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Much Ado About (Almost) Nothing

A paper presented to the Sphex Club of Lynchburg
January 31, 2008

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Over the past thirty years, I have occasionally been invited to speak to one particular local Rotary Club. A former student (and before him, his father) will call to invite me and suggest a topic—usually something I know absolutely nothing about. When he called last spring, he suggested that I talk about the "Space Elevator" project—as usual, something totally unfamiliar to me. As he explained it, the idea is to build an elevator that could move payloads from the surface of the earth into orbit, bypassing the need for the expensive and dangerous space shuttle. I thought to myself—"that's a ridiculously impossible idea!"—but I agreed to do some reading and see if I could create a talk.

Imagine my surprise when an Internet search turned up a huge amount of information—including a for-profit company dedicated to its construction, NASA websites and NASA-sponsored competitions for a solar powered drive mechanism to lift such payloads. My initial skepticism was fueled by my understanding of the basic limitations on the height of structures, based on the ultimate strengths of the materials out of which they are built. Using the best estimates of the strongest metals, structures will inevitably collapse at heights measured in miles and not in tens or hundreds of miles. But I had not been paying sufficiently close attention to some very interesting developments in materials science—my own research field—and that leads to the subject of tonight's talk—the science of very small structures. I'll say a bit more about the space elevator later. But first, I have to take you into the world of the very small.

I am holding a piece of calcite. It is hard and strong. It is tangible! But I assure that, quite contrary to your sense perceptions, it's mostly empty space! This single crystal is made up of atoms of calcium, carbon and oxygen arranged in the highly ordered fashion that we call crystalline. Each atom is about one ten billionth of a meter in diameter. One billionth of a meter is called a nanometer, so atoms are about a tenth of a nanometer across. Most solids are crystalline—a term that simply means that all of the atoms in the interior share identical neighborhoods. The crystal structure arises from electrical forces between the atoms—forces that bind the crystal together and that determine not only the structure, but also the properties of the solid material. Further, the atoms themselves are bound together by electrical forces. Since the early part of the last century, we have understood that each atom consists of a tiny nucleus, containing positive electrical charges, surrounded by a negative charge distribution which is, loosely speaking, comprised of negatively charged electrons. All of you have seen this "solar system" picture of an atom. What you may not have fully realized is that almost all of the mass of an atom resides in the nucleus, which is one hundred thousand times smaller than the atom. If you were to imaging enlarging a nucleus to the size of a basketball, for example, it would be about 12 inches in diameter. The atom would then be about 100,000 ft in diameter—a sphere about 20 miles across. Between one and 92 electrons, each smaller than a pea, would be scattered throughout that very large sphere.

You might think that the physics that describes the motion of planets and baseballs would be applicable at the atomic scale, but the physics of small things is more complicated than that. First, you have to consider the effects of scale. You all know what a scale drawing is, but there are some aspects of scaling that are typically considered only by physicists and engineers. As you change the scale of an object, you change every linear dimension by the same factor. But the surface area of the object changes by the scale factor squared and the volume of the object changes by the factor cubed. The relative surface area, or the surface area to volume ratio, changes inversely with the scale factor. As the size decreases the surface area to volume ratio increases.

On a practical note, this is why we grind sugar and other materials to make them dissolve more readily—more surface area is exposed as the pieces become smaller. Organisms exhibit a variety of modifications, both physiological and anatomical, to compensate for changes in the surface area to volume ratio associated with size differences. Small mammals have prodigious appetites—they have relatively larger surface area to volume ratios and so lose heat to the environment at a faster rate than do larger animals. Thus they have high rates of metabolism to offset the heat loss. Elephants have evolved very large ears to dissipate excess heat because their surface area to volume ration is comparatively very small. An elephant may weigh 200,000 times the weight of a mouse, but needs only 10,000 times the mouse's daily food intake. All of this means that as we look at smaller and smaller objects, surfaces and surface effects become more and more important in determining the characteristics of the objects.

Engineers must pay careful attention to the behavior of structures as they move from scale drawings to the actual structure. The reason is simple—the volume does not scale at the same rate as do the dimensions. In other words, doubling the size of a cube causes its volume to increase by a factor of eight, while its surface area increases only by a factor of four. You've all seen the bad science fiction movies about rampaging giant rabbits, or lobsters, or ants—all mutations caused by nuclear radiation. You may have watched an ant carrying a crumb seemingly larger than itself and marveled—wondering how much it could lift if it were human-sized. So how much would a giant ant be able to lift? The answer is—not even its own weight. If the size of the ant increased by a factor of 100, its volume would increase by a factor of 100 cubed—or 1000000—as would its weight. The cross sectional area of its structural members would increase only by a factor of 100 squared—or 10000. Since the structural strength is proportional to this area, the ant would simply collapse under its own weight. Think about the difference between an elephant's legs and a cow's legs. The cross-sectional area of the elephant's leg bones is far greater in proportion to other body dimensions than is the cow's.

Along a surface, the atoms experience unbalanced forces. These forces, which pull the surface atoms in toward the bulk material, create a "surface tension," not unlike the surface of a balloon or soap bubble. Surface tension causes small amounts of liquid to "bead up." A detergent simply acts to reduce the surface tension of water so that the water can flow between the thing to be cleaned and the particles of dirt—lifting them away. Surface tension has little to do with the behavior of macroscopic solids, but as objects become smaller, the greater ratio of surface area to mass means that surface tension can actually be sufficiently large to change the physical behavior of the atomic array.

Further, on this scale, the physics understood by Isaac Newton does not apply—rather the newer "quantum" physics provides the primary explanatory theory. Distinctions between energy and matter, between particle and wave are blurred at best and may not even exist at this scale. Quantum physics is strange indeed and is best left for a future talk.

Forty years later, that prediction came true and since then everything has changed. Before explaining how we came to this point, let me explain a bit about how we see things. Obviously, at least to us, light from the object we're seeing has to enter our eyes. It's much less obvious that there exists a relationship between the size of the object we see and the wavelength (or fundamental size) of the light we're seeing it with. Our eyes are sensitive to radiation whose wavelength ranges from about 400 nm (violet) to 700 nm (red). These wavelengths are approximately 1000 times longer than the size of atoms. In order to be scattered from an object and thus to enter our eyes, the wavelength has to be nearly as small as the object we're trying to see. Long wavelengths simply go around small objects. For example, elephants can communicate over great distances by making very low frequency, long wavelength sounds that are inaudible to us. These sounds travel around trees and through forests as if they were not there. Or, the shorter wavelength, blue part, of the light emitted by the sun is scattered by particles in the atmosphere, causing the sky to appear blue. The longer red waves are much less scattered, causing the sun to appear red when low on the horizon.

More critical to seeing is the idea of resolution. Imagine that you are on a high cliff, watching a distant light approach you along the valley floor. It looks like a single light, but as it approaches, at some point you are able to resolve the image into two separate lights. This ability to resolve objects that are very close to each other depends on two factors. First, it is directly proportional to the wavelength of the light--the smaller the wavelength, the greater your ability to resolve small objects. Second, the ability to resolve depends inversely on the size of the aperture, or opening, through which you are looking. The larger the aperture, the greater the resolving power. Larger telescopes have greater apertures and thus greater resolving power at any wavelength than do smaller instruments.

All of this means that, given the wavelengths of light, we will never be able to actually see individual atoms. But wait, one of the strange consequences of the quantum theory is the blurring of the distinction between waves and particles. It turns out that particles such as electrons can act like waves—the higher the energy, the smaller the wavelength. So we can build electron microscopes that have much greater resolution than any optical microscope. Won't they allow us to "see" atoms? Ironically, to create electron waves sufficiently small to resolve atoms, we have to create electrons that have high energies. That's very easy to do, but the necessary energies are just large enough to tear apart the atoms that we're trying to see. Again, there is little hope of seeing an atom by using an ordinary electron microscope.

Science done at a scale of tens to hundreds of nanometers and smaller is termed nanoscience, and nanoscience has led to the possibility of a series of applications called nanotechnology. Although the actual scientific research upon which much of nanoscience rests began early in the 20th century, the idea that small structures could be useful probably began with a paper entitled "There's Plenty of Room at the Bottom, delivered by Richard Feynman to a meeting of the American Physical Society in 1959. Feynman speculated that we would learn how to manipulate individual atoms and that we would then be able to construct things on the scale of a few atoms, which of course we can't possibly see.

Early in 1980, physicists resorted to a different way of seeing. The scanning tunneling microscope, whose inventor received a Nobel Prize, uses another quantum phenomenon—tunneling--as its basis. Tunneling simply means that, on the atomic scale, particles may go where Newton's physics would predict that they cannot go. If I throw a ball against the wall, it will always bounce back. Tunneling means that there is some finite and calculable probability that the ball will penetrate the wall and exit unscathed on the other side. Tunneling allows alpha particles to escape from a uranium nucleus, for example. In the STM, tunneling allows electrons from a surface to move through a vacuum onto the tip of a tiny probe, creating an electric current. In turn this current can be turned into information about the surface below the probe tip. So, moving the probe over a surface, or scanning the surface, allows one to form an image of that surface—an image with horizontal resolutions approximately the size of one atom and vertical resolutions about ten times smaller.

Instead of using the tunneling current, another type of microscope called an atomic force microscope, mounts the probe on a tab or cantilever. As the tip of the probe moves over the surface, it experiences forces due to the atoms in the surface and the cantilever flexes in response to these forces. The degree of deflection is measured and converted to information about the forces, or to information about the surface contour. This is quite analogous to the manner in which a phonograph needle extracts information that can be converted to sound as it moves up and down and side to side in the groove of a record.

These two technologies allow us essentially to "see" individual atoms. But that's only half the difficulty. In his 1959 lecture, Feynman had said "But I am not afraid to consider the final question as to whether, ultimately---in the great future---we can arrange the atoms the way we want; the very *atoms*, all the way down! What would happen if we could arrange the atoms one by one the way we want them." In 1990, IBM scientists did just that. They published a remarkable photograph, in which individual atoms of xenon were arranged on a nickel surface to spell out the letters IBM. The arrangement was made by using the tip of an STM probe to push the individual atoms into place.

As I said earlier, everything you see is made of atoms. If we change the arrangement, we can change the properties of the material. Carbon exists in several forms. One of these is an amorphous form that we call soot or lampblack. Arrange the carbon atoms so that they form hexagonal arrays in planes and you have graphite. The planes slip over each other with great ease, giving graphite its lubricating quality and making it suitable as pencil lead. Change the structure into a three-dimensional cubic structure and you have diamond. If we rearrange the atoms in soil, water and air, we can make carrots or corn.

We have great difficulty in envisioning manufacturing at the molecular level. The usual fabrication techniques such as milling, turning, or casting move atoms in very large numbers. Anything large enough to be seen with the unaided eye has tens of billions of atoms. As one author has said, it's akin to trying to build something out of Legos with boxing gloves on your hands. You can pile the blocks up, but you can't snap them together.

True nanoscience or nanotechnology will eventually allow us to snap the blocks together into whatever shape we wish. The brute force methods used in conventional macroscopic manufacturing are giving way to more sophisticated techniques. Lithography, for example, now allows the deposition of line widths on the order of 1000 nm and smaller, resulting in ever smaller wires and components for computer chips and other microelectronics. But such techniques which require the creation of a “mask” and the deposition of material onto a surface below the mask, roughly analogous to stenciling, are not appropriate for, say, placing individual atoms at specific sites on a surface substrate. Although such a technique is often referred to as nanoscience, it’s really at the upper limit of true nanoscience. Sometimes, the actual nanoscience or nanotechnology is referred to as molecular nanoscience. Its general aims are to develop techniques that will allow us to place every individual atom precisely where we want it to be, to create any imaginable molecular structure consistent with the laws of physics and to do so cheaply and repetitively.

In the mid 1980s, physicists discovered a new form of carbon, an almost perfectly spherical molecule containing 60 carbon atoms arranged in a series of hexagons and pentagons. They named the molecule BuckminsterFullerene, after the American architect who pioneered the use of the geodesic dome. The common name is Buckyball. By the early 90s, scientists found yet another form of carbon—another “fullerene,” in which the atoms are arranged in a tubular structure, as if a plane of graphite had been wrapped around on itself to form a cylinder. It’s somewhat like a roll of chicken wire—except that the diameter of the tube was a few nanometers and its length was a few microns. Also, multi-walled tubes were observed to be more like “Russian dolls” as opposed to a continuous roll. As researchers scrambled to study both forms, it was immediately apparent that carbon in these forms had properties quite unlike other forms. Buckyballs are very stable and can withstand extremely high temperatures and pressures. The stability of the molecule led to its initial discovery. The carbon atoms in a buckyball can react with other atoms and molecules, while maintaining the basic stable spherical structure. Nanotubes have even more interesting properties. They are very strong in tension, with strengths orders of magnitude above steel and other metals. Nanotubes are six times lighter than steel and as stiff as diamond. Yet they are far more flexible than the graphite in your golf club or tennis racquet. They may be metallic conductors or semiconductors, depending on the actual structure—how the tube was formed. It’s possible to have two or more concentric nanotubes, one acting as a conductor and the other as an insulator.

Buckyballs and nanotubes are relatively easy to make—they are present in ordinary soot; we just could not see them until recently. They have already found important applications as building blocks for more complex structures. Nanotubes have been made into fibers, long threads and even fabrics. They have been incorporated into very tough plastics, toxic gas detectors, and computer chips. Researchers have recently learned how to separate the metallic form from the semiconductor form, with the result that we can form nanowires, which will eventually connect nanotransistors—packing far more electronics into a given volume than is currently possible, and making possible far more powerful computers and much more compact data storage.

You may be wearing trousers or a jacket that has been coated with nanoparticles to make it both water and stain-resistant. You may be using a sun screen that contains nanoparticles to increase its ability to absorb solar radiation. The most widespread current use of nanotechnology is in cosmetics - particularly foundation powders, since the particles can fill in tiny blemishes. Nanoparticles can be used to improve the energy efficiency of traditional materials. Cambridge University scientists are working to develop very long-life light bulbs. Nanoparticle-based fuel additives may improve fuel efficiency, particularly in Diesel engines and scientists have recently used nanoparticles in the development of new fuel cell technologies. In 1995, it was recognized that carbon nanotubes are excellent sources of field-emitted electrons. Five years later, the "jumbotron lamp," a nanotube-based light source that uses these field-emitted electrons to bombard a phosphor, was available as a commercial product. (Jumbotron lamps light many athletic stadiums today.) By contrast, the period of time between the modeling of the semiconducting property of germanium in 1931 and the first commercial product (the transistor radio) was 23 years. Researchers have created a working nanoradio, made of a single carbon nanotube and are currently designing a new generation of solar cells, using forests of nanotubes.

Nanoengineering is extremely complex. At these sizes, as already described, building from the "top down" is essentially impossible. Scientists are working toward many techniques for building from the "bottom up," assembling nanostructures one atom at a time. Some nanomaterials, such as nanowires and other simple devices can assemble themselves under the right conditions. Many researchers are working to understand and demonstrate principles of self assembly. In some experiments, proteins, DNA, bacteria and other microorganisms are being used to assemble nanomaterials.

It appears that in the immediate future, the primary use of nanotechnology may well be in the development of new medical processes and devices, in development of new catalysts for industry, and in the area of nanoelectronics.

The research literature is full of references to medical uses. As one example, last week, scientists from UCLA and Northwestern University published a study about a localized and controlled drug delivery method that is invisible to the immune system. They used nanoscale polymer films, about four nanometers per layer, to build a sort of matrix or platform to hold and slowly release an anti-inflammatory drug. The films are orders of magnitude thinner than conventional drug delivery coatings. Tiny chips were coated with layers of the nanoscale polymer films, which are inert. The films provide a "cloak of invisibility" for the chips, hiding them from the body's natural defenses. They then added Dexamethasone, an anti-inflammatory drug, between the layers. The chips were implanted in mice, and researchers found that the Dexamethasone-coated films suppressed the expression of cytokines, proteins released by the cells of the immune system to initiate a response to a foreign invader. Mice without implants and those with uncoated implants were studied to compare immune response. The uncoated implants generated an inflammatory response from the surrounding tissue, which ultimately would have led to the body's rejection of the implant and the breakdown of its functionality. However, tissue from the mice without implants and the mice with the nano-cloaked implants were virtually identical, proving that the film-coated implants were effectively shielded from the body's defense system.

This is but one example of an incredible array of approaches to using nanoscience to deliver drugs precisely to the desired point of impact. There are research level techniques that allow nanobullets to effectively seek and destroy particular cells or types of cells. It turns out that cancerous cells have a different surface hardness from normal cells. Nanodevices can already detect those variations in hardness and may one day be able to inject drugs directly into cancerous cells while not attacking normal cells. Other research is pursuing the possibility that nanoparticles can interfere with a cancer cell's ability to grow by effectively starving it.

Research in nanotscience has already provided techniques for detecting and filtering toxins and will be especially useful in removing heavy metal and organic chemicals from water supplies. The catalytic converter on your car is more efficient and longer lived because of the extensive use of nanoparticles in the fabrication process. Light emitting diodes may well eventually replace conventional light bulbs.

In another vein, nanoscience may also hold the key to high-powered adhesives. Geckos' hairy feet alllow them to cling to the slickest vertical surfaces, even by a single toe. Scientists from RPI and the University of Akron have created a carpet of carbon nanotubes that mimic the structure of the hairs on a gecko's foot, creating an adhesive power 200 times stronger than the actual foot hairs.

As with any new technology, ethical concerns are and should be part of the process. In some ways the debate is similar to those engendered by the human genome project and other forms of biotechnology research. For example, we are introducing genetically engineered plant species into the environment with incomplete information on their long term effects. Because nanoparticles are so small, they can travel easily through skin cells and thus become part of the biological process. Some groups have asked for a moratorium on nano research, pointing out that we know very little about the toxicological effects of nanoparticles and that there are no regulations to control them. Some evidence indicates that high concentrations of nanotubes could damage the lungs of mice and that buckyballs might accumulate and cause brain damage in fish.

Eric Drexler is sometimes credited with many of the fictional ideas that inspired nanoscience research—he coined the term nanotechnology. In his 1980s novel "Engines of Creation," he described a extreme view of a future in which self-replicating nanorobots take over, essentially digesting every living thing on earth and leaving only a "grey goo."

Greenpeace has been an active voice in the environmental community and, as a result of an interesting joint discussion with Cambridge University scientists, they concluded that while the risks might be real, the innovations could also genuinely benefit the environment. Nevertheless, the environmental concerns are real and the debate continues.

And then there is the space elevator. A major hurdle in space exploration is the cost of getting massive objects into space. In a 1970s science fiction novel (The Fountains of Paradise), Arthur C. Clarke conceived the idea of a space elevator which would simply lift objects into geosynchronous orbit, avoiding rockets altogether. As presently planned, the space elevator would be a 62,000-mile (100,000-kilometer) cable, along which would ride some sort of carriage. Payloads would be lifted up the cable into space, avoiding the necessity for large launch forces, etc.

A space elevator would require simply a cable with one end attached to the Earth's surface stretching upward, to a point well beyond geosynchronous orbit, at 21,700 miles (35,000-kilometer altitude). Think about tying an object to a string and whirling it around your head. Your hand pulls the string continually inward. The string in turn pulls on the object causing it to move in a circle. The object pulls on the string, keeping it taut. For the elevator, the force of gravity at the lower end and centripetal acceleration at the farther end keep the cable under tension. The cable would remain stationary over a single position on Earth. Once deployed, the cable would be scaled from Earth by mechanical means right into Earth orbit. An object released at the cable's far end would have sufficient energy to escape from the gravity tug of our home planet and travel to neighboring the moon or to more distant interplanetary targets.

While conceptually simple, the problem has been finding a material sufficiently strong to make the cable--"unobtainium." The nanoanswer is a carbon-nanotube-composite ribbon. Small fibers of carbon nanotubes are placed side-by-side, then interconnected to form a growing ribbon. Many companies, both here and abroad, are now ramping up production of carbon nanotubes and soon they will be available in amounts measured in tons. The major hurdle has been the commercial fabrication of carbon nanotubes. Both U.S. and Japanese firms, among others, are ramping up production of carbon nanotubes, with tons of this now exotic matter soon to be available. Planners speculate that, given the great strength carbon nanotubes, a space elevator could be a reality within a decade.

Two space shuttle flights would lift 20 tons of carbon cable amounted on a reel into near earth orbit. The cable and reel would be lifted up to geosynchronous altitude by an upper stage motor. The cable would then be snaked to Earth and attached to an ocean-based anchor station, situated within the equatorial Pacific. That platform would be similar to the structure used for the Sea Launch expendable rocket program.

NASA is currently sponsoring annual competitions for schemes to lift the platform. Initial ideas are to use sunlight, or high energy laser beams, or even particle beams to provide the energy needed to operate the crawler motors as the platform rises. Once the initial cable is in place, the platform could be used to add more and more ribbon until the elevator is capable of moving 20-ton payloads. Current budget estimates indicate a cost of less than $10 billion for the project, which could launch a multi-ton payload twice a week.

In 2003, a group of companies dedicated to building the LiftPort Space Elevator joined to become the LiftPort Group. Their aim is to develop a mass transportation system to open what they consider to be the “vast market opportunities that exist in space.” Their website has a countdown clock to October 27, 2031 for the opening of their first space elevator. Interestingly, the group’s motto is “Change the world or go home.” Perhaps that’s a fitting place to end this discourse.