

Introduction to Nanoscale Materials Behavior - Why all the Fuss?

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Well, thank you Richard. This is kind of fun. That word, that little Greek word. That little Greek word means dwarf. A dwarf anything in sort of current parlance is anything that is a billionth of anything. So a nano is a billionth, its 10^{-9} . This is not nano 101, this is nano 201 and I am grateful to Richard. It is true that most of the people talking in this first session do not work in vision research. On the other hand, being sponsored by a vision agency is the highly appropriate thing to do because some of the people, not me, are among the most visionary of any of the people who work in the area of nanoscience. So, congratulations on putting together such a terrific program. My job is to provide the soft and squishy introduction. So, it's after lunch, we're in a resort institution, there are pictures of the sailfish on the floor. So, you can relax for this talk. What I want to try to do is nano 201, talk about what nano is and why all the fuss. Okay, we're over here. So, that's the menu. What is nano? What's so special about this scale? Why now? And what are the issues? Okay, so I'm going to start with some pictures that you can get off the web, which just relate to what the nanoscale is. And by definition the nanoscale is from one nanometer to a hundred nanometers. So, we're going to get there. We're going to get there not starting from down there, but starting from up there. What these slides will do for the next, I think 15 slides, each one is going to blow up what you are looking at by a factor of ten. Okay, so this is the southeast United States. That's northeast Florida and we'll go to the next one. That's been blown up and so what is 100 kilometers is 60 miles and that's northwest Florida. At ten kilometers we're in the state capitol which is Tallahassee. At one kilometer we're at the National Magnet Lab. That's where the highest magnetic fields in the world are available and lot's of great stuff is done there. But in each one, we are taking that simple thing and blowing it up on the next one to fill the whole space. Okay. So at 100 meters, this is a, an aerial view of the lake and oak trees. A hundred there is when the top of the oak tree. At one meter we are actually looking at the individual leaves on the oak tree. They, they clearly have some problems. But, I'll go down one more, 100 millimeters. This is actual size, okay so this is a 100 millimeters, 10 centimeters. This is the actual size. You can sort of see the central structure of the oak leaf. So, everything we have seen before has to be shrunk to get onto the screen and what we're going to see from now on and we're gong to do this for about seven more times, is going to be blown up in order to fit on the leaf. Okay. So at ten millimeters we're on the surface of the leaf, which has been enlarged ten times. At one millimeter, you can begin to see substructure. Okay. It's been a hundred times enlarged. You can do this with a microscope, clearly. At ten microns, I'm talking to a bunch of people who know about vision, so you know that this is about the frontier of human vision. And the unaided eye has no trouble seeing

those things. Sam Stupp and I don't know much about that topic, but some people do. And, that's the size of this whole screen. Okay, so we're looking at, at something that's a dimension of a human hair and it's 100 microns across. So we're looking at many cells and if we duck down, go down to ten microns, we're at the individual cell level. And at one micron, which is a thousand nanometers, we're at the nucleus of the cell. Now by definition, and the definition is silly, actually, by definition, the nanoscale is from one to a hundred nanometers. At 100 nanometers, what you see for instance, is the structure of chromatin. Okay, so these DNA strands that are so wound up on top of one another. If we go down to ten nanometers, you see the individual double helix strands of the DNA. Of course, these are computer representations. They are no longer pictures. And at one nanometer you are at the length scale of individual atoms and molecules. And that is why the fuss. The fuss is because this scale from one nanometer through ten to a hundred nanometers is the design scale of nature. It's the scale at which nature built us. So, this is the, the, as I said, by definition what people normally mean when they talk about the nanoscale. They mean the scale from a hundred to one nanometers and there are nice things in there. There is flu virus, bacteriophages. These are actually synthetic systems, so these two are obviously naturally occurring systems. These are synthetic systems. We'll hear a lot more about synthetic systems today. But these are very simple synthetic systems. They are just gold nanoparticles. There is a big one in the middle and some small ones around the outside. You can get smaller than that. This is actually the world's smallest abacus. The little structures that you see there are carbon-60 molecules, bucky balls. They look just like soccer balls but they are made out of 60 carbons. So, this has been magnified 15 million times and you can get on the IBM website and to the accompaniment of their music you can actually move these things back and forth. So if you know how to use an abacus, you can add or multiply numbers in Zurich on their website. Now the interesting thing about this is, well two things. One, how do you manipulate these things? Stop and think about that. Normally, with abacuses you manipulate them with your fingers. You can't get your fingers down to that size. You can't even get your hair down to that size. How are you going to manipulate them? That's one interesting question. The other interesting question is what happens down below here? Smaller structures like individual atoms, which are one-tenth of a nanometer, or atomic nuclei, which are smaller yet. That's not the nanoscale. That's sub-nano and we're not going to talk about that because that's not the scale in which the science and technology are done. Okay. The standard argument about why people care about this is computing. So the real abacus, about 2000 BC, and it's pretty macroscopic. That's the first general-purpose digital computer built at the University of Pennsylvania in 1946. Some of us remember seeing machines vaguely like this anyway. This thing used enough power to power 75 thousand houses and while the computer was running, of course, the vacuum tubes were burning out and so that guy's job was to run back and forth and replace the vacuum tubes while the computation was going on. What makes computing work, of course, is that they have been getting smaller and better since that time. So, Cray supercomputer is about 20 years ago. Again,

we are going smaller and smaller and smaller as the functional element. Here it was the magnetic core. Now we're clearly, now is ten years ago, we're at the level where everything is extremely small, thumbnail size or smaller, and more efficient and faster and cheaper and more reliable. So, it's not just that it's small, it's that it's small, it's different and it's better. And that's the standard reason people give for why nanotechnology. That's not the world's best reason. This is a form of Moore's Law. Moore's Law says that every 18 months the amount of square footage you need for single field effect transistor goes down by a factor of two. And so this is the historic trend. This picture from a guy named Stan Williams at Hewlett Packard, actually, and he gave it to me in 1999. So, a lot of this is sort of predicted data then. But you see where that dotted line is. It's exactly at 10^{-1} microns, which is a hundred nanometers, which is the beginning of the nanoscale. So, Stan's view at that time was that when you got to around 2013 or so you get to a size here where you can no longer use classical physics. You had to use quantum physics. And everything was going to get more complicated. And if you work for Hewlett Packard this is important because your company is going to go under if somebody else is able to do this and you're not. This is Moore's second law. Same guy, Gordon Moore. It talks about how much it costs to make a computer. Now we know how much it costs to buy one, but they make them in places called fabs, which are fabrication plants and the cost of building one of those is also moving exponentially up. So, as I said, I got this in '99 and that was the prediction. We're right on scale. That's basically where we are there, between 12 billion or so. The prediction was then there would be 50 billion in 2010. Nobody is going to build a plant for 50 billion dollars so something else has to happen. There has to be a change and the change has to come from designing at the nanoscale. So this is the Alumni Magazine from my institution and it says "Small is Big: The Amazing World of Nanotechnology". As Richard indicated the Feds have stepped up to the plate, starting with the Clinton administration. They have been pretty good about increasing American support for research in this area. We now have just about the same magnitude of support as Japan does. And so my institution, among others, got into this in a big way and they did this in the Alumni Magazine and then they began constructing structures to do research in the nanosciences. So this is the first nanoscience structure built at Northwestern. The guy over there is the Director of the Nanoscience Center. His name is Chad Mirkin and I'll talk some about his research later. That was actually Chad's office for a short time. And that was where the computer center used to be. Nobody has computer centers anymore, but that's where it used to be. So, this is the building that's there now and that's, it's called the Center for Nanofabrication and Molecular Self Assembly and stuff goes on there. So, we've talked about what nano is. Nano is basically a length scale. It's a length scale for inorganic and organic materials and I'll talk about both, actually. So, what's special? Well, we know what's special. It's the design scale of nature. Let's talk a little bit more about what makes nanoscale so exciting and so interesting and why it appears in places like, boy, Spiderman and Prey and places like that. It's a special kind of small, that's why. I've already indicated the fact that it's the design scale of nature. Individual atoms and

molecules are of the order of one nanometer in size. Some of them are a little smaller like water. Some are a little bigger like DNA. But that's the length scale in which most atoms and molecules work and since we're made out of atoms and molecules, it's pretty important to us. But it's also small because not only are these objects of a particular size, but they exhibit particular quantities and in particular, they exhibit self assembly. So if I look out at you guys and you look at your fingers, you don't see crystalline material, right? You don't see salt. You don't see metal. You see organic material and the organic material is almost always self assembled. It's not directed assembled, it's self assembled. And it self assembles to form unusual and wonderful behaviors. We'll hear lots more about this. But let me just preview a little bit. This is from Sam Stupp's lab and he will talk about this later today. But, I show this as an example. This little molecule, which is called a peptide amphiphile, is designed in such a way that under certain conditions of pH and salinity, it assembles to form this log like object. Now this is not science, this is Powerpoint science because what you see here are a bunch of pictures, right? And I could have said that it's going to twist itself to form, I don't know a golf club. But actually, it does form linear structures and you can see that from these micrographs. And Sam will talk a great deal more about this and some of the applications. The point I am trying to make is the assembly process is not crystallizing. It's self assembly. These molecules come together to form objects and those objects, which are larger objects, are in the nanoscale design. And, of course, that's how we work. That's how proteins fold and how bodily tissues are made. Now I said before that when you get down to the nanoscale you're really small. You can't see it. You can't see it with most electron microscopes. You can't see it with most methods, actually. You can use x-rays if they are crystalline, but they're not crystalline. So how do you see these things and how do you assemble these things? How do you move the C-60s on the abacus? Well, you move the C-60s on the abacus using these things and these are called scanning probe tips. And although lots of people claim to have invented the word nanofabrication or nanoscience or nanotechnology, the word is Greek. So, nobody gets any credit for doing that except the Greeks, I think. But these guys at IBM, Binnig and Rohrer, who invented these tips, really started this whole business. So the tips, these particular ones, are made at Northwestern and they're made of tungsten. But the point is, on the end there, the radius of curvature is a couple of nanometers. So these tips are the ones they use to assemble that abacus and they are also the ones that you can use to move the abacus around. And it was the invention of these that allowed people to understand what's happening at the nanoscale. The best way to do that is close your eyes. Take your finger, put it on your sleeve and move it with your eyes closed. Move your finger down across your sleeve. If you're wearing a watch, it's really good. Go over the face of the watch and then onto your skin. And what you'll feel is that it's a completely different resistance that you're feeling at each place, right? So, even if you couldn't see what you were looking at, just feeling and sensing the force that's dragging you back will tell you something about structure. That's what atomic force microscopy does, using those tips instead of your finger. So this is the, this was the insight, this was the development that

really started the entire area of nanoscience and nanotechnology. Now what can you do with those things? I told you that you can make things and you can measure things and you can push things around. Now my colleague Chad said "Okay, look. I know how a fountain pen works. A fountain pen works by having ink on a tip and writing on paper. Suppose I use instead of an ink pen, a really ultra fine nib, ultra fine at the level of nanoscale. What would that do?" Okay. So the similarities between this pen and that pen is that they both have an external ink reservoir. The differences are basically that this one is a hundred thousand times smaller than that. And if it's a hundred thousand times smaller, then the line that it draws is going to be a hundred thousand times smaller too. So what you see here is a drawing. Actually, this was produced using a program called WordPerfect which some of you know. And it was drawn using WordPerfect, but it wasn't drawn using your standard typewriter or it wasn't drawn with your standard printer. It was drawn with this special printer that we just talked about. What this is is the text of the speech that Richard Feynman gave in 1960 about nanoscience. And he says basically that there is a device on the market by which you can write the Lord's Prayer on the head of a pin, but that's nothing. That's the most primitive halting step in the direction I intend to discuss. He says by the year 2000 they'll wonder why it was done until 1960 that people thought about moving in this direction. What is this direction? This direction is assembling things bottom up from molecules and atoms, rather than top down by tearing away the marble to make Michelangelo's David. Now this is really pretty small print. You might be able to read it from the first three rows. You can't read it if you are in the back. But the letters are small. That "l" is 60 nanometers across. The "d" is 40 nanometers across. This entire little statement here is really very small. In fact, it's so small that if you could write in letters this size, you could get on your average piece of paper that is sitting in front of you, you could get ten thousand sets of the Encyclopedia Britannica. Now, would you want a piece of paper with ten thousand sets of the Encyclopedia Britannica? Probably not. But there are lots of places where people like to write things and encode things at a very small and reliable level. Let me mention just one that clearly relates to this. And that has to do with security. Alright. So I take Lipitor and I go out and buy Lipitor at my pharmacist's every once in a while. But if I'm out of the country I'd get it at a different place or maybe I'd get it over the internet. How do I know it's really Lipitor? So one of the things the pharmaceutical companies are very interested in is security of their product. So, if you buy something it's really what you think it is. And there is some concern obviously in the Congress about internet pharmacies and what kind of safety risks might be available to you there. When you buy something like this how do you know that it's really what you think it is? So one of the ideas that most of the companies are now very much seriously interested in is using something like the lithography that I just showed you which Chad called dip pen nanolithography. Using something like that to assemble structures at the nanoscale. In this case, to assemble codes at the nanoscale to tell you where you are. To tell you for instance that it's Lipitor and not something else. So, that's one technology for fabrication. Oh, I just wanted to mention that some of the stuff is visionary, some is not. This stuff is actually on

the market. You can go out and buy it. Okay, so we've talked about a special kind of small. We talked about the fact that it's the design scale of nature. We talked about the fact that these structures self assemble. The other thing that is interesting about it is that at the nanoscale there are size dependent behaviors. The way I like to think about this is if you take a gold ring and chop it in half you end up with half a gold ring. But it still has the same color, the same melting point. Everything is identical about it except it is smaller in size. If you did that, not once or twice, but 40 times, you'll get down to the nanoscale. And then the gold changes color. What used to be gold can become red gold or blue gold or green gold. And this has been known for a very long time. Stained glass. The very best stained glass has a great deal of gold in it and a lot of colors don't come from different pigments, they come from gold, gold of different sizes. The technology to do that was worked out in the Middle Ages. They didn't know what they were doing. They certainly didn't use the word nanostructures. But that is what they were doing. They were making particular assemblies of gold and different colors come from the different assemblies. Here is an example. This is some work again from Northwestern. This is from Van Dyne and Mirkin's labs and what they did here is silver and gold particles. But let's just talk about the silver ones. So there is a sort of dark blue silver and there is a sort of light gray silver. There is an off-yellow silver and there is a red silver. They are all silver, right? So, what's the difference? The difference is the sizes. These are silver spheres of 40 nanometers, these are 80 nanometers, these are 120, and these are prisms which are a little more interesting. They are about 100 nanometers. So the point is there is something special about the nanoscale. And one of the special things, one of the things that makes it more interesting than just another size is that at this size things can become size dependent in their properties. As I said, it's not new. This is a Chinese art glass vase that was made a couple of hundred years ago. And it's got, if you do the analysis, these little gold nanoparticles in it. Now, again they didn't know that's what they were doing but that's what they were doing. Now why does that work? Everything else that I am going to talk about is basically just what's out there. This is the only sort of explanation that I am going to talk about. The reason it happens is something called plasmons and this has been known for a long time. The way to think about it is if you get a big bell, it makes a low noise. Make the bell smaller, the noise goes higher in frequency. The reason for that has to do with the size of the bell compared to the wavelength of sound that it's generating. So as the bells get smaller and smaller and smaller the wavelengths get smaller and the frequencies get bigger and so you hear a higher pitch. That's exactly what goes on in these gold dots, okay. But the bigger the gold dot, so the bigger the gold dot there, the redder the light with which it interacts. So it's the same thing except it's light instead of sound. And these things are called plasmons rather than phonons. Now is that interesting? Yes, it's interesting. Is it new? No. I said people knew about it in medieval times. Scientifically the great advances here were actually made by Michael Faraday back in the 1820s, '30s, and 40s when he prepared what he called gold colloids. Now you would call them gold nanostructures. This is some work from Chad's lab and I mention it because we're talking about not

only nanoscience itself, but the technological applications of nanoscience. In this case the idea is can you use nanoparticles to sense bad stuff? Bad stuff because of who funded it, but it could be good stuff. We could be sensing antibodies for example. In this case he is trying to sense target DNA. So this could be the DNA from anthrax and the way it's cartooned here, this particular target DNA has a blue section and a red section. And, of course, the way DNA works, these are single strand and there's a complementary strand. This gold nanoparticle is functionalized with complementary strands to the blue structure. This gold nanoparticle is functionalized with complementary strands to the red structure. So, if and only if, these little targets are present, what will happen is that they will move around. That the red will bind with the red side. The blue will bind with the blue side. And when you are finished with this what you actually have done is to bind these gold dots closer together by the presence of the target. And what that does is to change the color. So you don't have to be too smart to see that is with the target and the color is sort of this vermilion color. Without the target, it's this bluish color. Now this, this analysis is made with gold nanoparticles, so it's expensive. It costs about four cents to do this. The reason it's only so expensive as four cents is that you are not using much gold. It's nanoparticle gold. So this is a combination of 20th and 19th century science right there. The 19th century is this business about gold changing color when you bring the golds together. The 20th century is complementarity of DNA. But this is a sensing technique, a sensing modality. And again this one is not just a laboratory phenomenon. You can even buy these things. These are systems that are for sale and used in hospitals to try to do diagnoses using this kind of methodology. Okay. So we talked a little bit about what the nanoscale is. I've talked about what's special about the nanoscale and why people care. Well, what are the issues that are out there? It's now 2005. Michael Crichton's book came out about a year and a half ago. The movie is going to come out probably this year. What are the issues and why now and what's exciting about all this? Richard indicated that there is a lot of money out there. In 2004, the federal allocation was around 980 million dollars for research in nanoscience. This number, the 1.2 trillion dollar number, is a number that comes out of NSF as the projected nano sales volume in the United States in 2015. Now these projections are very difficult to believe. What I think is true is that it's going to be tremendously important throughout this society and I think it's important not because of any particular single thing, but because this way of making stuff is the way nature makes stuff and it's going to allow us to do many, many things in materials and in medicine in particular. Materials and medicine are the first two places, but I think that it will be in more places than that. I'll give you some examples in a minute. There are 38 states at the moment in which the state government is appropriating funding to try to invest in nanotechnology because most people tend to feel that this is going to be the next sort of major wave of scientific progress that leads to commercialization after high tech and biotech. I think that it's a little bit different. I think it's more like the Industrial Revolution. This is a new way of making stuff. Not something particular, as in high tech, but something more general and more generic. So, right now, today, the two biggest nano products from the point of view of dollar volume, one is

something called GMR, Giant Magneto Resistance and that's what makes your hard drive work in your computer. And it's a technology involving nanoscale magnetic dots. That's about 50 billion dollars a year. This one is probably more because you've noticed the price of gasoline going up. But this is catalytic cracking of gasoline. It's actually used very broadly. It says 60 percent of the gas in Europe is made this way and 40 percent of the gas in the United States is made this way. The zeolites are alumino-silicates and they have these little pores in them and what you do is you expose the pore to a petroleum feed stock and what that does it to catalyze, using transition metals, the breakup of these large molecules into the small molecules. And because of the particular shapes of these pores, you can favor particular forms of the product. So, for example, you can increase the iso-octane, which is the one you want compared to the n-octane, which is the one you don't want. This was developed at Mobil about three to five years ago and as I said, it's a huge, huge industry. We're talking here about, surely tens of billion of dollars. You don't know about it because it's not called nano, it's called Exxon-Mobil or it's called Shell. But, that's what it is. It's nano. I was a post-doc in Denmark and if you're in Denmark you're told the Niels Bohr did everything that anybody has ever done that was important. And in particular people attribute him to all sorts of wise sayings. Bohr spoke Danish. He smoked a pipe and he always mumbled so you could believe he said anything. But, but predicting the future is difficult and you know, it's one of those things you get asked to do from time to time. Let me try to talk about what's out there right now rather than predict the future. So, clearly there are people are hyping the nanoscience business. Let me show you a little bit of this. This one comes from Forbes. Now Forbes is not known as a hyper, I guess, but they started this little thing called Nanotech Report way back in 2002 and it says "Premier issue, nanotech report. A new world is born". Okay, so what's the new world? The new world is what we're talking about. And of course they were talking about it from the point of the investments and finance. This one comes from a magazine called Red Herring and I think that's a well-named magazine. What this tells you about is advancements in science and technology lead to massive wealth creation. Textiles, railroads, automobiles, computers, and that says nanotech and it says it starts around 1997 and it comes to fruition about 2081 and I won't have to worry about that. But this is the information revolution, right. And what they all say is that nanotech is an enabling technology like the computer, the automobile, the railroad, the textiles. And I think that's basically right. It is an enabling technology. And it's enabling technology to do lots of things which is what we're going to hear about for the rest of today. Now I'm not funded by NIH. I get funded by NSF and DoD and normally when you get funded by those folks they are always interested in devices, you know. What can you do for us in the device area? So, when you're asked to give a talk on nanotechnology, you go on and think about what devices can I go out and buy? What can I walk out of this convention and to get the security fence, go into Fort Lauderdale, walk to a store and buy that's a nano object? Well, there are quite a few. So, that's one. That tennis racket is made Babolat. It costs about 450 bucks and it says right there VS Nanotube Power and here it says that carbon nanotubes stabilizers increase the torque and flex

resistance of that tennis racket. And carbon nanotubes cost now ten to a hundred dollars a gram so you're not getting very much carbon nanotube in that tennis racket, but I guess you're getting enough that these people thought that they could sell their tennis rackets as nanotube enabled. If you don't like that end of the court you can go to the other end of the court. This one I do know about. This goes back to 2002. What Wilson did is actually to put nanoscale clay flakes inside the latex on the tennis ball. So what the nanoscale clay flakes do is provide a better barrier. The reason tennis balls go flat, obviously, is air diffuses in and diffuses out of the tennis ball. So what they have done is to make a nanoscale composite and I haven't mentioned composites before, but they are going to be really important, nanoscale composite in the tennis ball, which prevents the air from going in and out so rapidly. So, in fact, they are high tech tennis balls that are nano enabled. We're in Florida and people play tennis down here. They do other things, too. This is another nano thing that you can actually buy. This is from the BBC a couple of weeks ago. It says "Nanotechnology: Building from the bottom up" and then it says here "The cosmetics industry already puts nanoparticles into lotions, creams, and shampoos. Nanoscale zinc oxide particles are used in sun creams." And then it says "The particles are particularly good at absorbing ultraviolet rays, but make the lotion transparent and smooth instead of sticky and white." I think that what they are using here is the old stuff because it looks sticky and white to me. But the point is that it's everywhere. I mean it's in the pants you wear. It's in the lotion you put on to keep the sun away. It's in the tennis balls you play with. And it's going to be inside our bodies fairly soon. So I said that Bohr said that predicting the future is difficult. It is sort of interesting to think about this. The Director of the U.S. Patent Office, actually the date is wrong, it is 1909, not 1929, but he basically said you might as well shut the patent office down because there is nothing left to invent in 1909. I like this one. This is Thomas Watson, Sr., modern founder of IBM who said "A few computers should be enough for society". The Surgeon General in 1959, "Infectious disease is now history", so he got the grammar wrong as well as his fact. This is the one that really gets me "640K should be enough for everyone". That's Bill Gates, 1982. So, predicting the future is difficult. But there are targets out there, I think, for nanoscience and nanotechnology. Some of them are obvious. Something like, well there are two of them that are obvious that are out there right now. Greaseless suntan lotion which we just talked about. Stainless ties for soup spillers. Basically, you can go and buy nano pants, nano shirts, nano ties, nano everything else. What they really are is they are impregnated with nanoscale fluorocarbons. So basically, they are teflon. But they are not macroscopic teflon like cooking pots. They are nanoscale teflon and that means that they don't have the unpleasant sort of physical properties. They don't feel bad. They feel pretty good. But they also work. So if you go buy Eddie Bauer nano pants and you spill ink on them, it doesn't stain because it just basically wipes off the fluorinated interface. So those two, who are in black, they are out there today. There are much more interesting things. Let me just point out a couple of them. Heatless light. Heatless light. Almost all light that we are familiar with is either incandescent light or fluorescent light and in both of those what's

involved is getting things very hot. In one case you're getting tungsten very hot and in the other case you're basically warming up a gas which is bounding into phosphorous. But you could imagine doing light in other ways. Light emitting diodes are the first place that I saw those. When I came in here today Craig was showing me around the AV equipment and he used this little light emitting diode structure. Light emitting diodes emit radiation not through heat, but through excitation of the electrons directly. And that's one that's a little, how should I say, less obvious, maybe less striking. One below that. Truly efficient solar radiation capture. Gas, I saw on the way in here today is \$2.29 a gallon for self pumped regular in Florida. We've got to solve an energy problem that confronts not just our society but the world and we have to solve it in a ecologically serious way. One way to do that, as Richard Smalley says is to capture fusion energy from the fusion source that's 93 million miles away and is not going to pollute the earth. Right? There is plenty of sun, we just don't know how to capture it. Probably devices that will permit that are going to be nano based. Human repair is something that Sam Stupp will talk about later today. Trying to use nanostructures to do things that could involve diagnostics. So, for instance a five minute health swab test, an integrated test, in which some cells are removed from the back of your tongue and not only could you find out whether you had, I don't know, strep or not, but you could find out about your whole genetic background. In fact, genetic medicine, individual genetic medicine, is going to have to be based on nanoscience. There are a lot of big targets out there on the technological end. There are some concerns though that go beyond nanotechnology and these are important. And most of them happen to start with "e". The two that don't are health and safety and security. Alright. Are nanoparticles good for you? What is the toxicology of nanoparticles? We know that black lung disease came from finely divided carbon. And asbestos clearly causes cancer in lots of people. Well those are relatively large compared to nanoscale, but what are nanoscale particles going to do? Are they dangerous? What is the toxicology? We really don't know a lot about that. Lots has to be done there. Security. You know what about secure aspects about manufacturing, secure aspects of destruction. Then all the "e"s. Education. What's this going to mean for education? I can tell you one little story. At the University of Copenhagen last year more entering students chose to work in nanotechnology than in chemistry, physics, and biology put together. So the students have figured it out and we probably need to. The environment. What are the environmental implications in nanoscience? Good ones like solar radiation capture and possibly bad ones. Economics. What does it have to do with globalization and training? Suppose you have one country whose people are nanotechnological adept and another country whose people are not. What does that mean for the manufacturing sector? What does that mean for the economics of the country itself? And of course, there are huge ethical issues. Ethical issues, in particular I think involving privacy and equality because if I have a nano enabled spy system that will allow me to paint your living room with sensors that are going to tell me everything that goes on in your living room, what's that going to do for your privacy rights? What about equality? These are big issues. They

are not issues that are normally discussed but since today is supposed to be about nanos altogether I thought it was worthwhile mentioning. So, the predicting of the future is difficult. I've shown you some people who didn't predict the future properly. I've shown you some pretty optimistic and a little bit of pessimistic view of what nanoscience will do. David Thoreau was 25 years old when he wrote Walden and this is the last line from Walden, actually. I think that's where we are in the nano business. We're at the point where we understand a lot of the fundamental science. You'll hear about that today. We're at the point where applications are beginning to appear. I showed you some. You'll hear about more of those today. We're at the point where we're asking big questions about how these little nanostructures, which are largely synthetic, interact with larger structures, which are largely non-synthetic. We would like to be able to control that. We'd like to be able to use that to make these things not just laboratory curiosities, but things that could really have something to do with the way life proceeds. So, I think Thoreau basically had it right. That's always true in all fields of science but I think it's particularly true at the moment in nanotechnology and I hope this will become clear as the day goes on. Thank you.