THE SPACE ELEVATOR:
Use of carbon nanotubes to link Earth and Space

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December 12, 2003
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**Project Summary**

The creation of commercially available carbon nanotube cables would be a significant technological breakthrough that would touch almost all forms of engineering. Carbon nanotubes have the potential to be used in circuitry, data storage, and interspace travel, but our focus will be on the use of nanotube cable used in the creation of a space elevator. The benefits gained from the use of a space elevator are fantastic when compared to the conventional rocket model: The first elevator’s projected cost to build is only $10 billion which it is believed will be recouped within the first ten years of operation. It is also estimated that it would only cost a hundred dollars a pound to put cargo in space using the space elevator as compared to the current price of $10,000 to $40,000 dollars a pound using rockets. The carbon nanotube technology is what makes this possible: a ribbon ten to twenty centimeters wide and only microns thick is capable of supporting loads of 990 kg. The ribbon can withstand the impact of small meteors and other debris and will allow a roller traction drive climber to ascend at rates of 200 km/hr. In future models the space elevator may be able to support loads approaching 100,000 kg which will make human transport possible.

**Introduction**

First predicted in a famous lecture given by the late professor Feynman, “There is more room at the bottom,” the carbon nanotube is a newly discovered allotrope of carbon and also constitutes its fourth crystalline state.

There are two varieties of nanotubes, single-walled and multi-walled nanotubes. The single-walled variety is composed of a single graphene sheet rolled into a tube. The multi-walled nanotubes are composed of several concentric single-walled nanotubes.

(single-wall nanotube)

(multi-wall nanotube)

**Nanotube Properties**

This miraculous structure is essentially a graphitic sheet rolled into a tubular shape and possesses extraordinary potential due to its
unique physical, mechanical and electrical properties. Physically, nanotubes can possess lengths millions of times larger than their diameters while still possessing low weight and extremely high Young's moduli (could approach 1.25 terapascals for both single and double walled types). They are also extremely sturdy (one hundred times stronger than steel and only one sixth the weight) due to very strong planar carbon bonds lending to their high tensile strengths and moduli. In the electronic realm carbon nanotubes also have significantly favorable properties. In general, they conduct electricity on a level equal to that of copper and heat better than diamond. Electrons can propagate freely in them similarly to the way they do in metals (because they are not localized) and are emitted at a low voltage while maintaining a high current density yielding low power requirements. Nanotubes also are extremely electrically versatile, depending on the dopants introduced into the material the tubes may act as metals, semiconductors or even insulators.

An ideal nanotube can be described as a seamless cylinder rolled from a hexagonal network of carbon atoms. Although only a few nanometers in diameter, the length of the cylinder can be tens of microns long, where each end is "capped" with half of a fullerene molecule. Many theoretical studies have predicted the properties of single-wall nanotubes.

Structure

Using high-resolution microscopy techniques, the structure of carbon nanotubes has been explored. These experiments have proven that nanotubes are cylindrical structures based on the hexagonal lattice of carbon atoms that forms crystalline graphite. There are three types of nanotubes that exist. These are called armchair, zigzag, and chiral nanotubes, depending on how the two-dimensional graphene sheet is "rolled up." The defining difference between the different types is clearly illustrated in terms of the unit cell of the carbon nanotube.

A carbon nanotube is based on a two-dimensional graphene sheet. (a) The chiral vector is defined on the hexagonal lattice as $C_h = n\hat{a}_1 + m\hat{a}_2$, where $\hat{a}_1$ and $\hat{a}_2$ are unit vectors, and $n$ and $m$ are integers. The chiral angle, $\theta$, is measured relative to the direction defined by $\hat{a}_1$. This illustration has
been created for \((n, m) = (4, 2)\), and the unit cell of this nanotube is bounded by OAB'B. To form the nanotube, imagine that this cell is rolled up so that O meets A and B meets B', and the two ends are capped with half of a fullerene molecule. Different types of carbon nanotubes have different values of \(n\) and \(m\).

As seen in illustration (b), Zigzag nanotubes correspond to \((n, 0)\) or \((0, m)\) and have a chiral angle of 0\(^\circ\), armchair nanotubes have \((n, n)\) and a chiral angle of 30\(^\circ\), while chiral nanotubes have general \((n, m)\) values and a chiral angle of between 0\(^\circ\) and 30\(^\circ\). According to theory, nanotubes can either be metallic (green circles) or semiconducting (blue circles).

- Zigzag
- Chiral
- Armchair

The properties of nanotubes are determined by their diameter and chiral angle, both of which depend on \(n\) and \(m\). The diameter, \(d_t\), is simply the length of the chiral vector divided by \(\frac{1}{4}\), and we find that \(d_t = (\sqrt{3}/\pi)a_{c-c}(m^2 + mn + n^2)^{1/2}\), where \(a_{c-c}\) is the distance between neighboring carbon atoms in the flat sheet. In turn, the chiral angle is given by \(\tan^{-1}(\sqrt{3n}/(2m + n))\).

Measurements of the nanotube diameter and the chiral angle have been made with scanning tunnelling microscopy and transmission electron microscopy. However, it remains a major challenge to determine \(d_t\) and \(\theta\) at the same time as measuring a physical property such as resistivity. This is partly because the nanotubes are so small, and partly because the carbon atoms are in constant thermal motion. Also, the electron beam in the microscope can damage the nanotubes.

Because each unit cell of a nanotube contains several types of hexagons, each of which contains two carbon atoms, the unit cell of a nanotube therefore contains a great deal of
carbon atoms. If the unit cell of a nanotube is \( N \) times larger than that of a hexagon, the unit cell of the nanotube in reciprocal space is \( \frac{1}{N} \) times smaller than that of a single hexagon.

**Nanotube Fabrication**

The main obstacle in bringing the full spectrum of nanotechnology into the business realm lies in the fabrication of the tubes. Presently, it is an extremely expensive and laborious task. However, researchers all over the world are searching for a low cost, effective method of production for the nanotubes.

Currently, there are three main methods of fabrication: Chemical Vapor Deposition, the Arc Method, and Lithography.

Chemical Vapor Deposition involves the heating of a catalyst material to a high temperature in a tube furnace and flowing hydrocarbon gas through the tube reactor. This dissociates the hydrocarbon molecules catalyzed by the transition metal and dissolves and saturates carbon atoms in the metal nanoparticle. The materials are grown over the catalyst and collected when the system is cooled to room temperature. This method works for both single and multiple walled nanotubes.

The Arc Method involves the vaporization of carbon atoms by a plasma of helium gas that is ignited by high currents passed through an opposing carbon anode and cathode.

The Lithography Method can be subdivided into three more specific categories: Standard Lithography, Shadowmasking, and Soft Lithography. Standard Lithography uses a series of masks and photoresist to pattern the catalyst material on which the nanotubes will be grown through CVD. Shadowmasking uses the same methodology as Standard Lithography with the exception that a Shadow mask is used in place of the conventional mask. Soft Lithography uses an ink/stamp method to pattern the catalyst.
When a relatively efficient way to produce bundles of ordered single-wall nanotubes was found by the Rice University group in 1996, it opened new opportunities for quantitative experimental studies on carbon nanotubes. These ordered nanotubes are prepared by the laser vaporization of a carbon target in a furnace at 1200°C. A cobalt-nickel catalyst helps the growth of the nanotubes, presumably because it prevents the ends from being "capped" during synthesis, and about 70-90% of the carbon target can be converted to single-wall nanotubes. By using two laser pulses 50 ns apart, growth conditions can be maintained over a larger volume and for a longer time. This scheme provides more uniform vaporization and better control of the growth conditions. Flowing argon gas sweeps the nanotubes from the furnace to a water-cooled copper collector just outside of the furnace.

Catherine Journet, Patrick Bernier and colleagues at the University of Montpellier in France later developed a carbon-arc method to grow similar arrays of single-wall nanotubes. In this case, ordered nanotubes were also produced from an ionized carbon plasma, and joule heating from the discharge generated the plasma. Several other groups are now making bundles of single-wall carbon nanotubes using variants of these two methods. However, the Rice group has had the largest impact on the field, largely because it was the first to develop an efficient synthesis method and has formed many international collaborations to measure the properties of single-wall nanotubes.
In a scanning electron microscope, the nanotube material produced by either of these methods looks like a mat of carbon ropes. The ropes are between 10 and 20 nm across and up to 100 µm long. When examined in a transmission electron microscope, each rope is found to consist of a bundle of single-wall carbon nanotubes aligned along a single direction. X-ray diffraction, which views many ropes at once, also shows that the diameters of the single-wall nanotubes have a narrow distribution with a strong peak.

For the synthesis conditions used by the Rice and Montpellier groups, the diameter distribution peaked at $1.38 \pm 0.02$ nm, very close to the diameter of an ideal $(10, 10)$ nanotube. X-ray diffraction measurements by John Fischer and co-workers at the University of Pennsylvania showed that bundles of single-wall nanotubes form a two-dimensional triangular lattice. The lattice constant is 1.7 nm and the tubes are separated by 0.315 nm at closest approach, which agrees with prior theoretical modeling by Jean-Christophe Charlier of the University of Louvain-la-Neuve in Belgium and co-workers.

While multi-wall carbon nanotubes do not need a catalyst for growth, single-wall nanotubes can only be grown with a catalyst. However, the detailed mechanisms responsible for growth are not yet well understood. Experiments show that the width and peak of the diameter distribution depends on the composition of the catalyst, the growth temperature and various other growth conditions. Great efforts are now being made to produce narrower diameter distributions with different mean diameters, and to gain better control of the growth process. From an applications point of view, the emphasis will be on methods that produce high yields of nanotubes at low cost, and some sort of continuous process will probably be needed to grow carbon nanotubes on a commercial scale.

(Dispersion relations in nanotubes)

**Nanotube Ribbon**

The carbon nanotube ribbon is the key to the Space Elevator's success. Its strength, size, and capability are the cornerstones of this concept. A nanotube ribbon is composed of a sheet of carbon nanotubes that have been grown together using an electric potential. As discussed earlier, it is extremely difficult to grow nanotubes in an ordered fashion, however, using an electric potential can generate small sections of nanotubes that can be used as building blocks for the Elevator ribbon. In the image below, the nanotubes shown in the left half of the picture are evidence of the functionality of using an electric potential, whereas on the right, are typical, unordered carbon nanotube growth patterns.
As initially designed, the ribbon is 10 cm wide x 100,000 km long. Currently it is impossible to grow something of that magnitude (see below), so much smaller sections of the ribbon will be fabricated and then joined together.

Through careful joining, we can achieve a ribbon as seen in the following picture. This ribbon will be able to support up to 10,000 kg of cargo with a safety factor of 2. Considering the weight of the climber, the natural frequency of the ribbon, and various other environmental factors, the ribbon is designed to withstand a maximum 20,000 kg of cumulative load.

This nanotube ribbon will span the entire distance from the docking station to the orbiting anchor satellite. Initial plans are for the climber to join sections of the ribbon until the full length is achieved. The climber will travel up and down the ribbon, joining more and more segments until the ribbon is complete. Below is a schematic of the sections of ribbon that will be joined together. The climber will use a bonding agent to join individual sections (still yet to be developed).

Fig. 1 – Evidence of how using an electric potential can produce ordered nanotube growth.

Current capabilities for nanotube growth
The ribbon is not a rigid structure. Due to the sectioning approach to assembly, the necessity for the docking station to be mobile, and the complexity of weight distributions, the ribbon will be a flexible entity. This helps protect the ribbon in environmental situations (hurricanes), natural oscillations (can be actively damped by the anchor station), and gravitation effects from the orbiting anchor. The ribbon allows for minor changes in attitude, which prevents violent forces on both the anchor station on the Earth and in orbit. Once complete, the ribbon will act as the bridge between Earth and space.

The Space Elevator

The Space Elevator is a carbon nanotube ribbon attached to a floating sea anchor at one end and a geosynchronous satellite at the other. Powered by a free electron laser, a robot climber is sent up the ribbon into space. All of this is feasible using current or near future technologies. The carbon nanotube ribbon is the missing piece in the puzzle. Once it can be commercially manufactured, the elevator can get off the ground. The anchor will be the same design as a oil platform which gives it about one kilometer mobility each day; this becomes important for avoiding a crash with other orbiting satellites. The climber originates at the platform and moves up the ribbon on rollers. It is powered by a twelve-meter diameter free electron laser that beams power to receptors on the climber that then convert it into DC power. At deployment, the ribbon will not be full length or width so the first trips the climber will make will be to add ribbon to complete the elevator. The satellite at the top of the elevator will be about 100,000 km from the surface of the earth in geosynchronous orbit.

“The space elevator would allow for the lifting of large fragile structures, such as solar energy satellites which would provide clean renewable energy to Earth, inflated stations for manned activities, factories for pharmaceuticals, and payloads for exploration of space. A second generation, larger space elevator (100,000 kg capacity) would allow for extensive human activities in space including a large geo- synchronous station (hundreds of permanent
residents) and settlements on Mars within the first few years of operation.”

There are many aspects to consider when engineering this project many of which have never been considered before for any project. The location of the anchor was chosen carefully to avoid storms, high winds, and lightening. The location is literally in the middle of nowhere, about four-hundred miles from the Galapagos Islands, which means it is many miles from shipping and air traffic routes. Also, such a long ribbon will have natural oscillations. It is estimated that they will be on the order of a frequency of seven days which will be actively damped by the anchor. Space radiation was also a concern but it was calculated that the ribbon should be good for a thousand years in orbit. Many scientific concerns have been taken into consideration and there has been nothing yet that can be foreseen as a huge flaw in the project.

The next two concerns are whether this can be achieved using current materials and how much it is going to cost. The answer to the first concern is unfortunately no. The problem again is with the ribbon. If the ribbon were built from steel there would significant drag introduced to the system. The only way to correct for this would be to install small rocket boosters along the length of the ribbon. This would be unreasonable because of the amount of fuel it would take to fuel them all the time; you could never turn them off.

The second concern about cost actually has more good news than bad. The entire project is estimated at $6.2 billion, including launch costs. With the elevator up and running it will not take much time at all to see the benefits it can afford over traditional rocket launches. Currently, the cost per pound to bring cargo into space is about $50,000 a pound whereas using a space elevator it is estimated it will cost about $100 a pound. Also currently only about 4,000 pounds of cargo are taken up to space a day on average whereas with the elevator over 12,000 pounds of cargo could be taken up to space every day. It is estimated the elevator can pay for itself in less than a decade.
The ability to carry large fragile cargos into space lends itself to many interesting possibilities. The elevator will allow for large space stations with hundreds of residents and for pharmaceutical factories in space. Also since the elevator can lift objects into very high orbit it does not take much effort at all to leave the earth’s orbit from the end of the elevator which makes travel in the solar system very easy. Mars exploration, settlements, and martian elevators are all very realistic with the space elevator.

**Conclusions**

Building a 100,000 kilometer elevator into space is not science fiction; it can easily and cost efficiently be built with current and near future technologies and we could see the beginnings of one within the next twelve years. The application of carbon composite nanotube cabling when applied to the space elevator model could possibly have huge impact on quality of life on earth.

The Space Elevator is a futuristic design which is capable of transporting humans, cargo, satellites and possibly space craft into earth orbit for a relatively cheap cost compared to today’s space transportation price (10,000-40,000 dollars per pound using conventional systems). The elevator will be constructed of nanomaterials which will enable it to survive the space environment (radiation, temperature fluctuations and meteorite impacts) and the extreme forces it will be subjected to by its sheer dimensions. These revolutionary materials will also reduce the weight and size of the elevator to a fraction of the size that would be required for conventional materials. However, many obstacles stand in the path of the elevator, a majority of which deal with the fabrication of the nanotubes and how to effectively use the tubes in a construction effort.

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