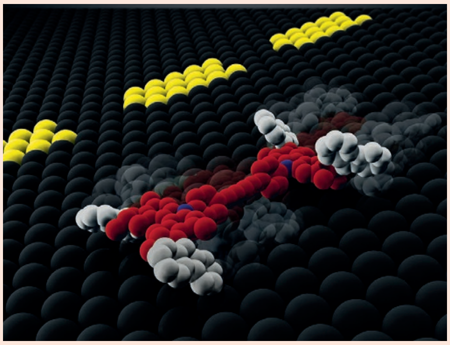
NOBEL PRIZE IN CHEMISTRY

Welcome to the machine

At *Nature Nanotechnology*, we often discourage authors from referencing Richard Feynman's famous 1959 lecture 'Plenty of room at the bottom', a text that has become synonymous with the foundations of nanotechnology, but in truth is more an inspirational thought experiment than offering any scientific underpinning. However, one of Feynman's most prescient and visionary ideas was the manufacturing of "infinitesimal machinery". As such, molecular machines have been wedded to nanotechnology since its origins. The 2016 Nobel Prize in Chemistry has been awarded to Jean-Pierre Sauvage, J. Fraser Stoddart and Bernard Feringa, "for the design and synthesis of molecular machines."

These three scientists took features from the everyday, macroscale world and overcame the inherent limitations of engineering them at the nanoscale. Although interlocked molecules (catenanes) had been known since the 1960s, Sauvage established a metal-templated route in 1983 that allowed them to be prepared in usable quantities. By removing the metal, the two macrocycles can move freely relative to one another. Sauvage later described molecular muscles based on the mechanically threaded rotaxanes that expand or contract on an external input (light, pH, fuel and so on) and were adapted to cause the macroscopic bending of a cantilever.



TIBOR KUDERNAC AND THOM PIJPER

In fact, Stoddart was the first to notice that rotaxanes could work as molecular shuttles. By careful design, for example by positioning two docking stations along the thread, the molecular ring can be driven back and forth in a well-defined manner. Stoddart and many others (several from his own group) have gone on to develop these systems for diverse applications, including in molecular electronics, to perform work and even to make other molecules.

Feringa took a different approach to molecular machines. In 1999, he used an overcrowded alkene as the basis of a light-driven, unidirectional motor. Irradiation-induced *cis–trans* isomerization leads to a 180° rotation. The rotor's shape stops it from going backwards, thus keeping it spinning in one direction. A central achievement of this work is that the rotational motion can be relayed through the molecule; this enables the movement to be propagated over nanometre distances or even further, for example to rotate a glass cylinder on a liquid crystal. In 2011, the rotors were attached as wheels to a molecular chassis in an electrically driven nanocar (pictured; T. Kudernac *et al.*, *Nature* **479,** 208–211; 2011).

A common criticism of molecular machines is that they offer only niche applications. But this misses the point. The research of these three scientists fundamentally changed the way we think about building molecules. They pushed the limits of synthesis from where creating small molecules is the endpoint, to building dynamic, nanoscale systems whose function is the true goal. Theirs is a conceptual as well as a functional leap forward, and together they showed that artificial, as well as biological, machinery can perform designed functions driven by physical motions. These minimal systems must now be adapted for practical applications, embedded in biological systems or for performing macroscopic work. Their foundations led to a Nobel prize inspired by ideas about nanotechnology from almost 60 years ago.

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