

Powering the Nanoworld

Manipulating matter at the molecular level to construct nano-scale machines and robots able to perform specific tasks is a long-term goal of the nanotechnology community. The three-year BIOMACH¹ project, funded by the European Commission in its Sixth Framework Programme (FP6), will build on early successes in this area.

'Robot' is a word of Czech origin and describes a machine that automatically performs complicated, often repetitive tasks – while a machine is any assemblage of parts that transmit forces, motion, and energy one to another in a predetermined manner. Although these formal definitions derive from the macroscopic world, assemblage, transmission and repetition remain key issues in the development of machinery on a nano-scale. In the BIOMACH initiative, a consortium of ten European research groups will pool expertise in biology, physics and chemistry to assemble machines based on molecular building blocks.

Realisation of nanoscale machines would pave the way for novel devices and processes capable of revolutionising medicine, or of reducing resource consumption and environmental pollution in manufacturing processes. This would bring enormous benefits in terms of human health and quality of life, as well as greatly enhancing the industrial competitiveness of any region able to gain a lead in the underlying technologies.

Complementary approaches

A molecular machine can be described in the broadest sense as an assembly of a discrete number of molecular components designed to carry out a specific action jointly – for example, by changing the relative positions of the components. The

¹ BIOMACH: "(Bio)Machines – Single-Molecule Handling of Biological Antecedents and Artificial Mimics" coordinated by Dr. Mario Ruben, Institute of Nanotechnology, Research Centre Karlsruhe, Germany

action requires an operating energy (fuel) and may be triggered by an external stimulus mediated by receptors communicating with the environment.

There are two distinct scientific and technological approaches to nanoscopic machines:

In the first, evolutionary processes occurring in nature over a billion years have resulted in very sophisticated and application-specific biomolecular machines. Living organisms comprise the synergistic integration of functionally diverse molecular engines. Cells contain hundreds of different types of molecular motor, each dedicated to a particular task. Such biological machines are completely embedded in the structural, chemical, energetic and genetic context of living organisms. They generally operate in very specific environments and accordingly are fuelled by the cells' biochemical energy – the most studied example is that of the ATPase family of bacterial enzymes (Figure 1). A challenge in using such biological functional units is to control the complex behaviour of the motors themselves and their isolation from the supporting environments within living cells. To date, only a few types of molecular motor have been studied at the single molecule level, but some spectacular results have emerged.

The second, and complementary, approach is the bottom-up fabrication of artificial molecular machines using relatively simple molecular and atomic 'bricks'. This poses several problems, particularly because it is difficult to steer the self-assembly process of the various modules. Nevertheless, research conducted during recent years, mainly by imaginative and creative chemists, has culminated in the synthesis of artificial engines carrying out opening-closing, translocation, threading-dethreading, rotary or linear movements. These machines do not necessarily rely only on chemical fuels; they may use alternative sources such as photons, electrons or mechanical energy. In particular, electron supply and photon irradiation have proven to be convenient ways to operate molecular devices and machines. Several electron- or light-driven molecular rotary machines have been constructed that could demonstrate unidirectional and repetitive rotary motion. More recently, it has been shown that linear motion mimicking the stretching/contraction movement of skeletal muscles could be induced in an artificial system consisting of specifically designed molecules.

The mechanical movement was driven by chemical reaction energy, but it is obviously hoped that electrons and photons might be used in future to power the artificial muscle (Figure 2).

New route: functional hybrids

Recent scientific advances in both molecular biology and supramolecular chemistry have opened up a third possibility: the build-up of functional hybrid machines based on natural motors. For example, researchers have now combined ATP synthase with a chemically synthesised molecule, to produce a hybrid rotating motor driven by chemical fuel (ATP). However, only five of a total of 400 investigated rotators proved to operate, which reflects the demanding nature of such experiments.

Accurate nano-handling techniques are essential to control intricate nanoscale systems such as molecular machines. Most of the work done so far relies on experience in the handling of single molecules, for which local probe techniques were primarily used for both topographical observation and manipulation.

Designing artificial or hybrid molecular motors from first principles, and manipulating them at the single-molecule level, will depend particularly upon a greater ability to manage the construction process of molecular machines on surfaces. The supramolecular self-assembly approach enables a high degree of structural organisation to be engineered, potentially allowing the controlled formation and hierarchical growth of fully integrated and connected operational systems. An impressive variety of structural elements – such as grids, cages, rosettes, chains and ladders – employing various self-assembly protocols has therefore been developed as components of a basic construction set for future molecular machines.

The continuing search for new fuelling concepts to power nanoworld machines will represent one of the long-term goals of the BIOMACH consortium. As described above, existing biomolecular systems can be powered by covering them with suitably energy-rich molecules, such as ATP. But if nanoscale machines are ever to be applied in a broader range of applications, they will need to use more readily accessible fuels, such as electricity or light. One possible way would be to integrate so-called 'light-fuelled molecular components', which form molecular interfaces for

the direct conversion of photons into mechanical energy usable by the machines (Figure 3).

Towards nanorobots?

Once the structural and operating features of artificial molecular and natural biological machines are known, they could open the door to the design of more complex nanorobotic functional devices, which might be able to perform complicated and repetitive tasks – such as the transport of drugs across membranes and along prefabricated nanostructures, molecular nano-pumping, or the gating of an ion-flux through nano-pores in response to environmental stimuli.

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Illustrations

Figure 1: Structure of a biomolecular machine (F₀F₁-ATPase)

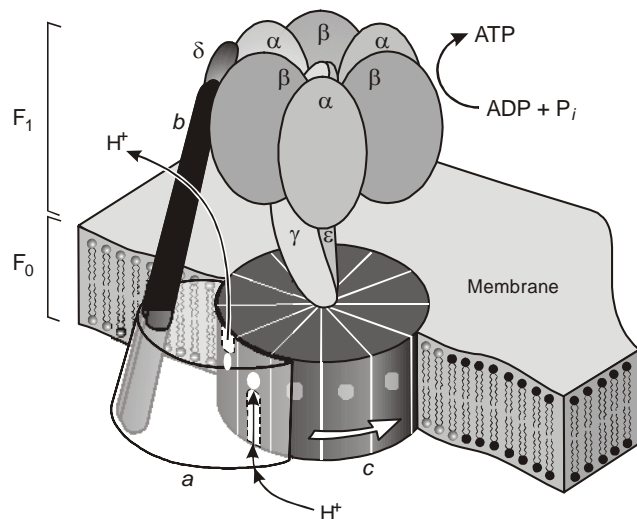


Figure 2: Working principle of an artificial molecular muscle

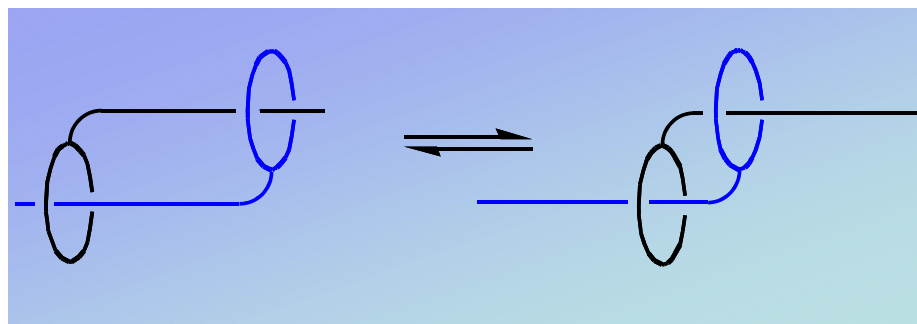


Figure 3: The realisation of a rotary motion by direct conversion of light into mechanical energy

