

the skin and exhaled breath. Bedbugs prefer skin areas that are not covered by clothing or beddings. To withdraw blood, bedbugs inject three types of substances through the skin: a pain killer that prevents the host from feeling the bite; an anticoagulant that prevents blood clotting; and a vasodilator, which is a substance that widens the blood vessels. Blood meals take between 10 and 20 min. How bedbugs find their way back into harborages after feeding is not entirely known. However, some chemicals that bedbugs use to repel enemies have, in low concentration, an attractive effect. Other unknown attractive substances are in the fecal spots, of which there are many in the harborages. Bedbug females in an infestation feed approximately every 2–10 days.

**Life cycle.** Females with access to food can live and continuously lay eggs for 1 year. How long bedbugs survive in untreated bedbug infestations is unknown. At high temperatures, up to approximately 30–35°C (86–95°F), females lay more eggs. Above that temperature range, bedbug females become infertile, likely because microbes (symbionts) that provide vitamins to bedbugs and that live in the bodies of bedbugs die under these conditions. Most bedbugs die when exposed to high temperatures of 48°C (118°F) [eggs: 60°C (140°F)] or low temperatures of approximately –20°C (–4°F) for 1 h.

Freshly laid eggs are 1 mm (0.04 in.) in length and whitish in color, and they hatch within 6–15 days, depending on temperature. Bedbugs undergo five nymph stages, each lasting approximately 5 days. Without a blood meal, nymphs do not molt. At each molting, bedbug nymphs increase in size by approximately 1 mm (0.04 in.). Adults do not molt. Some insecticides, called growth regulators, prevent nymphs from turning into adults. Instead, nymphs turn into a sixth stage and sometimes a seventh stage, reaching considerable sizes.

**Reproduction.** Reproduction in the bedbug is very unusual. To deposit sperm, the male uses a needlelike copulatory organ to pierce through the female's ventral (belly) side rather than using the vaginal opening. The injected sperm cells move through the female body, reach the genital tract, move through the walls of the oviduct to the ovaries, and fertilize the eggs in the ovaries. At the site where the female is usually pierced by the male, the female possesses a complex organ with antiwounding, antibacterial, and sperm-activating properties.

**Effect of bites on humans.** People vary in their response to bedbug bites, ranging from small, localized, red, itchy papules to substantial swellings of entire body parts. Few people do not respond at all to bites. People who are bitten the first or second time in their lives show a skin response at 5–10 days after the bite; this skin response occurs faster on continued biting. Development of insensitivity to bites is not known. The medical literature on bedbug bites has a poor evidence base; however, in addition to skin responses, blisterlike bullous eruptions, mental distress, and anxiety discomfort have been noted.

For background information see ENTOMOLOGY, ECONOMIC; HEMIPTERA; INSECT CONTROL, BIOLOGI-

CAL; INSECT PHYSIOLOGY; INSECTA; INSECTICIDE; PESTICIDE; PUBLIC HEALTH in the McGraw-Hill Encyclopedia of Science & Technology. Klaus Reinhardt

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## Carbon nanotube responsive materials and applications

Carbon nanotubes (CNTs) have attracted a lot of interest in the past 20 years. Superior mechanical, electrical, and thermal properties have made CNTs the desired building blocks for hybrid materials and devices at the micro- and nanoscale. Another advantage is that different forms of CNT materials have been developed for different applications. The powder form of CNTs is low-cost and useful as filler for polymers. Substrate grown CNT forests or arrays (Fig. 1a) can be micrometers to centimeters in height and can be processed into various material forms. Arrays that are spinable can be pulled into a translucent belt-like CNT ribbon (Fig. 1b). When the tension on the ribbon is released, the CNTs tend to stick together to form a strand. Ribbon or strands also can be twisted using a bench-top machine into a CNT thread with a diameter of 4–10 μm or larger. Recently, the smallest synthetic threads with a diameter of 350 nm were manufactured using a scanning electron microscope (SEM). These are called nanothreads (Fig. 1c). Two or more threads can be twisted together to form a CNT yarn (Fig. 1d). Threads can also be braided to form microbraid (Fig. 1e). CNT sheet drawn from the forest is a newly developed CNT material (Fig. 1f). The various forms of CNT materials each have different properties and are useful for specific applications.

**Carbon nanotube responsive properties.** An interesting aspect of CNT materials is that most of their properties change with their environment. For example, the electrical resistance of CNT materials can decrease with increasing applied voltage or current. The larger current heats the material and the resistance of carbon decreases at higher temperatures (opposite to the behavior of copper). The electrical impedance of CNT thread is greater than of copper at low frequencies, and lower than of copper at high frequencies. For a single CNT, the resistance will change if the CNT is bent to different angles. For a CNT ribbon or strand, small tension will decrease the electrical resistance. The double-layer capacitance of CNT thread in a liquid depends on the ion concentration in the solution. Fluid flow along the direction of the CNT induces a current in the CNT based on the Coulomb drag mechanism. Applying

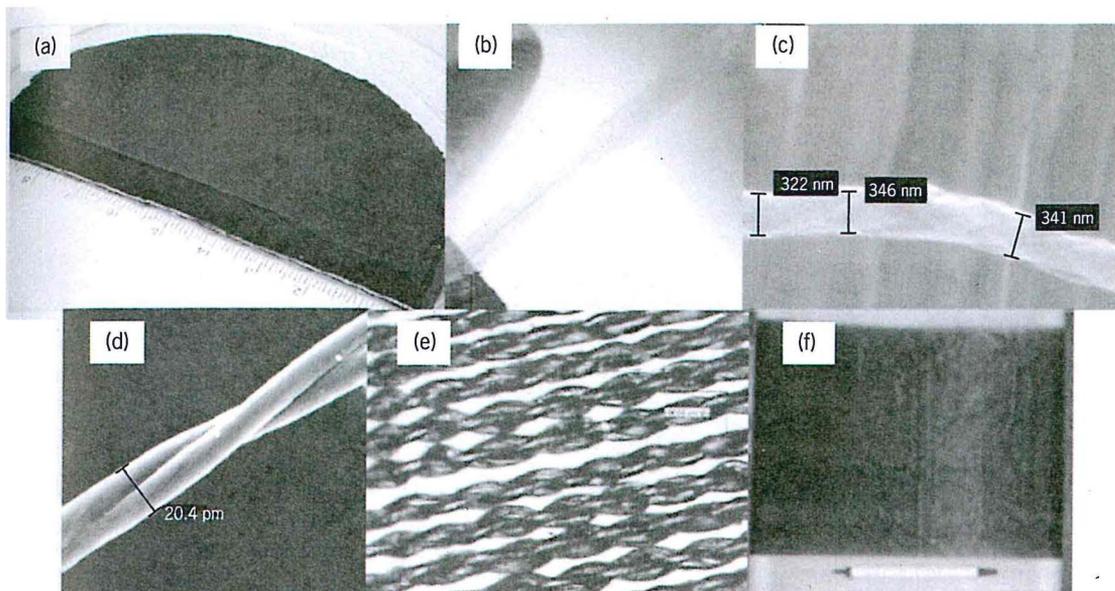


Fig. 1. Different forms of CNT material. (a) CNT forest or array. (b) CNT ribbon drawn from the forest. (c) CNT nanothread formed by twisting ribbon. (d) CNT yarn made of two threads. (e) CNT 4-end microbraid (*braid from Atkins & Pearce Inc.*). (f) CNT sheet produced from the forest.

a small voltage to CNT in an electrolyte causes the CNT to strain slightly, based on the electrochemical bond-expansion mechanism. Post-treatment methods, such as doping and annealing, will also change the electrical properties of CNT and the sensitivity to their environment. Nanotube thread can also be used as a temperature sensor or to generate a small amount of power due to the Seebeck effect. Based on such properties, nanotube materials can sense strain, chemicals, flow, and temperature, act as a wet actuator, or generate a small amount of power.

Responsive materials can be described as smart or active materials, based on different researchers' experiences. But the main point is that responsive materials change their properties (electrical, mechanical, or thermal, or their shape or function) in response to environmental stimuli. CNT materials respond to their environment in various ways and thus can be classified as responsive materials. Responsive materials might be considered to encompass a larger class of materials and effects than smart materials. Current research is focused on using CNT responsive materials to form hybrid materials and to investigate novel applications.

**Applications.** There are already many applications of CNTs being considered. CNTs are reported in the literature for use as *pn* junctions, transistors, computer memory, touch screens, loudspeakers, polymer reinforcement, electrical conductors, and nanomotors. Researchers are also putting CNT materials into various new and unique applications. CNT thread is being used to simultaneously reinforce polymer composites and act as a structural health monitoring sensor, for windings in a lightweight carbon electric motor, in firefighters' garments for increased heat dissipation, in biosensors as electrodes and conductors, wearable antennas, neural growth guides, and for electromagnetic shielding and devices. Some

near-term application research aimed toward commercialization is briefly discussed next.

*CNT thread neural scaffold.* This is being studied to determine how CNT thread can be used to promote neural tissue repair. The hypothesis is that CNT thread will promote the regeneration of damaged axonal tracts. Testing has begun with brain and peripheral nerve tissues (Fig. 2). The target of the application is for the CNT materials to serve as a scaffold to guide regenerating nervous tissues. The physical properties of CNT thread include characteristics that are known to promote neural tissue regeneration, including its linear geometry, high surface area-to-volume ratio, diameter similar to tissue features normally encountered by cells, surface with submicrometer roughness and its ability to conduct current. The combination of cells on the CNT thread can be considered a responsive hybrid biological-engineering material. The cells appear to align (respond) to the twist in the thread and the cells might communicate via, or be stimulated by, electrical conduction in the thread.

*Chemical and biosensors.* Chemical and protein sensors are being fabricated based on CNT tower electrodes. The detection of trace elements in magnesium alloys and chemical species in body fluid can be an indicator to track the degradation of biodegradable metal implants. CNT have also been used for detection of trace heavy metals by anodic stripping voltammetry. CNTs show promising potential for sensing applications *in vitro* and *in vivo*. Dissolved hydrogen gas and bone biomarkers also can be detected by potentiometry and electrochemical impedance spectroscopy (EIS) methods. The sensors might be used to understand how biodegradable metals degrade in simulated biological environments and possibly in the future to develop responsive biodegradable implants that control their own degradation.

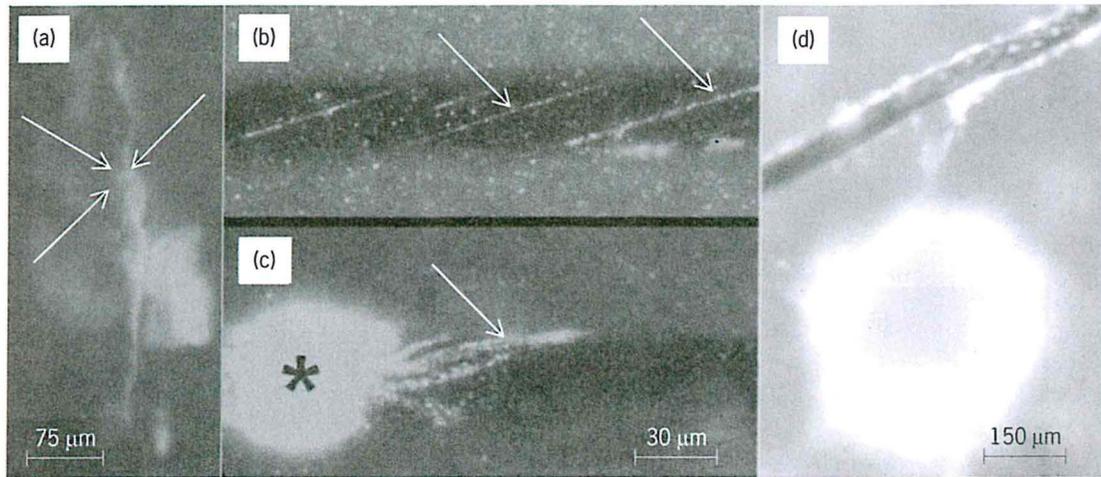


Fig. 2. CNTs as neural scaffolds. (a) Mouse neural stem cells align with an as-grown, vertically aligned CNT bundle (arrows show one cell, live cell stain). (b, c) Mouse dorsal root ganglion (asterisk in c) sends green neurites (arrows, immunostained for neuron-specific tubulin) along and spiraling around (b, c) a CNT thread. (d) Mouse brain neurosphere, with neural stem cells migrating onto CNT thread.

*Carbon electro-mechanical systems (CEMS).* Compared to devices made using metal, carbon devices have a very obvious advantage because of their light weight. The National Aeronautics and Space Administration (NASA) is seeking high-performance and light-weight electric motors and actuators. Physicians would like minimally invasive sensors and biomedical devices small enough to insert into the body. CEMS are under investigation to meet these needs. For example, a mostly carbon solenoid that will be used as the main part of electromechanical linear actuator devices is under testing. Manufacturing carbon systems is technically challenging because of the multiscales involved in transforming from nanostructured materials to micro- and macroscale materials and devices.

The operating environment of microdevices is very important because material properties and physical principles change as the devices become very small. Surface area-to-volume ratios, friction, lubrication, wear, and heat transfer change, such that macroscale devices cannot necessarily be scaled down and expected to operate at the microscale. There are two different approaches to making carbon electromechanical systems (CEMS): top down and bottom up. Top down is a method of starting from bulk material and cutting it smaller and smaller to make small devices. Top-down technology uses nanotube threads or sheets, which are easier to

handle than individual nanotubes. Bottom-up technology is starting from nanotubes or nanotube patterned arrays to build carbon devices. Manipulating individual or small bundles of CNTs is difficult and slow. Because only certain components can be fabricated by each approach, top-down and bottom-up techniques are both needed to manufacture CEMS.

In the near future, processor chips, sensors, computers, and micro-CEMS might be integrated into humans to extend our lifespan, improve our performance, and continuously monitor our health. The integration of devices into humans means the devices should be small, efficient, and precise. Small size could allow devices to be biocompatible and safely implanted in the human body. The size of human cells is about  $10\ \mu\text{m}$ . If we can make devices  $10\text{--}100\ \mu\text{m}$  in size, CEMS will be minimally invasive.

The current goal is to build a microactuator that could begin to fulfill the above requirements. A micromanipulator from Kleindiek Nanotechnik in Germany (Fig. 3a) is being used to build the first device. The resolution of the micromanipulator is about  $1\ \text{nm}$ . But it is difficult to manipulate a CNT with a diameter of  $10\ \text{nm}$ . Individual CNT easily break and stick to other parts. Nanothread is a new material form used to build microdevices. Nanothread is made by twisting and drawing CNTs, whereby twisting the thread creates a small diameter and

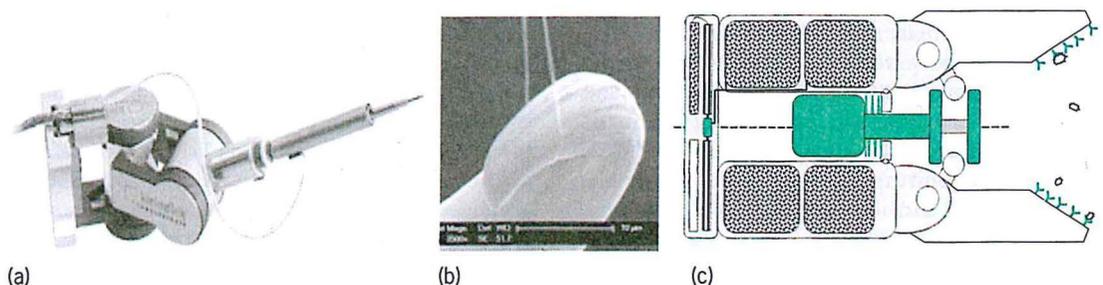


Fig. 3. Microdevice tools and design. (a) Main tool to make nanothread—a rotational tip. (b) The end of the rotational tip is a microhook that is used to easily grab a small bundle of CNTs from the array. (c) A proposed microdevice with a solenoid made from nanothreads.

smooth surface. A hook was made for grabbing CNTs for twisting (Fig. 3*b*). One possible CNT microdevice is shown in Fig. 3*c*. Two sets of nanothread coils will be connected to an external power source. They will generate magnetic forces to drive the core to move from one side to the other to actuate the tweezers for use as a sensor or surgical tool in the body. Different tools could be attached to the solenoid core to perform different tasks.

Readers might be familiar with robotic animals such as the Boston Dynamics Big Dog or the Festo Robotic Seagull. These robots will be very helpful to detect and rescue survivors in earthquakes. But what if the size of a robot could be 10 or 100 times smaller than these? Tiny robots could be useful for surveillance and inspection of urban areas, to monitor our environment, and to probe and repair inside our body. Since there is a need, what limits robots from going smaller? Weight, power, and communication are the barriers. Light weight means less power is needed. CEMS might be a solution to allow development of microrobots.

**Self-sensing composite materials.** Polymeric composite materials are used in the space and aerospace industry because of their high in-plane mechanical performance and low density. However, interlaminar stresses and microdamage at holes, edges, and caused by impacts can lead to delamination and premature failure of composites at low in-plane stress levels. This constitutes a fundamental weakness in polymeric laminated composite materials. A further limitation of composites is the difficulty in evaluating if damage has occurred. Since the structural integrity of composite materials can be compromised by unpredictable circumstances, it will be important to continuously monitor composite structures for damage, thus providing confidence to the system operator.

An integrated and distributed sensing approach based on nanotechnology is being developed, wherein CNT thread is combined with conventional fibers in composites. The nanotube sensor thread has piezoresistive properties and can sense strain and damage. The sensor thread has recently been integrated into composite materials and used to monitor strains and detect damage including delamination. This approach for monitoring involves transverse stitching of CNT thread in laminated composites before curing the composite. The stitching penetrates multiple carbon fabric plies and ties all the layers of the laminate together and causes only minimal decrease in the fiber volume fraction of the composite. Thus the thread can reinforce the composite while acting as a damage sensor. An example of this idea is provided next.

Two CNT threads were stitched into an IM7/977-3 10-ply unidirectional composite beam sample that was subjected to three-point bending. Delamination was indicated in the resistance versus displacement curve with a sudden increase to infinity resulting from breaking of the CNT thread as shown in Fig. 4. The delamination was captured by the sensor in the unidirectional fabric composite. Breaking the

CNT thread means the delamination reached the CNT thread. The delamination is located somewhere along the length of the thread, but the exact position cannot be determined. Introducing more CNT threads into the laminated composite can more accurately locate damage. Based on this initial testing, self-sensing composites were determined to be very sensitive to damage, especially delamination. These materials will help to revolutionize the maintenance of structures, which can now be based on the actual condition, not just usage, of the structure.

**Creating the future.** New materials drive innovation and CNT materials are opening up the field of responsive materials. However, there are some limitations to CNTs that might be overcome by designing new materials. The first step in developing new and improved materials is to look at why carbon nanomaterials have such extreme properties. CNT shells are one atomic layer thick, and the strong triple  $sp^2$  bonding of carbon combined with the hexagonal tessellated architecture of nanotubes provides high strength. The hexagon structure is the highest order polygon that tessellates and can be considered as a fundamental platform to design new atomic-layer tessellated compound and hybrid inorganic materials with 1-, 2-, or 3-dimensionality.

Looking toward applications, engineers desire materials that are almost unbreakable, with good conductivity or else an insulating capability, and the ability to survive high temperatures. To meet various design requirements, it is suggested that future research consider other elements to form tessellated structures that can provide desired properties for specific applications, such as higher-temperature applications. Boron nitride sheets and nanotubes are an immediate candidate material for high-strength and high-temperature applications. It is anticipated that sheets and nanotubes of other different

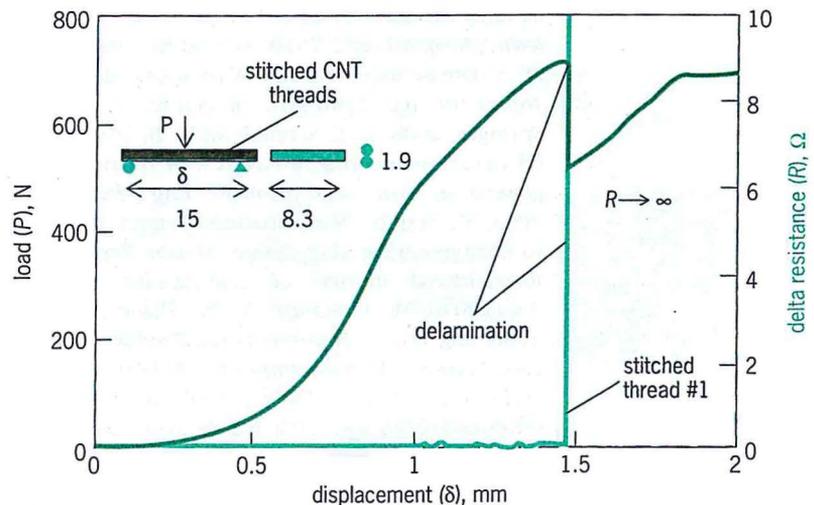


Fig. 4. Detection of delamination and debonding in a laminated composite beam. Load versus deflection and thread delta resistance (difference between actual and initial value) versus deflection curves are shown for an IM7/977-3 10-ply unidirectional composite beam subjected to three-point bending. The sample size is 15 by 8.3 by 1.9 mm. (Reprinted from L. Jandro et al., *Delamination detection with carbon nanotube thread in self-sensing composite materials*, *Compos. Sci. Tech.*, 70(7):1113–1119, copyright 2010, with permission from Elsevier)

materials could become available in the future. A potential advantage of heteroatomic nanomaterials is they might be less likely to form defects, or less sensitive to defects, which could make scaling-up the material easier. It is up to us to create the future, a future where carbon nanomaterials along with new compound, hybrid, and inorganic responsive nanomaterials will allow designers to dream big and develop new machines that were previously impossible to build because of the limited properties of traditional materials.

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For background information see ANALYTICAL CHEMISTRY; BIOSENSOR; CARBON NANOTUBES; COMPOSITE MATERIAL; ELECTRICAL IMPEDANCE; ELECTRICAL RESISTANCE; MICROSENSOR; NANOTECHNOLOGY; POLAROGRAPHIC ANALYSIS; SEEBECK EFFECT in the McGraw-Hill Encyclopedia of Science & Technology.

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## Cell-phone use and driving

The beginning of the twentieth century roughly marks the start of a number of technologically driven revolutions in transportation and communication

that have transformed our environments and everyday lives. Henry Ford's application of mass production helped to make the automobile ubiquitous, and subsequent technological innovations such as power steering and the automatic transmission have reduced the physical and mental demands associated with controlling a motor vehicle. The liberation of Alexander Graham Bell's telephone from its so-called landline allowed for the creation of wireless telephonic devices, including those that can accompany us in our automobiles. This technological combination of wireless telephony and automotive transportation has several positive features. For example, cars can incorporate wireless communications while we are driving them, allowing for improved navigation and safety; a driver or any passengers can phone for emergency assistance following an accident, which greatly improves health outcomes in cases when someone has suffered an injury; and passengers can continue to be productive while being transported in a vehicle (to the extent that communicating via telephone enhances their productivity).

Countering these positive features are the negative consequences for performance when the driver of an automotive vehicle (car, bus, or truck) uses wireless technology to carry on a conversation that is unrelated to the immediate task of driving. These consequences follow inexorably from well-known principles of human information processing. However, before discussing the mental or cognitive limitations that require that we keep our minds on the task of driving, let us first dispense with the more obvious limitations.

**Structural limitations.** In driver training programs and motor vehicle regulation guidebooks, there are two ubiquitous adages: "Keep your hands on the wheel" and "Keep your eyes on the road." The structural limitations implied by these adages are obvious. The steering wheel was designed to be controlled by our hands. As such, our performance in staying in lane, making planned turns, and avoiding unexpected obstacles is certainly faster and more accurate when our two hands are on the wheel compared to when we are driving with one hand, or with our elbows or forearms, or when we have relinquished all physical contact with this critical interface for controlling the direction in which our vehicle hurtles down the road. Most of the physical components of driving (such as accelerating, braking, and steering) are visually guided. The speed and accuracy with which these controlling behaviors are executed when we drive will depend critically on the timeliness and quality of the visual information on which they are based. Activities that require visual guidance, such as opening a package containing food and dialing a cell phone or texting with it, will necessarily cause detriments to driving behavior because the perception of important driving-related visual information will be delayed, if not entirely missed, when we are looking away from the road. For example, say that a visual distraction causes just a 1-s delay in when a signal requiring an emergency action is detected; then, before this action will be engaged, a vehicle

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