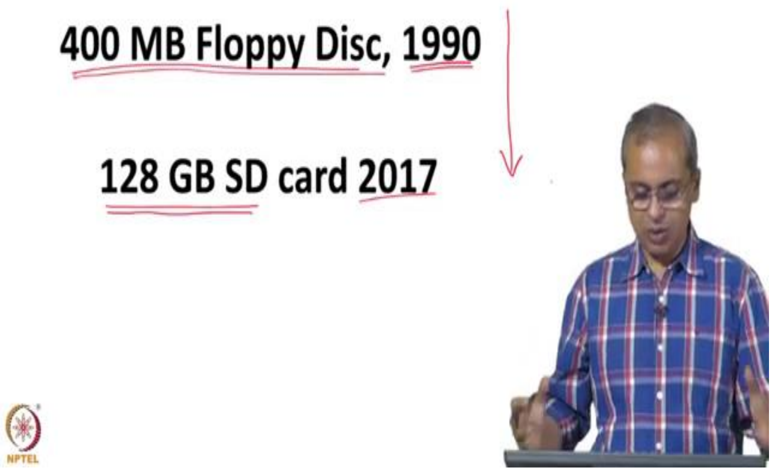
So, he moved from a few sheets of paper to a speck of dust. Going from the entire content being miniaturized to a few sheets of paper itself was a phenomenal sort of extrapolation or interpolation as you may want to call it. And then to go from that to a speck of dust is again a remarkable improvement in how well you are able to compress information.

And in fact, he jocularly compares it with microfilm reader which was very famous at that point in time, which used to be entire magazine or a journal would be converted to small black and white images on a negative kind of a sheet. A tiny once each maybe 1 centimeter by 1 centimeter or something like that. And then you could put it inside a reader where you will see through some glasses on top which would be sort of like a microscope this would just go underneath it.

And you could see it page by page you could read it page by page and note it down. That itself was considered significant miniaturization because an entire journal volume which could be otherwise quite thick and bound and quite heavy to keep would then become one sheet of paper. So, that was considered significant miniaturization where 1 volume of a book may be of 100 pages would become a single sheet of paper.

Now he is looking at 24 million volumes becoming a few sheets of paper and 24 million volumes becoming a speck of dust. So, he says there are the range at which the order of magnitude at which we are he is considering miniaturization is significantly different from what people would have seen when they were dealing with the microfilm reader which you, which was the way in which they were storing data in those days. So, this is with respect to data how do you store data? How do you read data? So, and do this with miniaturization. So, this is something that he did very nicely and explained very nicely.

(Refer Slide Time: 39:35)



And incidentally, things have moved on quite a bit since those days. So, even in our times scale, we see significant improvement in around the 1990 the kind of computer storage that we all used was about a 400 MB Floppy Disc which physically used to be something which was some square like that of that nature.

So, palm-sized something like the size of, a size of your palm was a floppy disc and we would students of that era faculty of that era would carry their data in it, it was not very reliable often data would get lost. So, you would have to keep multiple copies and but that was like a significant improvement for us that we could actually carry our entire thesis in a few floppy discs and then work with that.

From there we have now come to something from megabytes we have gone to gigabytes 128 GB SD cards are there in 2017 itself. They were available they are tiny ones; they are like the name fingernail-sized storage many orders of magnitude more than what was available in 1990. So, this miniaturization has been going on ever I mean he it has been going on all along he made some predictions and steadily we seem to have taken this direction. So, this is all with respect to data. How you get the data? How you miniaturize it? And how you keep it?

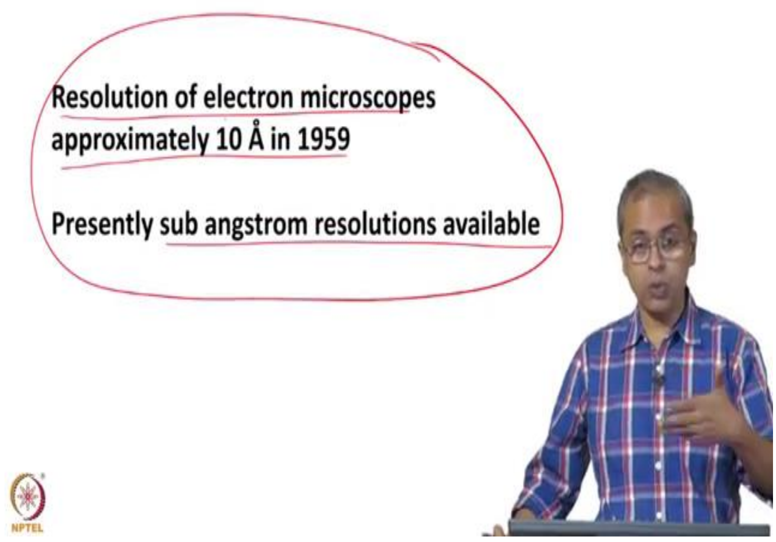
(Refer Slide Time: 40:55)

He also alerts us to the fact that although we are talking of miniaturization in this in the scope of computer data and information that maybe we read and do things like that, in reality in nature already miniaturization has been around for a very long time. So, all biological processes very large number of biological processes essentially display miniaturization. So, even the formation of life I mean birth of animals etcetera, including human beings we are essentially starting off as a cell.

And then from there it things multiply and there is a code they are not multiplying out of control. That is why we are all as human beings we evolve as our children are also of similar nature and so on. Every animal the offspring has the same look as the animal with some variations and so on. So, in other words, there is a code in that process that is followed when the copy is made with some modifications the copy is made and. So, that is miniaturization that is already existing at a scale well below what we could see with our eyes and it is happening.

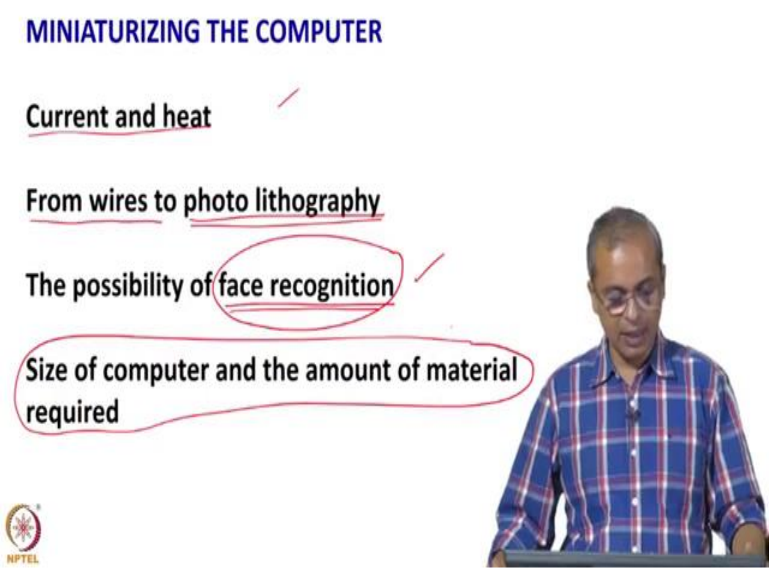
And so, this miniaturization has already existed in nature. He is just taking it further for something that we could put to general utility.

(Refer Slide Time: 42:10)



And as I said to read this information, he mentions that you need to use microscopes. In 1959 itself there were microscopes with 10-angstrom resolution available, today actually you have sub angstrom resolutions available. So, both writing this information, reading this information using it for biological applications are all possible with what you see here around today. So, that is the thing that we have to, I mean so that is a tool that we have at our disposal that we can utilize for all these activities.

(Refer Slide Time: 42:46)



So, now that you have with respect to data. What about the computing process? The computing process is another place where miniaturization has happened in a large way in the last several years and is also continuing seemingly endlessly in certain senses although there is seems to be some theoretical limits that we may eventually hit.

But again, this was something that was not really a major topic in the 1950. And again, he was the one who was very good at seeing were seeing the potential for miniaturization in the arena of computers and also seeing what needed to be done to enable this to happen.

So, the first thing was he pointed out that there is this huge issue of current and heat, that is there with computers. That was significantly accentuated in the olden day's computers because, in the olden day's computers, they were actually using wires to connect various things within the computer. So, lot of thick wires I mean wires, which would thin wires actually thin wires were used to convey this information.

And there were significant distances between various components and so, the signal had to go long distances during the process of computing. So, lot of heat used to get generated. And so, he in his talk predicts the need to go from wires to some deposited material which could act like a conductor and this is exactly what we do with the idea of photolithography. So, this deposited material is this idea of photolithography.

So, we will talk about that very briefly, but that is a prediction that he made which was very nice. Why do we need to have this physical wire and sitting over such a long-distance? you can make a deposit of the material which has all the properties of the wire. And therefore, we can bring components much closer you do not and you can wire them in a somewhat different manner.

And he says that there is a need to do this because if you want to do more and more computing, you will need to have lot of current moving to various locations within the circuit and the further apart these things are more heat will be generated and you may end up limiting yourself. You have to go to much smaller computers to enable all of this computing to occur without a whole lot of heat being generated and then you have the possibility that you can do complex computing.

And at that point in time, he again talks of something which today we are doing which is face recognition. He says that even though computers have evolved a lot at that time. And they had come to the where were computers which were taking few rooms or a few floors of a building, that was the size of computers in those days many of them could not do face recognition. In fact, they were unable to even something was the face of a person.

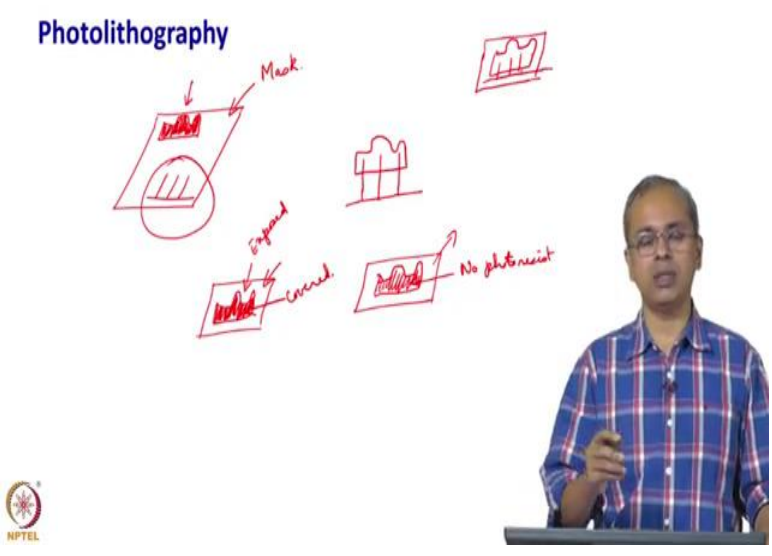
So, that was the rudimentary level at which those computers were relative to where they are today. And he says that if you want to do things like face recognition if you want to be able to say that so and so is this photograph belongs to so and so. You have to go a long way from the time at that point in time where it was not even able to say that it is a person's face.

Today if you actually see there are a lot of applications which run on your smartphone which do face recognition all the time I mean you can look at you tagged photos and then it is able to tag all photos a lot of things it is able to do. So, we have actually travelled down that path which is again a prediction of his. So, that need that you need this sophisticated computing to function. So, that you can do things like face recognition was something that he predicted and to do that you have to do something about miniaturizing the computer and for which again he provides a path. So, he makes a prediction and he provides a path which is all very nice about his talk. So, he talks about photolithography.

He also mentions that it is not simply about heat and ability that it can actually do something. He says even that in those days the computer was so huge that if you wanted to do the same kind of computing to enable these kinds of activities. You would need a massive computer which would consume a huge amount of material, the size of the computer would be huge and it would consume a massive amount of material. You may not even have that many resources you would start running out of material if you started creating computers of that gigantic proportions and they were consuming several tons of hard to get materials.

So, you have a lot of practical problems when you start making computers of that nature. So, therefore, multiple reasons why you would like to miniaturize it you can manage the current and heat better you can do much better computation. So, size and heat and computation activities and also the amount of material that you use would be significantly less.

(Refer Slide Time: 47:29)



So, what is this photolithography that he talks about? Photolithography is today used extensively in semiconductor industry; it is the way in which all computing components are made for your computer. So, basically, you will have a mask in which. So, it is usually a piece of glass very high-quality glass, on which you can draw various patterns.

So, for example, you want a circuit component to have this shape, in which you need three wires. And this going to go into some circuits somewhere if this is what you need.

Then a photolithography is a process where this same pattern is now converted into two patterns, one which has this and the other which is this object on top. So, you will have something similar. So, you have that and then you can take this and put it on some sample. You can place it on some sample. So, this is called a mask and what normally happens is you can actually put photoresist, it is called a photoresist it is basically some kind of a paint kind of a liquid which is sensitive to light.

So, just like you can expose it to sunlight and there are certain types of photoresist called positive photoresist and sometimes called negative photoresist. Depending on whether or not it will set because of the light or it will basically disintegrate because of light. And so, in either case, you will have a situation where after exposure to light some material will come away very easily, some material will remain. So, you can take a sample on that sample you can keep this part of the photo the mask on top of it. So, you will have that pattern here and then you expose it to light. So, this is all dark in colour.

So now, when you expose to light this dark area so, you first coat the sample fully with the photoresist. And then when you keep this dark area or this mask on top of it that dark area covers the one region of the photoresist. And now you expose that to light and when you a particularly UV kind of light when you expose it.

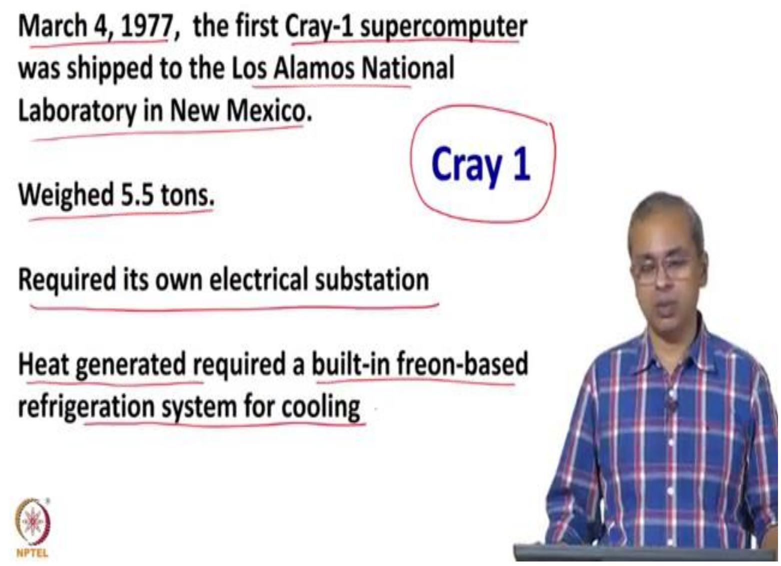
Then you will affect the exposed area. So, this region is exposed this region is covered. So, you; so, the photoresist has two regions, one region gets access to the light another region that is not have access to light. And it is such that after an exposure the photoresist sets and once it sets it does not come out easy. the kind of photoresist you have used. Now when you take this and wash it in some solvent you will find that your sample will look like this. You will still have photoresist outside, but this central part would have lost it is photoresist. So, the central part will no longer. So, no photoresist here and the rest of the place will have photoresist.

So, now, if you wash this and then you as you deposit another material that material will deposit in this region because this region has is open then you wash in another solvent this region will go away. So, you will now have a sample which has the material that you want in the inner location. So, step by step you basically do this. So, it is like a layered painting kind of thing that you are doing except that you are doing it in enough number of steps.

So, that you can get a layer of material at one location and you can keep the other locations free of that material. Same thing you will do with these lines here and that way you will get the lines here, you will get the lines here and that is how you make your circuit element. So, this is how you can make circuit elements using photolithography and this is exactly the process that is used in the circuits that we get these days.

That is why when you take a circuit these days you do not have you do not see loose wires you no longer see loose wires. And if you take an old mobile phone and you open it up or you take a computer and you look at what is inside you will see various carts that are present there. But you will not see any loose wires there because the wire is no longer in this format wire is in this format it is a deposit on that circuit. And this is photolithography and this is something that Feynman's talks about in his talk.

(Refer Slide Time: 52:22)



So, incidentally, I mean if you want to see the general scale of thing things March 4 th1997 the very first Cray 1 supercomputer was shipped to Los Alamos national lab in New Mexico. So, that was the Cray 1 and there are museums where you can actually see this original Cray machine. And it is fairly large structure it is several feet tall, quite a tall structure it is like a series of something like a few refrigerators kept side by side. And there is like a huge amount of wire that goes from one refrigerator to the other refrigerator you can see it will be like mesh of hair that is it is because they are thin wires like a mesh of hair going from one refrigerator to another and again a massive amount of wire going from the second to the third like that it could be.

And so, this is a these are available in some science museums if you get an opportunity you should take a look at it. It is very interesting to see, because it looks so, dramatically different from our current perception of what a computer is which is something so sleek, so light so easy to carry on a person. It is very dramatically different from our current perception of a computer which is something that is very light it is so easy for us to carry and carrying on a person and it does so many things for us. I mean so sophisticated and it is able to do a variety of applications for us.

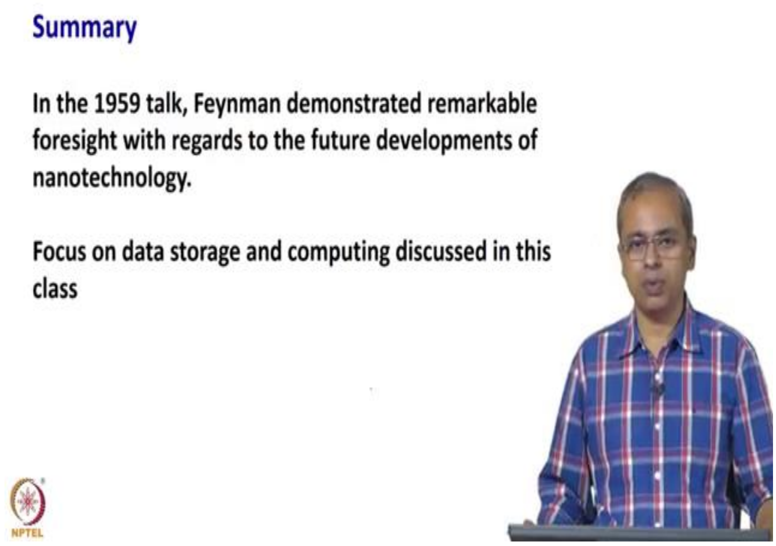
And if you compare that to this kind of supercomputer which it was there in 1977 and is virtually guaranteed to have much less capability than what we have in our, in computers that we carry on a person these days, that used to weigh 5 and half tons very massive piece of equipment and as was mentioned it would require it consumed a lot of electricity. So, it at that point in time it required a separate electric substation just to power that computer it generated a lot of heat massive amount of heat was being generated.

And so, it needed a built-in refrigeration system for the cooling process a built-in refrigeration system was required for the cooling process. Even today the highest end supercomputers one of the most major challenges for them is cooling. You would be surprised to know this, but if you look at this massively parallel supercomputers that people work on where you have like a huge hall in a building which is full of the high-end desktop processes that are present there and they are connected in parallel in some sophisticated way to operate.

In all of those computers and the current supercomputers cooling is still the major issue. And so, the flow of air-conditioned air inside the building is very critical. So, they spend a lot of time ensuring that there is sufficient flow of air to all the processors and sufficient cooling that is happening to all of the processes to keep the temperature down. So, that the processors can function correctly otherwise they generate a lot of heat.

So, air conditioning still continues to be a major aspect of high-end computing. Of course, what is high-end computing itself has dramatically changed. So, what was the top end of 1977 would not compare to anything that we have today. And today we are still pushing the boundaries of this computing. So, heat is one this is now we are talking of heat despite all the photolithography and so on. Because we are pushing everything is pushing limits and so, that is why we have this situation.

(Refer Slide Time: 55:48)



So, in summary in this particular class, we have looked at a section of the talk that Feynman's gave. He looked at various issues actually and we have only looked at a couple of them which was a significant part of his talk. Which is related in many ways to the computing aspect of it, which is both the data storage as well as the computational part of it. I mean although not formally connected that way in the top that is sort of what you can think of it as.

So, the first one was how you would store large amounts of data in small amount of space which is a very important step in computational systems. And there he looked at how you would encode how we would store data without any coding and also how you could store data with coding. So, both of that he looked at in the initial part of his talk and he showed how millions of volumes of information in more dramatically all the information that had been collected in human history could be actually stored very effectively in just a few pages of material without any encoding. And it could actually even effectively be stored in a speck of dust if you included no bits as the process by which you would do the encoding.

So, that is a remarkable foresight and ability to extrapolate where things were at that point in time to come up with this kind of miniaturization. He also looked at the possibility of what you could do with the computers, which could then be used to process such data and potentially do high-end computation. And particularly he predicts something about his ideas essentially are related to this field of photolithography which is exactly what we use today.

So, in all these ways that was a very revolutionary thought process from his side and it brings together many aspects of his personality, of clarity, of thought, of continuously asking questions and trying to explore things. So, with that we will halt in this class we will look at some more of his predictions in our next class and then build on things from there.

Thank you.