this unusual behavior to construct "spintronic" devices that switch on or off in response to electrons' spin, rather than merely to their charge, as electronic devices do.

Similarly, at the small size of a nanotube, the flow of electrons can be controlled with almost perfect precision. Scientists have recently demonstrated in nanotubes a phenomenon called Coulomb blockade, in which electrons strongly repulse attempts to insert more than one electron at a time onto a nanotube. This phenomenon may make it easier to build single-electron transistors, the ultimate in sensitive electronics. The same measurements, however, also highlight unanswered questions in physics today. When confined to such skinny, one-dimensional wires, electrons behave so strangely that they hardly seem like electrons anymore.

Thus, in time, nanotubes may yield not only smaller and better versions of existing devices but also completely novel ones that wholly depend on quantum effects. Of course, we will have to learn much more about these properties of nanotubes before we can rely on them. Some problems are already evident. We know that all molecular devices, nanotubes included, are highly susceptible to the noise caused by electrical, thermal and chemical fluctuations. Our experiments have also shown that contaminants (oxygen, for example) attaching to a nanotube can affect its electrical properties. That may be useful for creating exquisitely sensitive chemical detectors, but it is an obstacle to making single-molecule circuits. It is a major challenge to control contamination when single molecules can make a difference.

Nevertheless, with so many avenues of development under way, it seems clear that it is no longer a question of whether nanotubes will become useful components of the electronic machines of the future but merely a question of how and when.

Properties of Carbon Nanotubes

Going to Extremes

	PROPERTY	SINGLE-WALLED NANOTUBES	BY COMPARISON
	**Size**	0.6 to 1.8 nanometer in diameter	Electron beam lithography can create lines 50 nm wide, a few nm thick
	**Density**	1.33 to 1.40 grams per cubic centimeter	Aluminum has a density of 2.7 g/cm³
	**Tensile Strength**	45 billion pascals	High-strength steel alloys break at about 2 billion Pa
	**Resilience**	Can be bent at large angles and restraightened without damage	Metals and carbon fibers fracture at grain boundaries
	**Current Carrying Capacity**	Estimated at 1 billion amps per square centimeter	Copper wires burn out at about 1 million A/cm²
	**Field Emission**	Can activate phosphors at 1 to 3 volts if electrodes are spaced 1 micron apart	Molybdenum tips require fields of 50 to 100 V/µm and have very limited lifetimes
	**Heat Transmission**	Predicted to be as high as 6,000 watts per meter per kelvin at room temperature	Nearly pure diamond transmits 3,320 W/m-K
	**Temperature Stability**	Stable up to 2,800 degrees Celsius in vacuum, 750 degrees C in air	Metal wires in microchips melt at 600 to 1,000 degrees C
	**Cost**	$1,500 per gram from BuckyUSA in Houston	Gold was selling for about $10/g in October

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Further Information

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