Bucky Balls, Fullerenes, and the Future:

An Oral History Interview with Professor Richard E. Smalley

January 22, 2000

Nanotechnology is the art and science of building materials and devices at the ultimate level of finesse: atom by atom. Like a tiny poem with every word and space wisely placed, a thing built by nanotechnology has every atom in its place, and never two where one will do. . . .Today we begin a collaboration with NASA to develop a new kind of nanotechnology, one that starts with a perfect carbon structure that biology cannot make: fullerene nanotubes and fibers. The promise of this new technology is vast: cables 100 times stronger than steel at only one-sixth the weight and with the electrical conductivity of copper, nanocomputers of vastly greater speed and power in dramatically smaller packages than possible with the current silicon-based microtechnology, new batteries, fuel cells, solar energy devices, composites, sensors, nanomachines.

--Richard Smalley, Remarks delivered at a signing ceremony for a cooperative agreement between Rice University and NASA, Oct. 15, 1998.

Interviewers: Robbie Davis-Floyd and Kenneth J. Cox
Interviewee: Richard E. Smalley, PhD, Hackerman Professor of Chemistry and Professor of Physics, Rice University, and Winner of the 1996 Nobel Prize in Chemistry
Interview date and setting: Jan. 22, 2000, Rice University, Houston, Texas.

We are walking down the hall toward Smalley's office at Rice, and on the way we stop to examine a set of posters hanging on the wall. The first poster we look at shows a long cable extending from the earth to a satellite in outer space. About the poster, Smalley comments:

SMALLEY: It's an artist's impression of a bucky cable that extends all the way down from geosynchronous orbit to the equator. *[laughter]* Of course the scale is wrong. It would be farther away. The idea is that a cable made from bucky tubes would be strong enough and light enough to support its entire weight being hung from geosynchronous orbit. Now, of course, in order to hold it, you have to put force from the other direction, so there has to be cable that goes way on out into space for some counterweight, so that the center of mass would be in orbit. This was on the cover of an issue of American Scientist in 1997.

In fact just last week I fedexed a couple of copies of this to the White House because Clinton, in his remarks on Friday Jan. 21 at Cal Tech, was supposed to say something about super-strong materials. They had called us to check the numbers and they asked if there was anything written about this. So I sent them something. I don't know whether it ever got to Clinton's desk or not, but it's a rather dramatic indication of how crazy things can be if these nano dreams became a reality.

Explaining and Imagining Nanotechnology

Arriving in Smalley's office, we seat ourselves at a comfortable conference table. Windows surround us, and through them, the tops of trees. Smalley's 1996 Nobel prize graces one of the window sills. It is a large piece of leaded glass framed in wood. Embedded in it is an azure stained glass replica of a bucky ball. The caption reads, "For the discovery of fullerenes."

DAVIS-FLOYD: I guess the first and most obvious question is "Can you explain nanotechnology? What is nano-technology and what are its implications for the human future?"

SMALLEY: My description of nanotechnology is very simple. It is any technology that builds things that do things on the nanometer scale. A nanometer is a billionth of a meter. A billionth of the distance from here to Los Angeles is about an inch, so a nanometer is about enough distance for three or four atoms to fill. It's a big enough distance so that if you make it the length of the side of a box, it would make a box of one cubic nanometer. In that box you can put in enough atoms to actually build something that is architecturally rather interesting.

The idea is that you've got these little balls. You must have more than a couple to do something interesting, but you don't need more than 20. How much space that takes is about what would fit inside one cubic box. It's as though you're playing with a tinker toy set. In order to build something interesting, you need to have a certain minimum number of tinker toys and a desire to tinker.

As you probably recall from your childhood, tinker toys consist of lots of sticks and lots of little discs with holes drilled in them. You stick the sticks in the holes, and branch out from there. In this metaphor, the discs are atoms and the sticks are bonds. If you only have two of them, there's not a whole lot you can do. Likewise with only three, or only six. But if you have ten or twelve, you can make axles and cars. If you have 50 or more, you can really make something cool. But if you have 500, that's not necessarily better or cooler than having 50. Even with ten, you can do a lot. At ten, you start to get an emergent property: above a certain level of complexity, the system behaves in a way that cannot be anticipated from the individual properties of the elements.

The first Christmas I remember from my childhood, my dad had bought me a tinker toy set and had built an elaborate windmill. I came down the stairs, and there it was under the tree. I was dazzled! So today I ask, when humanity comes down for Christmas, what is the tinker toy set beside the tree? It has atoms in it, and there are only two naturally occurring kinds, of a certain size, and they are all a bit different. Those are the smallest things we have to play with here on earth, and they include energies of the strength of a normal chemical bond and temperatures of no higher than 10,000 degrees.

If we were inside a star, we would have something different to play with. There are smaller particles, like nuclei and quarks, but they are irrelevant to building gadgets. The amount of space you need to build something interesting in our universe with ordinary energies is one nanometer in size. I point this out to head off questions of when will there be a "pico" technology—will there be something even smaller? There won't be, because atoms have a fixed size and that won't change, and that minimum length for interaction between atoms turns out to be a nanometer. So chemistry is getting to the point where it's building things on the nanometer scale. That is really the frontier of chemistry.

Chemists are proud to tell you that we're unique among the sciences in that we create the very nature that we study. In many cases the molecule that a chemist synthesizes has never existed before. We chemists are fundamentally builders and architects.

DAVIS-FLOYD: Is that what differentiates chemistry from biology then? Biology is more about studying what is in nature and chemistry is more about constructing?

SMALLEY: Well, that's certainly true. Chemistry is rather unique. It's also the one thing that differentiates chemistry from physics. All the core sciences—physics, chemistry, biology, here at Rice are in the School of Natural Sciences. Why do we call them "natural sciences"? I suppose it means it was once thought that nature is something that's "out there" and we're somehow "over here." And scientists are people who are educated and trained to go out there, write down what they see and come back and tell the rest of us about it. The historical perception is that there is an objective reality out there. Most scientists are basically reporters—they describe what's out there and come up with grand theories to systematize what's out there, which leads you to believe that the sciences aren't very creative. In that sense, chemistry has always been sort of strange because many things that chemists came back and reported to us actually weren't out there before they went there.

I'm trying to think of examples. Any metal that is refined from its ore is an object of artifice, so that in naturally occurring metals, there are very few that are there in their reduced state. Almost all of them are oxides. The first metal refining was done in a campfire, by accident when some of the charcoal wood got close to an oxide ore, iron oxide maybe, and the combination of heat and the carbon reacted with the iron oxide and made metallic iron.

Since the middle of the last century chemistry has long since been a completely artificial art, building structures, pretty much like tinker toys. Some are built because they're known to exist, in plants for instance—biologically or medically active drugs that would be remarkably expensive if you had to go and extract them from plants. We learned how to build them from scratch. So we've always had that unique and privileged position in the past, but since about the middle of this century and particularly near the end of the last century, even physicists were building things that never existed before. Even though, in many cases, the reason they were building them was to get at the fundamental laws of nature, the things themselves were new objects.

DAVIS-FLOYD: How is nanotechnology new?

SMALLEY: I'll get really fundamental. I spend most of my time arguing that it's *not* new, that it's really a bold version of what's old, something that we can now talk about seriously, something that we can actually do in a short period of time, because of the capacity that has been built up over the decades, the development of fundamental science. But as we begin to build these things, we will be able to do things we could hardly have dreamt of.

DAVIS-FLOYD: For example?

SMALLEY: For example, the dream of electricity, in the sense of electrical current flowing along copper wire—to bring that into the molecular "nano" realm of the living cell. That's what you see in those posters in the hallway—to build circuits where the signals move at nearly the speed of light with hardly any loss, and to do that with molecular perfection.

DAVIS-FLOYD: And why will that be a good thing? What will it accomplish?

SMALLEY: It will give us more gadgets. *[laughter]* Gadgets are good!

DAVIS-FLOYD: What kind of gadgets will it give us?

SMALLEY: It would allow you to make computers very much smaller and store vastly more information in something you can carry around in your hand. We are talking about molecular electronics. It would allow you to make, we imagine, computers with memories that are cheap, tiny, and vastly powerful. Computers and sensors and memories that could be small enough that you could even implant them in a human body. It probably will end up giving us a new life form!

DAVIS-FLOYD: Here we go!

SMALLEY: I can tell you want to go there, so let's go there. Even our current tools, like our cars and this tape recorder I'm holding in my hand, will get to be vastly more powerful as new powerful nanocomputers and memories and devices get developed. I suspect that even now these little objects have already begun to change what it means to be a human being. By another couple of centuries the little nanocomputers will have had their effect as well.

DAVIS-FLOYD: What kind of effect will they have? Carry the thought through—if you're going to implant these things into people, how does that change people? Are you talking about better pacemakers? Are you talking about altering the brain? Are you talking about creating artificial limbs that function more like human ones?

SMALLEY: All those things seem possible. It's hard to know where that stops.

DAVIS-FLOYD: When you've fantasized about it, what are your thoughts about how it will transform the human body?

SMALLEY: My major thought is that *I hope somebody's watching,* 'cause Lord knows where this is gonna end up. It looks to me like there's virtually an endless frontier of how the very meaning of being alive could change.

DAVIS-FLOYD: Is this going to be like the bionic man from TV from a few years ago?

SMALLEY: I remember that. I was not thinking so much about that. I suppose you could create this really strong guy that could do all these things.

DAVIS-FLOYD: People who are stronger and smarter than normal and could remember more, that sort of thing?

SMALLEY: Well, smarter and could remember more, I think, certainly. I don't know about stronger. There are mechanical limits to the sort of forces you can exert on muscle and bone and I suppose you could end up having a complete robot that replaces these things with carbon nanotube structures which of course would be much stronger than steel, but really I was mostly thinking of information and the whole issue of what does it mean to “think.” There's a whole question about artificial intelligence. I suspect that it will turn out that there's nothing very special about the human brain being able to be intelligent. It's a matter of the complexity and the speed and the circuitry and the way that it's put together that enables it. I can imagine that a millennium from now brains are no longer meat.

DAVIS-FLOYD: How do you get from building nano-tubes to imagining that they can replace the brain?

SMALLEY: I simply go home and have a beer then I can do it. *[laughter]* Let me tell you that I think it's still very much an open issue whether or not one can build a thinking computer. I will be surprised if it turns out that you can't, but until one does it and decides what really constitutes thinking, let's just leave it alone. If one can build it, it certainly would have to have nearly and perhaps more than the number of neurons and connections that the human brain has, which is something like a hundred billion. Everything turns out to be a hundred billion, so let me guess this number at a hundred billion. Of course, the way the brain works is something we don't, by any means, fully understand yet. Many people—I'm not one of them—are spending their lives thinking about different ways of making computers that can think, and I just don't see any limit to that, so I suppose it will happen and I suppose we are, to put in a strange way, God's way of making this kind of life.

DAVIS-FLOYD: A while ago I asked you what's new about nano-technology and you said you spend a lot of time trying to convince people that it's very old, that it's building on what has gone before. On the other hand, you're talking about massive quantum changes in basically everything that we do and fundamentally who we are that would be potentiated by nano-technology, so it seems that there's a lot that's new about it. Can you talk about that a little bit more?

SMALLEY: I'm teaching a course right now, a freshman seminar. We're trying to figure out at Rice what a freshman seminar ought to be. We rather think it's something where the students get experience giving presentations and engaging in open and deep debate with each other. I decided to take a topic that I thought would be fun for them, so the topic of my seminar is "the origin of life." I had to be lashed down to keep from saying "the origin and the meaning of life." *[laughter]* It's really delightful. Over half the students are musicians and philosophers and actually very few of them are freshmen but we're having a lot of fun. I just think it's fascinating what we've been learning, particularly the last fifty years about the machinery of life and reasonable scenarios for the origin of the universe. It's incredible the degree to which this universe appears to have been fine-tuned to allow something as complex as life to exist, almost as though whatever's going on, it might as well have been the purpose of having life, whatever the purpose of that is. So that sort of figures into this business about what happens in the future with computers and building intricate things that can think, with the level of complexity we're talking about.

As we were walking down the hall I was pointing out to you that a nanotube is a completely artificial structure and I guarantee you that it does not exist in human bodies, yet there is a way of dressing it up so that from the outside it would look like anything you wanted it to look like inside the living cell, but inside that coating it is conducting electricity. Actually it looks as though it conducts it with complete coherence. The electrons go from one into the other without stopping.

DAVIS-FLOYD: You know that anthropologists and sociobiologists have been talking for a couple of decades about human and nature co-evolution and human/technology co-evolution, that we've evolved to this state where we've begun to create our own evolution through the technologies that we develop and that that's a process that's been going on for millions of years, but that has drastically escalated and intensified. Those posters in the hall struck me profoundly because now you are working on creating the next step in human/technology co-evolution at the most fundamental level, which I think IS new.

SMALLEY: OK. *[laughter]*

DAVIS-FLOYD: Ken said something at lunch that helped me understand. He said people who have been working with computers have been taking the big ones and shrinking them to get ever smaller and that you are starting at the absolute smallest possible level to see what you can build up and that that's a fundamentally different approach and has massively more possibilities than just trying to shrink what already exists. Is that right?

SMALLEY: That's largely true. It can't be completely true. I don't think that we'll be able to build a really fascinating machine in the simple mechanical way that Eric Drexler *[author of a book fundamental to nanotechnology]* envisions.

There's actually a very interesting reason why Drexler's mechanical assembler machine is fundamentally flawed, having to do with what chemistry really is and what happens inside that little one nanometer box. Even though you may think that there are only three dimensions in there, there is a hypernumber of dimensions—three dimensions of motion for every atom in the structure. *If* you had fingers that were tiny enough to get in there and pull out a single atom--which, of course, you don't, but if you did, and you pull out a little atom, the other atoms it was connected to and the atoms they're connected to all realize it and they do something about it. So it's not as though it's a stack of bricks where I can take a brick out and everything will be stable. It's not true—they're all talking to each other.

So when you go move these things you've got to hold the rest of them in place—"now, you guys just stay there while I pull this one guy out." Chemistry, although most chemists don't realize it, is the art of making not just the atoms where you're gonna make the connection do what you want, but controlling and orchestrating the activity of all the atoms in the near vicinity. And usually that's somewhere between five and fifteen atoms. And every one of those has to be controlled in three-dimensional space, so that's 15 to 45 degrees of freedom. So chemistry happens in a hyper-dimensional space.

COX: So it's the interconnections, the fact that they're not separate.

SMALLEY: You've got to control things in the hyper-dimension. You've got to have a lot of controls. If you're gonna build a robot assembler, one robot hand is not enough, you need one for every atom in the set to have the ability to move them in three-dimensional space. You're trying to add a new atom to this group of atoms, so you need one hand to hold the atom you're going to put in, and then another hand to hold the atoms you're going to add to. This is not so hard to do when all the atoms are far apart, but it is much harder when they are close together. But then there's the "fat finger" problem. There are no fingers that will do that. At the energies that we're dealing, if these energies are our playground, our tinker toys are atoms.

DAVIS-FLOYD: What about the Star Trek fantasy of replicators or transporters?

SMALLEY: I don't have a clue how that works. I'm dying to find out! *[laughter]*

DAVIS-FLOYD: So that's not on the horizon?

SMALLEY: Well, chemistry turns out to be a lot more subtle than even chemists give it credit for. It's interesting. It's very similar to the ordinary use of the word "chemistry," as in "the chemistry is right or wrong." You don't make a boy and girl fall in love with each other just by pushing them at each other. There are multiple dimensions going on.

DAVIS-FLOYD: Which include energy and relationship from what you said.

SMALLEY: And many dimensions.

Particles and Dreams: The Question of Consciousness

DAVIS-FLOYD: So do you actually see consciousness in those atoms when you say they talk to each other?

SMALLEY: Consciousness. I didn't know we were going to be talking about consciousness today. That's a good question. What would it mean for an atom to be conscious? It's certainly thinking about *itself*, that's for sure. In a moment you're gonna get me into quantum mechanics. You wanna go there?

DAVIS-FLOYD: Just to have fun for a minute before we get back to the more concrete stuff, please carry that through. You say an atom thinks about itself, certainly. The language that you use metaphorizes the atom as conscious. They "think" and "talk" to each other, they "react." That implies consciousness, so I was just going to make what's implicit explicit and see if you really think there is consciousness.

SMALLEY: Of a sort. It depends on what sort we're talking about, but let me just go with it for a moment. An atom is a bunch of electrons associated with some heavy positively charged nucleus which is holding it in this region of space and the electrons are particles. You may have heard about this wave-particle duality thing? *Forget it*—they're particles.

DAVIS-FLOYD: The electrons are particles. So there are no waves?

SMALLEY: There are no waves. It's just that the particles don't do what you think they do. If you get a chance get Richard Feynman's little book titled "QED." It stands for "Quantum Electron Dynamics" and is the written-up version of a series of four lectures he gave to an academic crowd at UCLA in the mid-seventies, trying to explain what he got the Nobel prize for, which was quantum electron dynamics. It's a wonderful little piece of lucid explanation and the idea that "it's a particle and forget the wave" comes right from Feynman. But these particles aren't what you think particles are.

Our experience with particles is that at one time a particle is over here and some other time it's over there and there may have been many paths that it might have taken to go from here to there, but it took one particular path. Ah, but the particles in our universe--a single particle, when it goes from here to there, doesn't take *a* path. What it does is just incredible and nobody really understands it, but the most perfect theory that has ever been created by a human mind is quantum electron dynamics. It's been tested to a ridiculous number of digits of accuracy. People make careers trying to knock it down and it just gets better and better.

In quantum electron dynamics there is a way of calculating the probability that it goes there which seems to be perfectly correct. In this calculation it is as though the particle—and now I'm adding and defining, but I think you'll be happy with these terms—it's as though the particle "dreams." It's sitting here asleep and it dreams about going to a particular place over here, and in the dream, when it gets to its point of destination, it makes a little mark, a little arrow on a piece of paper *[this "arrow on a piece of paper" is an accurate description of complex numbers in mathematics, which contain both real and imaginary components that can be graphically represented as arrows]* which turns out to be the only thing that's remembered of that particular dream. The arrow is a certain length and points in a certain direction on a flat piece of paper, and the length of the arrow and which direction it points depends on the details of the path and the dream, and quantum electron dynamics. The arrow he leaves is an indication he was there, and it points in a particular direction and has a certain length.

In quantum electron dynamics, should you be interested in calculating the arrow you have to go through years of graduate school to get to use one of the calculators, and it's like long division—don't ask! *[laughter]* There is a very clear description of how you do it. When I tell my students about it I draw a little picture of the "dreamer." He's got a vest and a hat and he's got a little wristwatch with one long hand. The wristwatch is his quantum mechanical phase. As he walks, the hand goes around clockwise. The longer he walks the shorter the hand gets--it starts shrinking, and if he bounces off a wall, the arrow flips. The faster he walks, the longer the length of the arrow, so that the direction it points depends on how long it took for him to get there. At the end of one dream there'll be a little arrow and then the particle has another dream and takes another path and in that dream there's another arrow and then there's yet another dream and a different path. The night goes on and there are more and more dreams and the particle dreams about getting from here to there and then to everywhere in between, including all times, backwards and forwards, everywhere in the universe.

DAVIS-FLOYD: So you seem to be saying that every particle exists everywhere. But I need more concreteness—how does the dreaming translate to reality? If you go somewhere in one state of consciousness, does that mean you went there in all states of consciousness?

SMALLEY: Every particle doesn't exist everywhere—the essence of being a particle is that you exist in a particular place only. The problem is that particles don't move the way you think they do. You think they get from here to there by following a particular path. That *is* what macroscopic particles do. But individual particles really do something much more weird—it's as though they dream before they move--they dream about taking all possible paths. Not only does this particle dream about going to the particular destination an infinite number of times, taking different paths and leaving different arrows, but also, it then turns around and dreams about going someplace else. So it has an infinite number of dreams about getting to an infinite number of places through an infinite number of paths.

Then it wakes up. Waking up is a 100% probability, unless it gets killed. But the probability of waking up in any particular place is less than one. That probability is determined by those arrows that the dreamer dreamt and left for that particular destination. It is the only reason the arrows are worth anything, because you go to the blackboard at that destination and add up all the arrows through complicated math. If you take the length of the arrow and make a box, the area of this box is the probability that you will wake up in that position.

DAVIS-FLOYD: What exactly do you mean when you say "dreaming?" Only conscious beings dream and if you say that a particles dreams all these different directions and, therefore, has gone in all these different directions, where's the difference between dream and reality?

SMALLEY: Feynman answered that nobody knows. He taught this in his lecture. You ought to read it. It's really great, beautiful, much better than anything else I've seen on it. You asked me what do these paths in these dreams mean, and the answer is that we're not sure they mean anything. All we know is that if you calculate all these paths, and you add up the arrows that result from your calculations, it's *as though* they dreamed. We use the word "dream" because it's the only thing that I can think of that's like that. When you wake up in the morning, you don't generally know how many dreams you've had.

But the good news is that this way of predicting where a particle wakes up works with incredible precision. The part I find exciting and spiritually deep is that this clunky mechanical universe we thought we lived in, in every aspect is doing incredibly bizarre things. The weird thing is not that a particle dreams and wakes up, but that in what it does it's affected by everything in the universe, by all possibilities. This non-locality in space and time is the weirdest aspect of quantum mechanics. I find it's such a magnificent thing about science how weird it is and yet how true.

Let me make a brief digression. We've been talking about the motion of one particle, but the world has many particles and they interact with each other. The result of all these interactions is to effectively localize the dreams. There are complicated rules for how long the arrows are—the arrow is shortened abruptly when the particles start bouncing off of the others, and there become many more paths. So it is possible that there is symmetry in the universe. For every path, there is a corresponding anti-path. When you add up all the arrows you get 0, which is called a node of your wave function.

For example, if a particle is in a box and is energetically incapable of getting out of the box, it turns out that the particle can't just sit there, it has to have some minimum energy called "zero point energy"—every energy lower than that is a node. It can't *be* there. This is the entire reason why there are quantum levels and why atoms have the size they do, why the electron doesn't just fall into the center and marry the proton. This is why Feynman has to say it's an "arrow"—it's a complex number. Einstein was always upset by this, because he never thought God would work like this.

Most physicists feel it's too weird, but it is reality. It's at the root of the mystery of chemistry—why doesn't the electron just stick to the nucleus? Positive and negative charges attract each other, so why doesn't the electron just latch onto the nucleus and stick? If all you believe in is the physics of Newton and Maxwell, the electron and the proton would be right on top of each other. The only reason they are not is that these dreams keep things from just sitting on the bottom of the box. Zero point energy is "confinement" energy—it is the kinetic energy the particle has because it is confined. The smaller the box it's confined in, the greater the amount of energy. In confinement energy there is a constant tension between the desire of the electron to get close to the proton and its hatred of being confined.

SMALLEY: This is the fundamental weirdness of quantum mechanics, this non-locality and non-causality that you can go back as well as forward in time. It's crazy, isn't it? Just amazing. Anyway, at the end of all these dreams, an infinite number, the particle wakes up in this new position, this particular position and with the probability that is calculated by adding these arrows together, you get one final resulting arrow and we make that the side of a box, and that area determines the probability that it wakes up in. It just wakes up in the new position. Every particle in our universe in our current theory of quantum electron dynamics is doing this all the time—dreaming and being, in a sense, aware of waking up in this position as a result of every one of these arrows being added up. So, even the simplest particle, a photon of light--not a wave, a particle--is somehow aware of the entire universe and about all time, forward and back. That good enough for you?

DAVIS-FLOYD: Mystic, poet, and dreamer.

SMALLEY: Yeah. So I think it's pretty wild, this universe. Now she's afraid to ask any more questions! *[laughter]*

DAVIS-FLOYD: It's endlessly fascinating--everything that mystics and poets and dreamers have dreamed is grounded in science. It unifies the disciplines in a way that you don't get to unless you get to that level.

SMALLEY: Yes. First of all, that story that I told you had a special flavor to it. It runs shivers up and down your spine—at least to me, the notion that what happens to the particular atom or the electron that's buzzing around it is somehow some complicated consequence of everything in the history of the universe forward and backward and all over time, is weird! But what is special about it is that the theory of quantum electron dynamics was worked out over many years and has been tested to incredible accuracy. This story is deeper and more polished than any of the other discussions about these sorts of things—it's the key aspect of physics. In the overall history of human beings thinking about things, our finest hour, our greatest accomplishment has been quantum electron dynamics, and it is still doing just great.

I want to go back to the point about atoms having a consciousness. An atom, like an atom of carbon, has six electrons and a nucleus. The electrons, we like to say, are buzzing around in their orbits. But, remember, they're particles and particles don't do what you think they do. They don't follow a particular path.

I remember when I was in grade school and I was told about atoms for the first time, they told me that the electrons in the atoms traveled in orbits and that somehow these electrons got from this orbit to the next without going through the space in between. This really bothered me *[laughter]* and now after I've seen this argument so many times it still bothers me, two ways. One is that I'm sure none of the teachers or any of the people who've read the books actually know what the heck they're talking about. But there *is* a sense in which it doesn't go through the spaces in between--it dreams and just wakes up. Anyway just for the carbon atom to sit there and be what it is, it has to be doing these dreams all the time. That's what makes it stay in the space that it is.

Geodesic Domes on the Nanoscale: The Naming and Potential of the Fullerenes

COX: Could you talk some more about the potential of nanotechnology for people who don't have a significant scientific background?

SMALLEY: Well, my definition of nano-technology is that you do things with perfection at the atomic scale and you build things with a tinker toy set. That allows you, if you have that ability, to build things that are as strong as the tinker toy set will let you build. So if the tinker toys are atoms—we've got 90 or so versions of atoms that are stable, not subject to radioactive decay, and 120 or so that we can make in artificial environments—those are the things that come in the tinker toy kit. And now we know, very well, why they stick together, how strong they are, and after you have stuck them together, how robust they are when confronted with the sorts of things that we have around in the world—air, moisture, corrosion, so forth . So, you can well imagine that out of that tinker toy set there's gotta be something that is stronger than anything else. You can't be always finding something stronger. There's a finite set of atoms.

So what is that? Well, we think we know what it is. It's carbon atoms stuck together in a hexagonal network, kind of like chicken wire, that's wrapped up in ways that the edges of that chicken wire, sheet to sheet, are seamlessly connected to one another, so that there's no place you can start a rip. That sounds like the description of a bucky tube.

DAVIS-FLOYD: A dome?

SMALLEY: Well, it could be, if you just made a spheroidal object, that it would look like a dome. In fact, when I first imagined this up here about three feet from where we're sitting, back in 1985, it was hard to really visualize because there were so many atoms. Even in the crudest version of this we were thinking about 60. I was trying to think of some structure, a lattice, and I asked my colleague Harry Curl, "Who was that guy who built those domes?" “Oh yeah, Buckminster!” So we were just sort of laughing and we said, "This would be a Buckminster fullerene, with the "e-n-e" at the end, because we knew it had to be an aromatic molecule like benzene and naphthalene.

DAVIS-FLOYD: What does "aromatic" mean?

SMALLEY: It means that it has an aroma. It all comes, really, from benzene and the molecules that are like it that have the characteristic of having carbon stick together in rings, where every carbon is connected to only three other atoms, rather than four as a normal set. Carbon has a genius for doing this, it’s special of all the atoms in the periodic table.

So that's why we called it "Buckminster fullerene." Buckminster Fuller was a great fan of structures that distributed the stress along the geodesic lines of the sphere, so they were called "geodesic spheres." It turned out this object we were thinking of had the structure, made out of carbon, but had a structural bonding that was identical to the patented Buckminster Fuller geodesic sphere. It had exactly the same structure. It had 12 pentagons and 20 hexagons, so it was a nano-implementation of a geodesic sphere, distributing the stresses and strains around a spheroidal object. A three-dimensional sphere is the best you can do.

Then, as we refined our knowledge in looking at Buckminster Fuller's printed work and the work that his followers have carried on, there are many variations of this—-big spheres, little spheres, oblong ones, but all these things must be made from pentagons and hexagons and to be closed they must have 12 pentagons. They can have any number of hexagons, except, interestingly, one. For some reason, deeply connected with mathematics, that won't work. But you can have an infinite number—a million--and you can use the hexagons to put the pentagons far apart from one another to make a really big sphere, or you can keep the pentagons all grouped together in two sets of six to form the hemispherical caps at the end of the tube and put all the hexagons in the middle to get the long tube and that long tube then has this property I was talking about.

If you can imagine holding it in your hand and pulling it, it is predicted to have the highest stiffness of any object that you can make out of any atom in the tinker toy set, or the universe—it’s the all-time winner. We don't know for sure, but the prediction is right now that if, being the strong, macroscopic person that you are, you get a hold of this, and you stretch it and stretch it and stretch it, and before it breaks you can stretch it to 20 or 30 percent longer than it was to begin with. The tensile strength is very high. And the indication is that when it finally does break, it doesn't break brittly but pulls out a little chain of carbon atoms—the break is a plastic failure, not a brittle failure.

One thing that we do know from actual tubes that have been made and distorted, is that you can take this tube and you can bend it. You can bend it so much that it buckles like a soda straw and then when you let go, it just snaps right back—it doesn’t break. So, any tube, like the soda straw, as you begin to bend it, the material of the soda straw at the top of the bend has to stretch and underneath, on the inside of the bend, so that the bending stiffness of it depends on just how hard it is to stretch that material and this is the hardest material in the universe to stretch, so the stiffness of this little nanotube will be higher than any other object you can build out of the tinker toy set, forever and anon.

DAVIS-FLOYD: That's incredible!

SMALLEY: So that's one reason why we think we oughta learn how to make this stuff and to be able to make macroscopic objects where that incredible stiffness and strength, toughness, becomes manifest on a macroscopic scale. This little tube we're talking about is only a nanometer in diameter. It can be very long.

DAVIS-FLOYD: It could be infinitely long, theoretically?

SMALLEY: Right. It is, in fact, a little bit smaller in diameter than a DNA double helix, very much on the same length scale as DNA. But it has this incredible strength—the all-time winner.

DAVIS-FLOYD: And at the macroscopic level, where does that strength come in the most useful? In computers? In buildings that would withstand earthquakes?

SMALLEY: Well, actually, in all the things you mentioned it does. Let's get back to our topic we can't seem to get off these days—computers. To could conduct electricity as it is conducted in a copper wire, for example, the electron moves long distances before it loses its energy. When it scatters it doesn't lose much energy. You get a wave that will propagate down the wire near the speed of light—-that sort of conduction.

In order to get that to work on a moleule, you have to find a way that the molecule won't bend in a way that causes the electron to stop. Every molecule that anyone has looked at as a potential conducting wire has had that problem, that the electron will go a couple of bonds down the wire and then it just stops. Then it's negatively charged and things move around it and you lose all the forward momentum and you have to start again.

The answer to how to keep that from happening is to make the wire rigid, so it takes too much energy to bend it, so this incredible stiffness is critical. It's one of the reasons why this works as a wire. If it did not have that strength, it would not work as a wire. So even there it's critical, at the nanoscopic and microscopic level. A lot of my research, in fact all of the research I did with NASA is devoted to learning the art and technology of building things that you can hold in your hand, big things that you can build—-aircraft and so forth, out of tubes, perhaps even pure tubes, where this incredible strength and toughness now is manifest in the macroscopic object.

DAVIS-FLOYD: If you built an aircraft entirely out of nanotubes could it withstand a crash, for example? How strong would it be?

SMALLEY: Well, the simple answer is that we don't really know. We haven't really made any macroscopic objects where the nanotubes extend over the full length. I used to have, scotch-taped to my computer, one of our first bucky ribbons. It's just like a little ribbon that you'd tie a package with. You could play with it and curl it. That ribbon is made from nanotubes--we got them to all align along the length of the ribbon parallel to one another by using a very strong magnetic field. So inevitably, these things are now called "bucky ribbons." And all the tubes in these ribbons are all going one way and the fact that it splits up like this, with these sharp edges, indicates that this material has a natural cleavage direction, which is a characteristic aspect of the crystal--a natural cleavage point.

Characteristics of Nanotubes: Ropes, Cleavage Points, and Chirality

SMALLEY: One of these days, when you come back, I will show you something that looks kinda like this, a little shinier, but it will be a crystalline form of matter, a new one that has never existed before. It'll be composed of bucky tubes that all go one way. They'll have thickness and they'll have weight. They'll weigh about the same as this does. If you hold it in your hand it will feel sort of strange. The tube will be going one way and if you put your fingers on the top and the bottom and it'll feel pretty much like plastic or wood, but if you put your fingers on this edge which is where the ends of the tubes are and on this one, you'll feel cold, like diamonds. The tubes have the thermal conductivity of diamonds along their length, but the thermal conductivity of wood perpendicular to that. If you get all the tubes going this way and this thing is made of nothing but tubes, it will have this really remarkable property of feeling like both copper and diamonds. It'll be cold. It will actually conduct heat from your fingers, which is why a metal feels the way that it does. So, it'll be a rather bizarre object.

If, in fact all the tubes go one way, and you've got a hunk of the stuff, then it will be easy to break it parallel to that direction, because there is a natural cleavage plane that goes that way. On the other hand if I bend it perpendicular to the natural cleavage plane, then it will be very tough, and you can bend it back and forth millions of times and it won't break, but if you bend it along the natural cleavage plane it will just break, as the tubes are very weakly coupled--you're not breaking them, just separating them from each other.

What we've made so far are objects where the tubes don't extend the whole length, but stop and start. That's what we know how to make now, we don't know how to make the perfect crystalline object where the tubes go the whole length, but we need to do that if we're ever going to get humanity off this planet. The tube itself only goes a millionth of a meter, a micron, but then there's another tube that takes off.

DAVIS-FLOYD: Why can't the same tube keep going?

SMALLEY: I haven't learned how to make that yet, but, in principle, it could. I've asked myself the same question and there's no reason that it couldn't, but then I ask myself how would I do that? Therein lies the research project.

DAVIS-FLOYD: Well, how do you make them that short?

SMALLEY: Oh, it's making them short that's hard for you now? Well, how do you make them at all?

DAVIS-FLOYD: You make them and they just come out short and the trick is to learn now to make them longer?

SMALLEY: I'm actually quite pleased that they are short right now, short enough that when I put them in water and I put soap in the water and shake them up, they all disperse and make a slurry, kind of like a black ink, and our belief, now, is that immediately after the shaking up (actually we use ultrasonic vibrators), most of the tubes are now individuals wandering around in their thermal jiggling and every tube is coated with a single molecular layer of soap molecules that are there because if they weren't there, the water molecules would have to form an ice-like layer on the surface and that would cost too much free energy flow. It's basically the same reason why soap works with dirt.

So I have this suspension. Now what we believe happens is that as it just sits there on the table, the nanotubes are moving around chaotically in the form of jiggling and they get strong enough that the little soap layers part—they're actually touching---and the nanotube interaction is very strong and if that happens it's not gonna come apart again. It's going to start turning like this *[takes two sticks and crosses them]* —here are the two tubes, when they hit crossed, it is very likely they will just scissor together until they align along their whole length, so that they will be stuck together and will be very difficult to get them apart.

So now there are two of them and there's soap around them and gradually you get more and more and you get a long "rope." The rope contains about 100 tubes in cross-section here, that is tens of thousands of feet long.

DAVIS-FLOYD: But do they stick together side by side and end to end? Just on their own, floating around in the soap?

SMALLEY: Yes, you bet they do.

DAVIS-FLOYD: Oh my gosh!

SMALLEY: They think about themselves.

DAVIS-FLOYD: I think you think that they are conscious. You certainly talk about them that way.

SMALLEY: Well, there's a great cohesion here, two tubes. But it turns out that the tubes, at least the ones that we make these days, come in different types, depending on how many hexagons there are as you go round and whether the hexagons, as you go from one to another to another and another, come back exactly to where you started or you come back one hexagon down and kept going around in a spiral. That's called the chirality of the tube.

Since the tubes are of different chirality, a whole diversity of types, when they come in contact with one another—it's called van der Waals contact, that's very energetically favorable, they're not going to come apart unless you physically rip them apart--the atoms in the hexagons in this tube don't quite fit into the little middles of the hexagons in this other tube. Some of them do, but other ones get offset and have to be sitting right on top, so that they're like two gears with different teeth that don't mesh at all. The result is that there's very little difference in the energy as you move it along; there's very little friction. Our current belief is that at room temperature these guys are scooting along all the time. If here are just two tubes, they'll just slide until they get to the maximum possible contact and it will cost energy to pull them apart.

DAVIS-FLOYD: So they are groupies.

SMALLEY: They love each other. They're not real fans of anybody else.

DAVIS-FLOYD: "Stick to your own kind" acquires a whole new meaning!

SMALLEY: Okay, so you have this ink (a suspension of tubes) that you just shook up. The tubes that are making it inky-looking are now individuals—they have been separated by the shaking. But then they start aligning with each other, roping up, so that if you took a magic snapshot you'd see a lot of ropes.

COX: But what you're really seeing, macroscopically, is black slurry stuff.

SMALLEY: Yes. *[Holds up a vial of a dark substance.]* These are in fact bucky tubes. All of this sounds great, but when you look at it looks like *dirt. [laughter]*

If you take this bucky tube ink, soapy water after it's shaken up, it still looks black and smeary--you can't see any individual tubes in it with the naked eye. But if you then filter it, take a little bit of it and pass it through a filter, all the nano-tubes will be trapped on top of the filter and the water will filter through. When you look at it, it just looks like a shiny piece of carbon paper. You remember carbon paper?

DAVIS-FLOYD: Yeah. Back in the dark ages.

SMALLEY: I don't know how old you are.

DAVIS-FLOYD: My *mother* used a lot of carbon paper.

SMALLEY: Okay, it looks like carbon paper, and if you look at in the finest, most powerful optical microscope that exists, it still looks like carbon paper. But if you look at with a scanning electron microscope, which is able to see things only a couple of nanometers wide, what you see is a whole bunch of tangled ropes. *[holds up a picture of what looks like tangled vine roots]* See those tangles? Those are individual tubes.

DAVIS-FLOYD: So the tubes make themselves into the ropes.

SMALLEY: And they were ropes before they settled into the carbon paper.

DAVIS-FLOYD: They look like roots or ferns.

SMALLEY: So that huge magnet in the other room--it's job is that before I filter this stuff and get this random tangle of ropes of nano-tubes on paper, I'll take that roped-up ink solution of nanotubes and I'll put it into that magnet's electro-magnetic field heading east, because these ropes very much prefer to be aligned along the parallel to the magnetic field. As you move it away the energy goes up.

DAVIS-FLOYD: So does that straighten them out?

SMALLEY: It straightens them out and makes them all parallel.

DAVIS-FLOYD: Nobody has to go in and untangle the mess?

SMALLEY: And that's part of the point of nanotechnology. We're sort of getting back to what Ken was saying, that the direction of doing nano-technology is often set from the bottom up, but, in fact, it's gonna be more complex than that. You've got to assemble these carbons into the tubes first. That's a condition that takes a gas heated to about 1000 degrees; it's not a condition where you want to get your fingers in there. Then once the tubes are assembled, I've got to assemble them in another pattern in different stages of construction.

DAVIS-FLOYD: They seem so cooperative!

SMALLEY: You see the trick of chemists is to find ways of controlling the things we can control in the laboratory, like the size of the beaker, the temperature of the water, what we put into it, so that chemistry and physics conspire to make what happens to be what you want to happen. When you cook you do something like that too.

Cooking Up Nanotubes

DAVIS-FLOYD: So how do you actually make a nanotube?

SMALLEY: Ah, well, there are many ways. Unfortunately none of them as yet involve making them at room temperature in water or in any liquid. I wish we could find a way to do that, as it would greatly facilitate large-scale production, but we haven't found it yet. It may, in fact, be flat-out impossible.

The simplest way to make them is to first make a little one-nanometer diameter ball of iron. It only takes about a hundred atoms of iron to make a one-nanometer ball. So let's pretend that somehow you do it that. I can tell you three or four different ways of doing it. Then you take this little ball of iron and you heat it up to 700 or 1000 degrees centigrade. Don't get it much hotter than that or it'll evaporate. Then you expose to that little particle of iron a gas of a hydrocarbon like methane or ethylene or my personal favorite, carbon monoxide. The same thing happens in each case. When one of these molecules happens in a random chaotic motion to hit by accident the surface of this hot iron particle, at least about 10 percent of the time it doesn't bounce off--it sticks and sticks long enough (it’s a hydrocarbon) for one of the hydrogen-carbon bonds to be broken. The hydrogen goes off and bonds to the iron particle by itself. The carbon is bound and if another hydrogen comes off someplace else it's very likely those two hydrogen atoms will diffuse around and stick to each other and make H2 gas and off it goes to leave this poor molecule behind on the surface without enough hydrogen to get back to the gas state. It's stuck. In fact, if it spends much more time there, all the hydrogens get stripped off and they're outa there, hydrogen molecules drifting on downstream in the gas flow.

So here you’ve got the iron particle and now it's got the carbon atoms and the iron makes good strong bonds with those carbon atoms and also allows the carbon atoms to effectively dissolve--it's like water is to sugar. It dissolves the carbon atoms so they can go inside the particle and wander around. It's only a nanometer in size. It only takes three or four atoms to get from one side of the particle to the other.

So the carbon atoms are rendered into a form where they're highly mobile. They can move around. They can make and break bonds with iron atoms in the ball. They can also make and break bonds with each other and once there are enough carbon atoms with this particle—-we don't know exactly how much is enough, probably ten--the overall circumstance that would be most favorable for energy and entropy would be to have the carbons link together in the form of a little hexagonal sheet that conforms to the curvature of the particle. We call this the "yarmulke mechanism" because it makes a little skull cap, and then as more hydrocarbons come down they lose their hydrogen, leave their carbon behind and that carbon migrates on and adds to the skull cap and it starts growing. So, most of the time, unless you've done something special, it will just simply grow all the way round and it will embalm the iron particle, the iron ball, encapsulate it in this little shell, a little bucky ball around it.

If the iron particle is sitting on a surface of alumina or silica (the oxides), or probably magnesia as well—refractory oxides--so if there's one surface that's actually bonded to the surface so it’s not really a ball, then usually the carbon "yarmulke" doesn't go all the way around. It gets about half way around and then lifts off and all new carbons that are added just form hexagons and the tube gets longer, the particle remaining at the root of this growing tube. If the particle is in the gas phase—just the metal particle wandering around not on the surface—if the particle is big enough, like a couple of nanometers in diameter, our experience is that it always overcoats and never goes to tubes. But if it's really small, the strain of the carbon sheet trying to curve around it is so high that often it only makes a little half cap and then begins to make a tube. Then it invariably makes a single-walled nanotube--and therein lies the art, which is really the art of making single-walled nanotubes entirely in the gas phase. We use carbon monoxide to do this because at the temperatures we're dealing with carbon monoxide is perfectly happy to stay carbon monoxide.

DAVIS-FLOYD: Okay, you're describing the mechanism of how the nanotube gets created at the micro level--but you're not in there at the micro level pushing atoms around. You're a macro person. So what are you doing at the macro level?

SMALLEY: I built the machine and I configured it so the metal particles could be formed in an environment where there's high temperature.

DAVIS-FLOYD: Okay, so you pour in iron, you pour in carbon, you pour in hydrogen and you let it happen?

SMALLEY: I just let it cook. Chemists have always done this. That's what happens along the Houston ship channel in the refining of oil and getting various kinds of petrochemicals out of it. They're not doing it one at a time.

DAVIS-FLOYD: They just smoosh it all together and it happens.

SMALLEY: Yeah. You got the idea.

COX: Well, you do have to stir it a little.

DAVIS-FLOYD: Do you talk to it? Do you pray over it? *[laughter]*

SMALLEY: Yeah. It doesn't help, but it does make you feel better. But that's the art of chemistry. The nanotube is, itself, a new kind of polymer, like polypropylene, polyethylene, or kevlar or nylon-- just that in this case the monomer is a carbon atom. Unfortunately, as I mentioned earlier, we do not have a way of getting the polymerization to happen in a liquid with ordinary temperatures. It always has to be a gas at higher temperatures. I wish that weren't true.

DAVIS-FLOYD: That means it's expensive and has to be done in this very special equipment?

SMALLEY: Right now it's ridiculously expensive. Yes. But this process I was describing to you goes under the new word "HiPco" –-"H-i," which is there for "High pressure" and "P-c-o" for "Pressure of carbon monoxide." So "high pressure carbon monoxide"—"HiPco." (In this new world, we're allowed to give more than one capital letter to a word, so "H" and "P" are capitalized, just like in FedEx.) This process, we suspect, once really good chemical engineers have their way with it, will produce bucky tubes of a wonderful degree of perfection, a high degree of purity, for about a dollar a pound and will, ultimately, be a big business.

DAVIS-FLOYD: How far away are you from that happening?

SMALLEY: Well, somewhere between a day and infinity. *[laughter]*

DAVIS-FLOYD: How much did it cost to produce this much? *[pointing at the small container]*

SMALLEY: Nothing. It's all from NASA. *[laughter]* That's about half a gram and it was made in about an hour and a half. The apparatus took probably $250,000 worth of capital and probably $300,000 worth of labor, so it's very pricey and that apparatus, in its current form, has never made more than a gram in a day. Tomorrow or the next day we expect to change that, but if you sold it from that apparatus commercially it would be a hundred more times expensive than platinum. The same was true with aluminum originally.

DAVIS-FLOYD: So you're expecting chemical engineers to figure out ways to make this on a large scale.

SMALLEY: Yes, and actually, for the time being, we're pretending that we're chemical engineers. It's fun! It's remarkable these days with the possibility of the business coming up how students respond to it. They all wanna do it! Back in the sixties you wouldn't want to touch it-—it was the time of the grey flannel suit. The last thing anybody'd want to do is be a businessman; now everybody wants to do it. It's remarkable!

DAVIS-FLOYD: Will you be able to make money off this as a business enterprise, even though you're doing it at Rice?

SMALLEY: Well, yeah, it's possible at Rice. The intellectual property, the patents for this, even though it's been developed on federal grants and contracts--a lot of NASA work--the university owns the patents. Rice actually owns quite a few patents and pending patent applications over the past ten years from my group over the fullerenes, and the university is just dying to find a way of turning that into money. One way to turn it into money is to license it to a company like Dow, for example, but another is to give an exclusive license to a startup company and own a piece of equity in that company. If it's successful, it could be worth an awful lot of money. Or I could just help the company get going and have a piece of it through Rice's intellectual property.

Back to the Past: Smalley's Development as a Chemist

COX: Well, let me go back in time. What was the background that led to the Nobel Prize and the fact that you were given this prestigious honor? Was this a twelve-year history? I know you were at another university before you came to Rice and I wondered if you could talk a little bit about that.

SMALLEY: Well, when I was at the University of Chicago I developed a technique of using supersonic beams, supersonic jets and beams to cool molecules down to nearly absolute zero while they were still in the gas state, without them condensing, so that we could probe their details to a degree of perfection that previously was only known for atoms. Without having been perturbed, a molecule of four or five atoms has 3n minus 6, so a four-atom molecule has six vibrational degrees of freedom and, of course, is tumbling in space and has three rotational degrees of freedom and, at room temperature, once you quantize that mechanical system, you get billions of quantum states that the molecule can be in. So if you really want to understand what that molecule is, you've got to understand the whole structure of the quantum states.

The way to do that is with spectroscopy. That's the way the atom's structure was first figured out. In fact, our detailed understanding of how the bonds are made between atoms comes from very high resolution, detailed spectroscopy of, primarily, diatomic and triatomic molecules. That was, by and large, developed and pretty well run out during the first half of this century. It was still going on a bit when I was in graduate school in the sixties but it was pretty much done.

But as you get from diatomics to triatomics things start getting more complicated because of these other vibrational states, and by the time you get out to five atoms it's just hopeless, not just because of a lot of states but because the molecule can't exist in any one of those states long enough for you to be able to distinguish it from the others. So there really is a true continuum of states.

It occurred to me, when I went to work with Don Levy at the University of Chicago, who was then working on NO^2—three atoms (the attitude of most physicists is that that's two atoms too many *[laughter])*--NO^2 was a celebrated problem in those days because lasers had just been developed—-tunable lasers-—and we were using them to detect that molecule and it was really an embarrassment and an irritation to molecular spectroscopers that they couldn't completely understand NO^2, a simple triatomic molecule. NO^2 absorbs everywhere on the visible spectrum. We used to say, "It absorbs the brown." *[laughter]* It was the most celebrated issue in all of molecular spectroscopy and in chemical physics, which is really the intellectual background I came from at Princeton. And it occurred to me that if you were able to cool the NO^2 molecule in a supersonic jet, that you could simplify that dramatically.

Anyway, to make a long story short, Len Wharton, Associate Professor of Chemistry at Chicago, had some big supersonic gadgets--beam machines--so Don Levy and I went to Len Wharton and gave him the suggestion that we try doing this and he just lit up like a light bulb. He thought it was a great idea.

We did it and it was one of the most elaborate experiments I ever built in my life. We finally did record the first supersonic jet cooled spectrum of NO^2 on the night just before Richard Nixon announced his resignation—1973 or 1974. It was an experiment that really broke open that whole area, so molecular physics is now an accessible subject at this very highly detailed level of resolution.

I was a post-doc there and I applied around various places. I knew that Bob Curl was here at Rice and he was in the same sort of area. He wasn't into supersonic beams, but he was in spectroscopy, so I thought Rice would be an interesting place to apply.

So, when I did come here I wanted to distinguish my group from Don Levy's group and Len Wharton's group in Chicago, so I headed off into the ultraviolet with pulse beams to deal with more ordinary molecules and we had a lot of success with that. I got sort of bored with the molecules that we could find and decided to start looking at pieces of molecules called free radicals, ones that you can break apart. So I did that for a while and got bored with that. One of the most interesting pre-radicals is just an aggregate of a couple of a couple of metal atoms or a couple of silicon atoms, semiconductors--for that matter, anywhere in the periodic table, because at this stage—this was in the late seventies--computer calculations in the quantum mechanics of molecules had gotten to be quite a business. They felt that they could pretty well calculate the bonds between anything. What I was saying—we pretty well understand how atoms stick to each other.

Well, this is an experimental science so you say, “You think you understand this—-I'll tell you what. I'll go off and I'll measure it in the laboratory in a circumstance where there's nothing that is perturbing. It is precisely what you're calculating. So if we don't agree, we've got a problem.” I always try to do experiments that have what I call an "intellectual tension" to them.

DAVIS-FLOYD: What do you mean by “intellectual tension”?

SMALLEY: I mean a circumstance where you make a prediction that is demanded by a worldview, a theory, and so you *really care* whether reality turns out to be in agreement. Because if it doesn’t, your theory is wrong. In this case, the theory was the quantum theory of molecules, and researchers that are using this theory to predict the behaviour of particular molecules often made very vivid statements about what the theory predicts, so I tried to pick a case that if I showed them they were wrong, it wouldn’t be an issue of mild concern but would shake them to their core. We like to think we are testing the quantum theory itself, but it is really a test of the approximation the theoretician has used—after all, a molecule is not just a single electron. Even a small molecule has hundreds of electrons and many nuclei, so it is a many-body problem. Even in classical mechanics it is impossible to solve in closed form.

In quantum mechanics, it is ludicrous to think of doing this with the full QED theory, so theorists, when they predict the behavior of a molecule, are using an approximation to the full true quantum theory. And they can be quite good, so good they start to feel their theory is the truth, but sometimes, it ain’t. So I wanted to get them to make a really vivid prediction that was clean and irreversible, so that when I told them they were wrong, they had to rethink their whole worldview.

So I developed an apparatus, or rather a change to my supersonic apparatus, that would use a laser to vaporize whatever metal target I was using—make it into atoms and then very quickly condense it to form these small particles which then would be supersonically cooled in the jets. We had a lot of fun with that. Several new areas of research were formed out of that which are still very active now. Often this is called "cluster beams," "metal" or "semi-conductor cluster beams," which is a field that, in many ways, I founded.

Carbon Clusters and Harry Kroto: The Discovery of Fullerenes

SMALLEY: And in that connection, once we were up and running, we had the most powerful apparatus in the world. And Harry Kroto was interested in studying carbon chains, linear carbon chains, because he was interested in the microwave spectra of the molecules and had long been fascinated with molecules in space and molecular astrophysics. He had a theory of how these long carbon chains were, at that time and I think it's still true, the longest and biggest molecules known to exist in space. They exist there in vast numbers.

DAVIS-FLOYD: In outer space?

SMALLEY: In outer space.

DAVIS-FLOYD: Where? Floating around in a vacuum or--?

SMALLEY: Right. Well, I'm sure they're in planets, but principally, they're floating around in the vacuum of space and they're very abundant in interstellar clouds, particularly around carbon-rich red giant stars. Many other molecules have been found there as well. Virtually every small molecule you can think of has been found in space—water, ammonia, cyanide—a whole big list. But the long carbon chains are real oddballs. Well they're not “balls.” They were known to be long sort of batons because, in fact, the spectral signature is due to their rotational motion and as they rotate around they radiate light uniquely in the microwave spectrum.

Kroto was interested in how these molecules were made in the interstellar medium and he had a cockamamie theory which I knew was wrong. It was silly, but still he wanted to pursue it. The first part of the theory is not silly. It is that they were made in a red giant star. Most red giants, as they get to this stage, will go through a short period when they are actually carbon-rich. Under those conditions they are gigantic soot producers, so his theory was that when these stars are in this soot-producing region, really black soot coming out of the star, that these long chains were made. Then they migrated out into interstellar space and that's where we find them.

Now, what is silly about this theory is that these molecules are known to photolytically break apart, so what protects these molecules for millions of years as they're drifting away from this star? He didn't have an answer for that and he still doesn't and as I used to remark in those days, "These molecules don't have sunglasses. They're not gonna survive." Therein comes the title of the Nova piece (a one-hour television show that was run in 1991 in the Horizons series) on bucky balls, which is “Molecules with Sunglasses.”

In any event, he wanted to test this theory that these chains are made in condensing carbon vapors, so he came and visited me here. Bob Curl was a long time friend of his and the story has now been retold many times about him coming down here and us putting carbon in the machine. I understood the experiments that he wanted to do. I thought that probably they would succeed. I didn't think they were very important and, in fact, I had better things to do!

We were making these little metal clusters learning about how many atoms of nickel it would take before it really is a metal and, for that matter what is a metal? What do you mean by "metal" when you've only got ten atoms, or if it’s silicon or germanium, what is the surface chemistry of this object and all these fundamental questions of what makes atoms stick to each other and the whole chemistry and physics of surfaces. So I didn't want to hear about carbon. Carbon's got to have been studied more than any other element on the periodic table. It didn't seem to me it had anything to do with anything important in those days, which was catalysis, energy, semi-conductors and so forth. Astrophysics was the least of it. Besides, I thought Harry was sort of a loose nut and I just wanted to get rid of him, so under those circumstances we put carbon into the instrument.

Another reason I didn't want to put it in was that my colleagues, who had evolved into our principal competitors, were a group at Exxon in Linden, New Jersey--Exxon Central Research. Andy Kaldor had one of our machines. Why did they have it? Because I built it for them. We actually had a contract with them back in the late seventies to study laser isotope separation. We did a really great job of it. Unfortunately, it was just after Three Mile Island. After three mile island, Exxon got out of the isotope separation business—they didn’t want to have anything to do with nuclear energy, nor did anyone else.

Andy was so impressed with what the machine did that he wanted one for himself. So we built a second generation machine for them. So they were the only other group in the world who could do this same sort of experiment. And they'd already <u>done</u> it. They'd already put carbon into the apparatus and seen carbon clusters and seen a very bizarre thing. They had seen all the clusters that you can think of, all the number of possible atoms from 1 all the way up into the early 20s. And it had an interesting little pattern about it. It turns out that cluster distribution had been seen before in carbon in the work of pulling carbon ions out of a carbon arc. This distribution had long been understood correctly. The small ones up to about ten atoms in size are actually these long carbon chains that Harry Kroto wanted to study, the ones that are known to exist in space. Carbon clusters above ten in size were thought to be chains that had curled around to grab their tails to become simple monocyclic rings. This was the pattern we expected.

But the bizarre thing that was seen by the Exxon experiment was that there was sort of a quiet period in the cluster distribution where very little was seen followed by a broad distribution of huge carbon clusters. The bizarre thing about this huge cluster distribution was that only the even-numbered clusters were present. They wrote an excellent paper about this in which they presented a crazy explanation that didn't actually make sense. Even as an explanation it was inconsistent and completely wrong. But if you look at the picture they presented of their carbon cluster distribution, you will see that the 60th cluster is actually quite a bit bigger than the other ones. But they never mentioned this in their paper. I found out later that they actually had drawers full of data, where sometimes the 60th cluster would be seen to be ten times bigger than any other cluster in the distribution. They had plenty of opportunity, and they missed it.

Anyway, I had known about this result. In fact Harry and I talked about it and talked about what this even-numbered distribution could possibly be about. That's one of the reasons I didn't want to do put carbon in our machine. I didn't want to get in there and needlessly compete with the Exxon group.

Well, anyway we got into it and it turns out, interestingly, our apparatus, the original one, was the first one built in the world using pulse supersonic beams. I didn't know how long into the pulse of gas you had to go before the gas got cold. (The previous experiments I'd done in Chicago were with a continuous gas jet.) I wanted to pulse the jet so I could get more gas out and therefore get more cooling. But I didn't know how long I had to go into the pulse before things got cold, so I built the biggest apparatus I could. The idea is that as the pulse of gas goes out into the vacuum chamber, the gas hits the wall and reflects back to eventually fill the chamber, so at first you can pulse as much gas as you want—so I just made the biggest chamber I could *[laughter]* with the only restraint that I didn't cut a hole in the floor. I had a big huge chamber and it looked really like a big steam engine. It must have been five tons.

For the next generation apparatus, the first thing I wanted to do was shrink it down and make it smaller and that's what we built for Andy Kaldor and his team at Exxon, but for this experiment in vaporizing carbon to see the big even number distribution of clusters, it turns out that the original big machine was much better. The key insight was not just to have seen the distribution but rather to see how it changed as you allow the carbon vapor to cook prior to its expanding in the supersonic jet. It's very much like cooking soup on a stove—chemistry happens. And here, the more the carbon vapor has a chance to cook at high temperatures, the more the carbon atoms cluster and the more vividly C60 shows its special stability. In this apparatus the gadgetry that does the cooking consists of an adaptor to the supersonic nozzle. We developed it in our previous study of semiconductor clusters. This gadget with its cooking zone has the effect of spreading out the time period of the pulse. You need a lot of gas to fill it and you need a huge vacuum chamber to give you enough time. So the second generation apparatus we built for Exxon wasn't nearly as good as the original one for this carbon cluster work. That turned out to be the principal reason why we won, why *we* got the right explanation for C60, and they didn't.

The other reason that we won is that we had been doing research with my colleagues Bob Curl and Frank Tittle and a group of four graduate students for several years on semiconductor clusters. The whole business was to look at the pattern of the semiconductor clusters you were forming and see how it changed as you cooked it and as you reacted other molecules onto the surface of those clusters. All these clusters are so small that they are things you cannot see. Tjhey were all being studied on the fly in the supersonic beam machine. You could never collect them because in the very act of collecting them you would change them, so instead we would have to conjure up hypotheses for what the clusters looked like and how they behaved, and test these hypotheses with experiments in the supersonic beam machine. We'd sit in what used to be this room and we'd spend the whole morning conjuring up these hypotheses and experiments that we might design to test them. It turns out that's precisely the thinking process you have to go through to come from this magic distribution of even numbered clusters and how it behaves as you cook it to thinking about what's going on at the surface that makes them specially special.

COX: When did you find out that this assignment that you weren't that enthusiastic about, really might have this potential?

SMALLEY: Well, we were talking about these even-numbered clusters. We would sit here and we'd say, "Okay, look, I've built this apparatus and I've built it so that there aren't a lot of extraneous explanations for how things could be." I know there's no hydrogen in there. The experiment says quite plainly that there are carbon clusters present that have even numbers of atoms, but there are no odd-numbered clusters. I know they're not there--now what happened to them? Our whole line of thinking with our previous semiconductor research was concentrated on questions about the surface chemistry. What happens to the dangling bonds of these atoms that are on the surface of the clusters? In the bulk crystalline phase, these atoms have a certain number of nearest neighbors, but on the surface, they don't have that many nearest neighbors, so they can't make as many bonds as they would like. So they're left with what are called dangling bonds.

Something must have happened to the odd ones so that they are no longer present. And there must be some answer to how one arranges an even number of carbon atoms so that there are no dangling bonds. If you add to that the experimental fact that C60 is preeminent, and that there is nothing specially stable about C58 and C62, there turns out to be only one explanation: C60 is a soccer ball—in other words, it's a truncated icosahedron. The data were completely inexplicable with any other structure.

DAVIS-FLOYD: What does happen to the odd numbers?

SMALLEY: Well, there's no way of making a fullerene that isn't closed. Every atom in a fullerene is connected to three others but it makes a double bond to just one of these. They're paired. So evrey atom has to have a partner, the one with which it shares a double bond. The atoms therefore come in pairs, so all fullerenes are made of an even number of atoms. If you've got an odd number you can't give them all just one double bond. So the fullerenes are objects where all the carbon atoms have organized to make a closed structure which no longer has a dangling bond.

And of the fullerenes, the ones that do this in a way that leave a concentration of curvature over In order take something and wrap it around to make a spheroidal object, there's a certain amount of curvature you have to put in, which can be smooth or sharp, and those concentrative places will be reactive because the atoms at the highly curved place will be tempted to make a fourth bond, because to be happy with three bonds the atoms like to all lay in a plane, as they do with benzene and napthalene and graphite, so when you bend the sheets the atoms are no longer in a plane, and they become more reactive, so you don't want to bend them more than you have to.

So if you want to make unreactive clusters, you have to make the smoothest possible curve. By geometry, there is a unique answer in three-dimensional space, Nothing to do with atoms. It has to do with mathematics. There are Platonic aspects about this. It turns out that the largest number of identical objects that you can arrange around the surface of a sphere, so that every one is identical to every other one by a simple rotation, is not just any old number—it's 60. *[He holds up a bucky ball made of purple plastic]* This is the most symmetrical object in 3D space. I can make *this* vertex *[pointing to one of the interconnections]* look exactly like *that* one by simple rotation, by just rotating the sphere. And the striking thing is that you can never have any more vertices that have that property--60 is special in three-dimensional space.

It's also, getting back to Spookyland now, the most special of all integers. This point has nothing to do with three-dimensional space or rotations or symmetry—it's just a point about numbers. The number 60 has the greatest number of factors--60 is the most factorable of all numbers. You can divide it by 2, 3, 4, 5, 6, 10, 12, 15, 20, 30. Consider any range of integers. The number within that range that has the greatest number of factors is either 60 if it is in that range, or some multiple of 60. This is why the Babylonians used 60 as the base of their number system. It's why we have 60 minutes in an hour and 360 degrees in a circle. It's because you can divide it so many ways. There's got to be some reason why 60 is both special in math and in 3D space.

There are two singularities here. 60 is also the most symmetrical possible object. You can rotate it more ways than any other thing and have it look the same. That has to do with geometry, three-dimensional space. Nothing about numbers. But it's also the most factorable of numbers. Now I've been asking every mathematician I can get to if they can tell me if this is just a complete coincidence or if there's some deep reason why the nature of three dimensional geometry has to do with numbers and so far, no one has a clue.

So anyway, it's all concerned with the issue of 60. In the truncated icosohedron structure (the structure of a soccer ball), every carbon is identical to every other one, so they all have exactly the same curvature, so that it is the smoothest of possible fullerenes. There is a certain total amount of curving that you have to do to close a geodesic sphere, so it is better to smear it out over all atoms than to have it concentrated in any one spot (which would make that spot very reactive).

The fact that the 60th piece of carbon stands out so much higher than any other is a direct consequence of that symmetry property of the number 60 in the chemistry of carbon which, of course, has to do with the dreams and all that.

So that's how that discovery was made and of course it was such a wild discovery that if it's true, it's a fundamental insight in chemistry. I used to think, when I learned chemistry in high school that carbon was special. That's what I was told, but my feeling was, "Yeah, but look at all those other elements in the periodic table. It's just a matter of time and we'll be making silicon people" and so forth.

The one thing I have learned in all my years of research with these supersonic cluster beam machines is that carbon really *is* special. No other element bonds in quite this way. Without that bonding quality, there would have been no life.

DAVIS-FLOYD: So that's why we're carbon-based life forms?

SMALLEY: Yes. And probably any life form you're likely to meet, if it originated like we originated, I suppose spontaneously, is almost certainly going to be carbon.

DAVIS-FLOYD: When did Buckminster Fuller die?

SMALLEY: Unfortunately, in 1983.

DAVIS-FLOYD: So he never knew—

SMALLEY: Actually, it's just as well. From what I've been told about bucky he would have been absolutely insufferable on this point. He was pretty insufferable anyway. He gave wonderful talks. I understand his normal talks would start off—-they'd give him an hour to talk and he would start off in the upper left-hand corner of the blackboard and just start writing and it would just be this stream of consciousness. It was just a trance he was in that could potentially last three hours--he still has a very strong occult following.

DAVIS-FLOYD: Why would he have been insufferable about this?

SMALLEY: Because once you got him going he just never stopped. He just had something to say about everything and it was always quite fascinating, but in a rather arcane and somewhat lunatic way. If you go and read in to virtually anything that he's written he drives off in his own way of thinking, with his own words and so forth and rarely takes the time to be a scholar.

DAVIS-FLOYD: You could have given them your own name---"smallerenes" would have been pretty appropriate!

SMALLEY: Some people have called them "Smalley balls." *[laughter]*

Winning the Nobel Prize

COX: Can we talk a little bit about your perspective on the Nobel Prize, not from the standpoint of how prestigious it is, but what's the process? How does it get decided whether it was you and Dr. Curl or four others or--.

SMALLEY: I'm pleased to say I don't know. And I don't think I want to know. It's a remarkable phenomenon. The entire Swedish nation has embraced this prize as a part of their corporate identity, their self-image and certainly the king of Sweden, the royalty have adopted this. It is part of the seasonal celebrations in Sweden in December. They desperately need something. It's so dark there! They throw a lot of parties. I never realized it before I got there, but they take it very seriously and it's not just that this is a private foundation; this is a will that they have to fulfill every year. But the entire Swedish nation is bound up into it, all of the Swedish scientific establishment, the royalty, the king--

DAVIS-FLOYD: Do they have people who stay on top of all the latest developments in all fields so that they can best judge who should be qualified?

SMALLEY: Yes. And I would think it would be a terrible burden. It would be something to do it once but then the next year after you do it, where's your life?

DAVIS-FLOYD: Well, maybe your life is staying on top of things. *[laughter]* What, exactly, did you win it for? Obviously it's for this stuff, but what part of this stuff?

SMALLEY: The prize reads "For the discovery of the fullerenes." Not just the bucky ball. It's the fact that there's this infinitely large family of molecules that were imagined before by mathematicians and in a few cases by chemists, but nobody had a clue on how you would ever make it. But what the real discovery was, was not that carbon could be stable in this structure, but rather that carbon has within it the genius to self-assemble into this structure. It's somehow wired into it, the talent for making a geodesic dome. That no one had ever imagined.

Whenever you make a major, or what you think is a major scientific discovery, it with irritating regularity turns out that, in fact, you weren't the first. Even Columbus was not the first, you know. This particular discovery has been looked at by, I suppose, thousands of minds now. Not once, in any place, has anyone found a publication that points out the following: (1) Carbon has an interesting talent to bond with three other carbon atoms and thereby to take on these flat network structures like benzene, napthlaene, graphite. (2) If you have anything that is three coordinates and takes on flat network structures, if you throw a bunch of them onto a surface and you just jiggle them in two dimensions, they will spontaneously assemble into a hexagonal lattice. (3) If, instead of doing this in two dimensions, you jiggle these three coordinate entities in three dimensions, they will spontaneously assemble to form a geodesic dome. The dome forms because only then can all the dangling bonds be connected. This cannot happen in two dimensions—in flatland there must always be an edge. But in 3D the sheet can curve around and connect to the opposite edge. Had somebody written that in the past, and concluded that one should look at condensing carbon vapors to find geodesic domes, it would have been a stroke of true genius. But as far as we can determine, no one ever wrote those words.

What we did was not so brilliant at all. We had this instrument that we had developed for completely different reasons that turned out to be, metaphorically, a new kind of microscope, which, when you put carbon in it and you kind of adjusted it, reveals this property of carbon that's always been there but no one has seen before. It's much more like putting the first living cell under the first microscope and saying, "Ah there's a cell." I suppose you could have guessed there'd be a cell but, in fact, that's what Leuwenhoeck saw when he looked in a microscope. Or when Galileo turned his telescope to Jupiter and saw dots, I suppose he had to look at it at different times to see if the dots were moving, and have a mental picture of what those dots were doing—orbiting. Only then could he say he had discovered the moons of Jupiter.

Early Influences: High School and the Colossus of Rhoads

COX: Let me ask one transition question here. I'd like to get a little bit of background on Sputnik and the space program and what effect it had on you.

SMALLEY: Well, I was just a freshman in high school in 1957. It wasn't Sputnik so much. I think, at that time, I wanted to be an architect. I'd gotten over my wanting to be an opera singer at that stage. My voice changed, but I still wanted to be an architect. I was a pretty erratic person in school, particularly in those days. For example, I was president of my 6th grade class and played hooky 55 times during the year. *[laughter]* It shows a little independence for sure.

DAVIS-FLOYD: Did you get away with it?

SMALLEY: No. My sister was a year older than I and was always turning me in. I think it was later in my freshman year, in the school auditorium there was an assembly and two engineers came in to talk to us about being a scientist or an engineer. I wasn't alone—everybody was turned on by it. In those days, because of Sputnik and the Cold War—-this was only a couple of years after the "duck and cover" era of the Cold War. I remember being in grade school just a block down the street from the high school and actually going into the hallways and ducking and covering.

Being a scientist or an engineer was one of the most romantic things you could possibly be. So that was either my freshman or my sophomore year. By the summer of my junior year, I'm not quite sure just what happened but we said at the time that I “snapped.” Not that I was going crazy, but I snapped out of my stupor and got deep into my studies. I made a study for myself up in the attic of the house and that fall I took the first course class I ever took with my sister, who was a year older than I and always much smarter and better in school. The course was a chemistry, with a terrific, then young and fresh chemistry teacher, Victor Gustafson. The romance of science and engineering certainly entered my life because of Sputnik. My getting serious was not directly related to Sputnik but certainly my desire to be a scientist was related.

DAVIS-FLOYD: Why did you suddenly get serious?

SMALLEY: It was a combination of taking the first class with my sister and the fact that I just got into this chemistry text and I just nailed it. There wasn't a word in that book I didn't know. When I go back to the house, one of my sisters went back and photographed the rafters in there. I put the whole periodic table up in the rafters and it’s still there. I was that into it. The next year I did very well in physics too but I'd already been sort of imprinted by my chemistry class. My aunt was an organic chemist at the University of Wyoming. She was, effectively, my mentor. There was no other scientist or engineer in the family and I regarded her as just incredible.

My aunt's name was Sara Jane Rhoads, and I used to call her the Colossus of Rhoads. She was just magnificent, really inspiring. I didn't think it was possible for anybody to be smarter than her, and a wonderful person. So that was very important in my life. That class in chemistry was very important too. My recollection is that Linda, my sister, and I finished with the top two scores in the class. She remembers she was first. I'm sure that I was. *[laughter]* I talked to Victor Gustafson, the chemistry teacher. He, unfortunately, didn't keep the records. *[laughter]*

DAVIS-FLOYD: I bet he's glad he didn't keep them. Nobody wants to solve a question like that. What did your sister go on to do?

SMALLEY: She went to the University of Michigan and got a degree in mathematics, then she taught high school in Florida for a number of years until she got married and raised a family. Now she's working for the Mayo Clinic in the development office.

Cyborgs and Nanotech: Imagining the Future

DAVIS-FLOYD: Do you know the word "cyborg?"

SMALLEY: Yes.

DAVIS-FLOYD: What does it mean to you?

SMALLEY: I think a cyborg is a living computer.

DAVIS-FLOYD: Where have you heard the word? Why do you know it? A lot of people have never heard the word cyborg, so I'm just wondering?

SMALLEY: Did I hear it on Star Trek or did I read it in science fiction books?

DAVIS-FLOYD: I don't know. That's why I'm asking.

SMALLEY: Did you create this word?

DAVIS-FLOYD: No, I did not. It was actually created by Klyne and Clines in an article they wrote about an astronaut in a space ship in the 1960s. They were the first to coin the term—"cybernetic organism—cyborg."They were thinking about a man inside a space ship, where the technology and the human are totally interdependent with each other.

Since then the word has changed into its popular following in large part because an anthropologist named Donna Haraway wrote an essay called "The Cyborg Manifesto" back in the mid-eighties, where she took the concept of cyborg and expanded it into a whole paradigm of thinking about life and living, strongly feminist in orientation and strongly pro-technology with a humanistic flavor. She even says we are all cyborgs now because we have become so codependent and interwoven with our technology. So she uses the word to talk about human-technology interfacing, human-technology co-evolution.

SMALLEY: What would feminists say?

DAVIS-FLOYD: Well, because she is a feminist, she was careful not to frame “The Cyborg Manifesto” as a masculinist or patriarchal kind of concept where the machine dominates humans or organisms or men dominate women, but rather to talk about the possibility of a cyborg future, in an egalitarian, postmodern way, one full of multiplicity and diversity, one in which humans become more mechanical, machines become more organic and there are multiple possibilities that result from all of those possible combinations. You said, "A living computer." Your nano-technology extends the concept of cyborg.

For instance, if you have an artificial arm, a prosthesis, that would automatically put you under her definition of cyborg, but if you go down to the nano level, if you start sticking nanotubes into human cells and wrapping DNA around them or wrapping organic molecules around them and unblocking heart valves as a result or expanding brain capacity or whatever, that's the deepest possible level of cyborg, the ultimate fusion of human and machine. That's why I asked if you knew the concept because it's a very rich theoretical way of thinking and talking about what you're already doing.

SMALLEY: I had no idea it had a feminist angle. This is fascinating.

DAVIS-FLOYD: I don't imagine that you envisioned the possibility that comes from your nanotechnology in ways of somebody having power over somebody else because of it. Don't you imagine it more in terms of the possibilities that exist for everyone as a result?

SMALLEY: Well, I do, but I can imagine that, like all new technology, it could end up having its down side too.

DAVIS-FLOYD: Well, that's why Haraway frames it in this particular way.

SMALLEY: As a manifesto.

DAVIS-FLOYD: Exactly. So that *imagining* that kind of future for the cyborg is a way of helping *create* that kind of future for the cyborg. Rather than assuming the cyborg will follow the same patriarchal, technology-dominant, capitalist, "rules the rest of the world" kinds of scenarios that have already played out, she envisions an egalitarian kind of future that levels the playing field and brings everyone's capacities to more or less equal levels, with multiplicity and diversity, but not necessarily with “power over.” This may not be the way these technologies will play out, but this is how she wants it to play out, as expanded opportunity for all rather than expanded power for the few. It's a way of thinking about questions about what you're doing.

SMALLEY: I'll make it part of my freshman seminar next year. *[laughter]* It will give me a new angle on it.

DAVIS-FLOYD: Well, when I saw that poster on the wall, with the nanotube, the fullerene wrapped around the organic molecule, that's what made me think about it. Have you worked in biotechnology? Obviously, this is a deeper level than biotechnology.

SMALLEY: I'm very interested in it and I think it'll get to be much more important as time goes on, if I can ever get off this deal of bucky tubes and a stronger elevator to space and so forth.

DAVIS-FLOYD: *[laughing]* What *is* the elevator to space thing about?

SMALLEY: You're just not catching this, are you? You just don't get it, do you? You know about Arthur Clarke? *[laughing]* Have you read <u>Fountains of Paradise</u>? No. Have you read the book <u>3001</u>?

DAVIS-FLOYD: I've never read anything Arthur Clarke wrote.

SMALLEY: Well, you see, that's why you don't get it. The story is if, in fact, you can do this, if you can make something strong enough, build a cable and there are no other problems, you can really take an elevator to space and the cost of getting to space goes down so much that in Arthur Clarke's latest, and probably last book, 3001, he envisions that by 3001 the inhabited world consists of a giant ring that surrounds the planet from hundreds of kilometers up. It's hung by four cables and the earth is now a giant park and the only rockets that are set off are on the 4th of July as a historical tribute. The space elevator is the answer to how humanity was liberated from the confines of the planet. In the latest edition, he says this idea has become much more plausible now that Dr. Smalley in Houston has learned to form bucky tubes. *[laughter]* So you see this is my little job in life!

I'm not so sure that I'm gonna be able to get into to the biotech thing. But we're very interested in bio-tech and Rice, itself, one way or another, will probably, over the next five years, launch a major push for nanobiology, the nanotechnology aspect of bio-tech.

DAVIS-FLOYD: Who coined the term nano-technology?

SMALLEY: I understand some Japanese person gets credit for that.

DAVIS-FLOYD: When did you first hear the word?

SMALLEY: I heard it reading Eric Drexler's book in 1992.

DAVIS-FLOYD: So you had already discovered fullerenes before anybody was calling this "nano-technology."

SMALLEY: Yes.

DAVIS-FLOYD: What were you calling it?

SMALLEY: It was "supersonic beam laser vaporization cluster—" *[laughter]* I've come along the path a little bit since.

DAVIS-FLOYD: How did you feel when you heard the word "nanotechnology"?

SMALLEY: Well, I picked up one of Eric Drexler's book on one of my little forays to the bookstore and read it mostly in the bathtub and I just thought it was really neat. It bothered me—what's wrong with this picture? If it was really right, then all the chemistry we've learned would be irrelevant—we'd just tell one of the nanobots to go build a molecule and that would be it, and we'd just stick them together as if they were Legos. It kept on eating at me until finally I thnk I saw what's wrong with the picture. Regardless of what is wrong with the Drexler book, it affected me pretty deeply. Eric did something pretty remarkable and I think his Foresight Institute actually has done some very good things. They have a conference every year and the past three or four years it's really been an excellent conference. They really have had the guts to open up and consider *any* way of getting to nanotechnology, not just Drexler's nanobots.

Drexler himself is difficult to engage on this topic, at least he was the last time I talked to him, which was a year ago. I tried to talk to him about what I think is the fatal flaw and he just didn't want to consider it in depth. His theory is too naïve; in reality it won't be nearly so simple—the much more complex nature of reality will almost certainly prevent a nanobot from existing in the first place. (If they could exist, it would be a totally alien new life form.) I thought it was a parlor game, but after this article by Bill Joy in *Noir* magazine, titled "Why the Future Doesn't Need Us," I realized it was a more serious problem. The article voices deep concern that we're about to elimate the human race--the nannites will run amok and outmode civilization. That's a silly fear and we will do ourselves great harm to be terrorized by such a silly dream. Turn on the lights, wake up, it's not as scary as it seems. We're not Frankensteins creating a dangerous new life form

Chris Peterson, Drexler's wife, is the one who organizes everything. She's very good and the whole group has been very effective in embracing the broader view. And now that the president has decided to accept, and make as his own, an initiative with the word "nanotechnology" and all the agencies have gotten on board, it's okay now. The word has been cleansed. *[laughter]* For a long time we didn't know whether it was going to be cleansed or not. It's okay now, it’s in the mainstream.