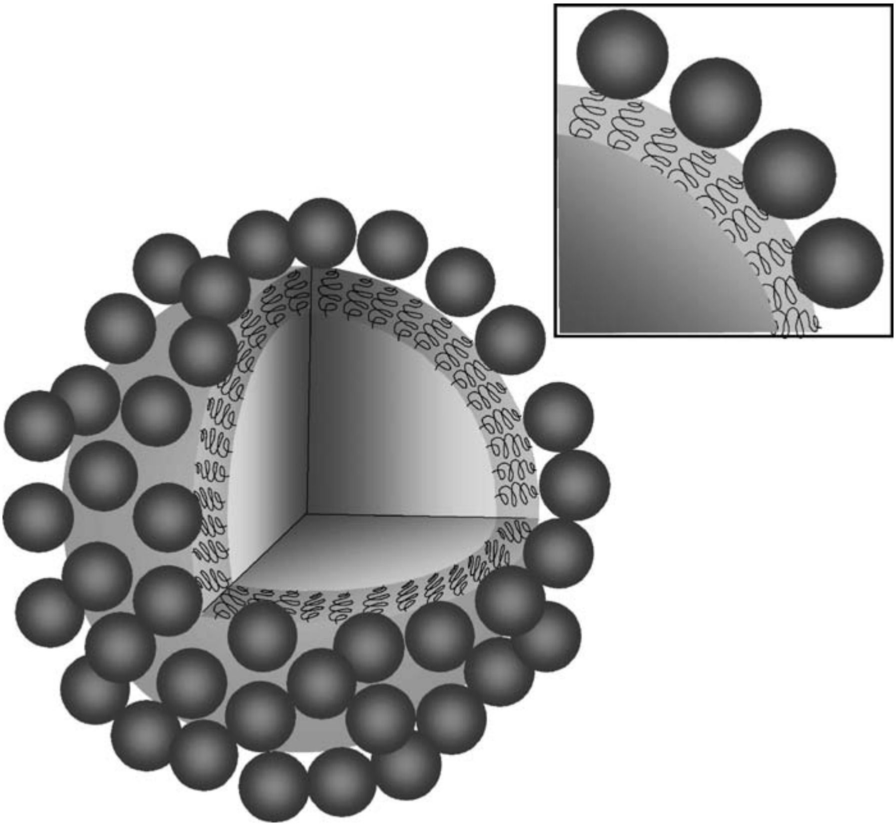

Figure 3.1 Schematic of the nanoparticle superstructure of the nanothermometer. (Image: Dr N. Kotov)

calculate. Nanothermometers, in principle, allow us to measure it with spatial resolution smaller than a typical cell.''

Featured scientist: Nicholas Kotov
Organization: Chemical Engineering, University of Michigan, Ann Arbor, MI (USA)
Relevant publication: Thermometer design at the nanoscale, *Nano Today*, **2,** 48–51.

3.2 Nanotechnology Reinvents the Wheel

The invention of the wheel has been at the origin of major scientific and technological developments: from the creation of astronomical clocks or calculating machines to motor vehicles. At the molecular level, the smallest at which a wheel can be created, it represents a major challenge for scientists. For years, researchers have been working on the design of molecular machines equipped with wheels. After observing the random rotation of a flat molecular wheel in 1998, designing and synthesizing a monomolecular wheelbarrow in 2003, and then synthesizing a molecular motor in 2005, a European group of researchers managed to operate the first molecular rack with a pinion of 1.2 nm in diameter. They controlled the rotation of a 0.7 nm diameter wheel attached to a 0.6 nm long axle in a molecule. This molecular 'wheel' could revolutionize machinery built at the nanoscale. Nanowheel rotation has been claimed before, but never shown directly.

Initially, manipulation of single molecules with scanning tunneling microscopy (STM) led to a hopping motion of the molecules from one adsorption site to the next. Then, a group of French and German scientists demonstrated the first rolling molecular wheel. Figure 3.2

"This is fascinating as it shows that rolling, a motion that is of fundamental importance in the macroscopic world, is also possible at the atomic scale," Dr Leonhard Grill explains. By understanding and controlling how nanosized vehicles move across atomic terrains, nanoscientists may be able to design a new generation of molecular machines equipped with wheels.

Grill, whose research group at the Free University of Berlin focuses on the study of single functionalized molecules on surfaces, together with

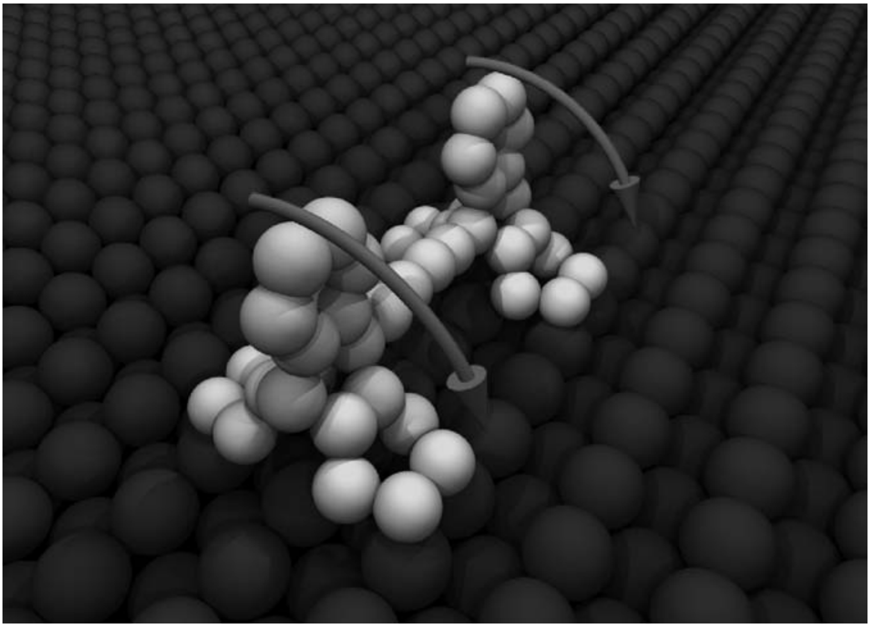

Figure 3.2 Illustration of the wheel–axle–wheel molecule. (Image: Dr L. Grill/Free University Berlin)

collaborators from the Nanosciences Group at CEMES-CNRS in Toulouse, shows that triptycene groups, which resemble three-bladed paddlewheels, can act as wheels only 80 nm wide. They fixed one triptycene to each end of a rigid axle, then pushed this primitive molecular vehicle over a copper surface using the tip of an STM. The type of wheel and surface were very carefully chosen. Two notched, 'tireless' wheels were used because of their maximum adherence to the running surface, an ultra-clean copper plate. Its natural roughness presented rows of copper atoms separated by a distance of $\sim$0.3 nm, and about one atom high.

The way the molecule moves depends on how it is aligned to the row of copper atoms on the surface. In previous experiments, molecules have hopped across the surface when pushed by the microscope tip. However, when the molecules are aligned properly with respect to the ridges on the copper surface, one of the wheels rotates by 120° when pushed by an STM tip.

While rolling the wheel, the STM operator followed any variations in electrical current passing through it on the control screen, in real time. Depending on the handling conditions of the molecule, the operator could turn the wheels or make the molecule advance without rolling its wheels. "We could also show that hopping and rolling motion can be induced separately in a controlled way from the experimental parameters, in particular from the corrugation of the substrate," says Grill. "It turns out that the surface needs to have some corrugation in the direction of motion in order to enable a rolling motion. On a completely flat surface, the wheel doesn't roll, it hops."

The pathways of the hopping and rolling motions are completely different, which reflects the different mechanisms. Long pathways can be observed in hopping, but only very short ones in rolling, because there the STM tip is already behind the molecular wheel after a 120° rotation, and thus cannot induce any further displacement.

Grill points out that a rolling wheel behaves differently on a surface than a hopping molecule. "Firstly, rolling allows motion only in two directions—forward and backward but not sideways," he says. "Secondly, it might be possible for rolling molecules to overcome nanostructures or step edges on a surface, something that cannot be done by hopping molecules."

This experiment enables an approach to understanding at the mono-molecular scale the functionalities that are already known at a macroscopic scale. Without the wheel, some technological advances would not be possible. This analogy may also hold true for molecular vehicles.

Featured scientist: Leonhard Grill
Organization: Experimental Physics Department, Freie Universität Berlin (Germany)
Relevant publication: Rolling a single molecular wheel at the atomic scale. *Nat. Nanotechnol.*, **2**, 95–98.