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Motor Proteins at Work for Nanotechnology

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The biological cell is equipped with a variety of molecular machines that perform complex mechanical tasks such as cell division or intracellular transport. One can envision employing these biological motors in artificial environments. We review the progress that has been made in using motor proteins for powering or manipulating nanoscale components. In particular, kinesin and myosin biomotors that move along linear biofilaments have been widely explored as active components. Currently realized applications are merely proof-of-principle demonstrations. Yet, the sheer availability of an entire ready-to-use toolbox of nanosized biological motors is a great opportunity that calls for exploration.

A huge amount of biological research in recent decades has spurred the realization that the living cell can be viewed as a miniature factory that contains a large collection of dedicated protein machines (*1*). Consider the complicated tasks that a single cell can perform: It can create a full copy of itself in less than an hour; it can proofread and repair errors in its own DNA, sense its environment and respond to it, change its shape and morphology, and obtain energy from photosynthesis or metabolism, using principles that are similar to solar cells or batteries. All this functionality derives from thousands of sophisticated proteins, optimized by billions of years of evolution. At the moment, we can only dream of constructing machines of similar size that possess just a fraction of the functionality of these natural wonders.

One particular class of proteins is formed by molecular motor enzymes, which are catalytic proteins that contain moving parts and use a source of free energy to direct their motion. Upon studying these motors, their resemblance to machines becomes more and more clear. We find rotary motors that comprise shafts and bearings, as well as linear motors that move along tracks in a step-by-step fashion.

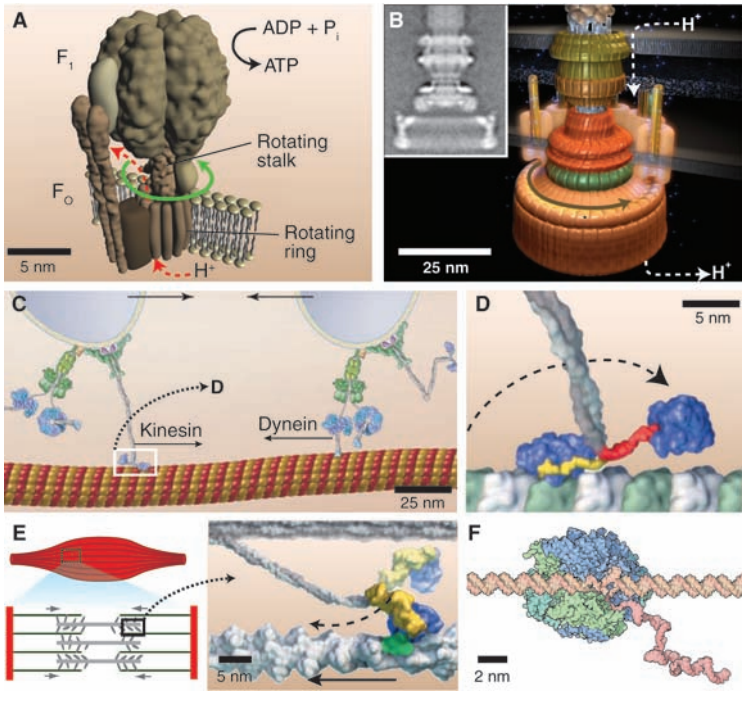

Fig. 1. Motor proteins in the cell. (**A**) Representation of F_OF_1-ATPase [reprinted with permission from (*45*); copyright 2006, Wiley-VCH]. (**B**) Representation of the bacterial flagellar motor (image courtesy of Keiichi Namba, Osaka University). Inset shows an electron microscopy image of the motor [reprinted with permission from (*46*); copyright 2001, Elsevier]. (**C**) Conventional kinesin and dynein transport cargo in opposite directions along microtubules [adapted from (*7*)]. (**D**) Kinesin is a processive motor, consisting of two heads, that walks in alternate steps of 8 nm along the microtubule [adapted from (*6*)]. (**E**) Muscle contraction is caused by the sliding of interdigitated actin and myosin filaments in a sarcomere unit. The nonprocessive myosin II motor detaches after each power stroke so as not to impede the further sliding of the actin filament caused by other mysosins [adapted from (*6*)]. (**F**) RNA polymerase moves along a double-stranded DNA template, transcribing a RNA copy (image courtesy of D. S. Goodsell, Scripps Research Institute).

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It is of interest to ponder whether we can employ these biological nanomachines in artificial environments outside the cell to perform tasks that we design to our benefit (*2*, *3*). Or, at the very least, can these proteins provide us with the inspiration to mimic biocomponents or design artificial motors on comparable scales?

Nature's Workhorses in the Cell

In contrast to macroscopic machines, motor proteins operate in a world where Brownian motion and viscous forces dominate. The relevant energy scale here is k_BT, the product of Boltzmann's constant and temperature, which amounts to 4 pN·nm. This may be compared to the ~80 pN·nm of energy derived from hydrolysis of a single ATP molecule at physiological conditions. Thermal, nondeterministic motion is thus an important aspect of the dynamics of motor proteins.

Let's briefly consider some examples of biomotors. The rotary engine F_OF_1-ATP synthase (Fig. 1A) synthesizes ATP from adenosine diphosphate (ADP) and phosphate (*4*). The flow of protons along an electrochemical gradient through the membrane-bound F_O motor drives rotation of the F_O ring and the central stalk connecting the F_O and F_1 motors. This induces conformational changes of the F_1 motor that drives the catalytic formation of ATP. Remarkably, the complex can also work in reverse, using the energy of ATP hydrolysis to drive the reverse rotation of the F_1 motor and subsequently pump protons against their electrochemical gradient.

The rotary bacterial flagellar motor (Fig. 1B) is used by bacteria such as *Escherichia coli* as a propulsion mechanism by spinning a helical flagellum (*5*). This powerful motor, assembled from more than 20 different proteins, is driven by an inward proton flux that is converted by several torque-generating stators into a rotary motion of the cylindrical rings and central shaft. The motor generates torques of more than 10^3 pN·nm (250 k_BT) and rotates at speeds of over 100 Hz (*5*).

Linear-motion motors are found among the members of the super families of kinesin, dynein, and myosin proteins (*6*) (Fig. 1, C to E). These motors move in discrete steps along tracks made of long protein polymers (actin filaments for myosin, microtubules for kinesin and dynein) that form

We find motors that are powered by chemical energy, derived from hydrolyzing adenosine triphosphate (ATP) molecules (the cell's major energy currency), and motors that employ a gradient of ions, using both electric and entropic forces.

the cytoskeleton that extends throughout the cell. The structural polarity of these filaments (denoted by a plus and minus end) allows unidirectional movement of motors along their tracks. Cytoskeletal motors are involved in almost every aspect of controlled motion and force generation within cells, such as intracellular transport of materials (Fig. 1C) (*7*), cell division, or powering eukaryotic flagella and cilia. The contraction of a muscle is driven by the orchestrated sliding of series of actin filaments with respect to arrays of myosin motors (Fig. 1E). Typically, a linear motor can generate forces of up to ~10 pN.

Many other proteins exist that can use energy to perform work, such as ion channels, DNA- or RNA-processing enzymes (Fig. 1F), ribosomes, or light-powered electron pumps, but these fall outside the scope of this review.

Muscle Power for Nanotechnology

One striking demonstration of a biomolecule-powered nanostructure is the construction of a nickel nanopropeller that rotates through the action of an engineered F_1-ATPase motor (*8*) (Fig. 2A). The directed assembly of the devices was controlled through genetic engineering of histidine tags that stuck the F_1-ATPase onto nickel posts, with its central stalk protruding upwards. This connected to a nickel propeller of ~1 μm length through biotin-streptavidin bonds. Addition of ATP caused rotation of the propeller. A metal-binding site was engineered into the motor and acted as a reversible on-off switch by obstructing the rotation upon binding of a zinc ion (*9*), similar to the action of putting a stick between two cogwheels.

On a larger scale, gliding bacteria have been used to power a micromechanical device comprising a cogwheel-shaped rotor of 20-μm diameter rotating in a silicon track (*10*). Bacteria adhered to the rotor, turning it with ~2 rpm (Fig. 2B). The increase in size (cells compared with individual proteins) is accompanied with larger torques, together with self-repairing properties. Cardiomyocytes (heart muscle) have been used to drive a self-assembled microwalker (*11*). The coordinated contraction of muscle bundles, which were assembled onto a ~0.1-mm large two-legged SiO_2 structure, drove its stepwise movement with a speed of 38 μm/s.

Linear cytoskeletal kinesin and myosin motors have dominated the emerging field of protein-powered devices because they are relatively robust and readily available. Actin and tubulin can be commercially purchased, whereas the motor proteins can be purified from cells or expressed in recombinant bacterial systems and harvested in large quantities. In their most basic geometry, these motor systems are employed in a so-called gliding assay, in which the cytoskeletal filaments (usually about 1 to 20 μm in length) are propelled by surface-bound motors (Fig. 2C). The rotational flexibility of the motor stalks is high enough to rotate the randomly bound motors into the correct orientation for binding onto the microtubule or actin filament. Plus-end–directed motors will then propel the filaments with their minus end leading.

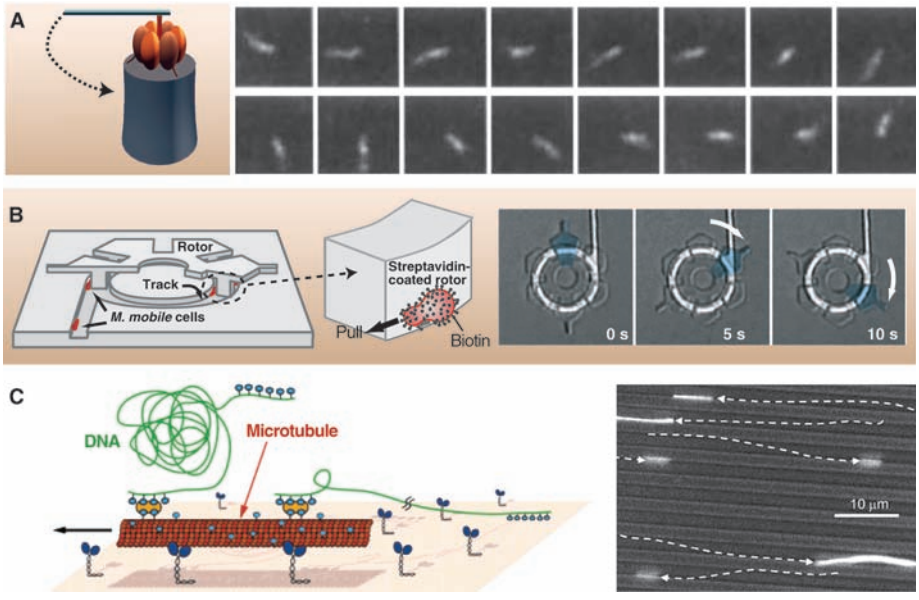

Fig. 2. Motor proteins in nanotechnology. (**A**) An F_1-ATPase–powered nanopropeller [adapted from (*8*)]. Fluorescence images (133-ms interval) are from the earlier experiment (*47*) that first demonstrated the rotary motion of the F_1-ATPase motor by using a fluorescent actin filament connected to the stalk [adapted with permission from (*47*); copyright 1997, Macmillan Publishers Ltd: Nature]. (**B**) A microrotor (20-μm diameter) powered by bacteria that adhere to the rotor and glide unidirectionally through the track. Photo images show the clockwise rotation of the rotor [adapted with permission from (*10*); copyright 2006, National Academy of Sciences USA]. (**C**) Schematic of kinesin motor proteins adsorbed to a surface propelling a microtubule shuttle, which binds cargo such as a DNA molecules [reprinted with permission from (*12*); copyright 2003, American Chemical Society (ACS)]. The fluorescence image shows kinesin-propelled microtubules moving through open polyurethane channels [reprinted with permission from (*16*); copyright 2003, ACS]. The velocity of microtubules is typically about 1 μm/s, whereas actin motility can reach speeds up to 10 μm/s.

Like nanoscale trucks, the microtubules or actin filaments can act as shuttles that transport an attached cargo such as nanoparticles or DNA (*12*) (Fig. 2C).

In an alternative geometry, motor-coated cargo can move along cytoskeletal filaments that are adsorbed onto a substrate. This requires the controlled placement of filaments onto a substrate and precoating of the cargo with motors. The inverted gliding geometry offers better opportunities, however, for actuation, functionalization, assembly, and control and is thus preferred. In general, multiple motors attach to a single filament shuttle, so that large forces (>>10 pN) can be generated. Another advantage is that the shuttles can routinely be interfaced to a variety of cargo using the biotin-streptavidin linkage or through antibodies.

Kinesin- and Myosin-Driven Transport on Chips

One vision is that motor proteins will be used for controlled cargo manipulation on a chip, with applications in sorting, separation, purification, or assembly of materials (*2*, *13*). To reach this goal, one needs to develop controlled motion along specific routes, directionality, coupling to cargo, external control, and steering.

A prerequisite of any useful transport system is that motion and transport can be (uni-) directionally guided along predesigned pathways. When filaments are absorbed randomly onto a substrate, the direction of cargo transport is random as well (Fig. 3A-I). Therefore, considerable effort has been directed at creating confined motility by employing either chemical patterning of active motor proteins (*14*) or fabricated topographical patterns (Fig. 3A-II) (*15*, *16*). A disadvantage of purely chemical patterns is that filaments easily derail from their tracks, which occurs when the leading end of the filament cannot find a new motor to bind to, whereas in purely topographically structured surfaces the selectivity of functional motor absorption is lost.

A combination of topographical and chemical patterning (*17*), with the motor proteins only at the bottom of the trenches (Fig. 3A-III), has proven to combine the best of both approaches with respect to guiding and confinement of microtubules (*18*) and actin (*19*). The recent use of enclosed fluidic channels (*20*, *21*) can be considered as a logical final step in the development toward confinement, offering much better perspectives for packaging (*20*), and for the addressability of individual filaments through electric fields or flows (*21*).

For sorting applications, it is desirable that motion occur unidirectionally. Because the motors bound to a surface are rotationally flexible, unidirectional motion in gliding geometries can only be achieved through reorientation of the filaments. One method exploits asymmetrical arrow-shaped structures (*17*) (Fig. 3B) that rely on the principle that the probability to traverse the rectifier structure depends on the direction from which the filament enters. This hands-off method can achieve up to

92% efficient rectification per arrow (*22*). A different, active-control method is to use external force fields that bend and align the leading end of the motor-propelled filaments parallel to the field, which can be electric (*15*), magnetic (*23*), or flow fields (*24*). By subsequent fixation of the filaments to the underlying motors (using a chemical such as gluteraldehyde), the carpet can serve as a directionally aligned surface for motor-protein–coated cargoes (*25*, *26*).

The coupling of cargo to protein shuttles is relatively straightforward. The simplest configuration relies on the nonspecific electrostatic or hydrophobic adsorption of cargo onto kinesin, which was used for unidirectional transport of materials such as gold, polystyrene, and glass (*25*). Biotin-functionalized microtubules and actin filaments can be interfaced to any cargo with streptavidin groups. Using the inverted assay, transport of polystyrene beads (*16*), DNA molecules (*12*, *27*) (Fig. 3C), and quantum dots (*28*) has been demonstrated.

A disadvantage of these methods is that the cargo has to be prefunctionalized. Therefore, a promising and versatile method is the use of microtubules that are coated with antibodies to the cargo that needs to be transported (*29*, *30*). This technique was used to pick up tobacco mosaic virus particles (*29*) and specific proteins (*30*) from solution, which can be advantageous, for example, in sensing applications. A similar example is the use of microtubules coated with single-stranded DNA oligonucleotides, which could hybridize very specifically with its target DNA in solution, with sensitivity for a single-basepair mismatch (*31*). Another interesting approach is the report on myosin-driven transport of gold nanowires (*32*). The nanowires were created by catalytic enlargement of gold nanoparticles bound to actin filaments, while leaving some actin free to interact with the myosin-coated surface. This method could offer a way of assembling small electrical circuits.

One way to achieve reversible starting and stopping of the motility is to control the concentration of ATP or other necessary cofactors in solution. Light-controlled switching of the motility was achieved using caged ATP, an inactive form of ATP, in conjunction with hexokinase, an ATP-consuming enzyme. Flashes of ultraviolet (UV) light liberated the ATP, which was concurrently depleted by the hexokinase, creating spikes in the motility that lasted several minutes (*16*). A faster time response of about 10 s was obtained through simply flushing hexokinase or ATP into the flow cell (*33*), but this requires more elaborate handling.

Temperature modulation in a flow cell, as through the fabrication of an electrical heater on a cover slip, allowed for reversible control of the velocity of actin filaments (*34*), although the motion could not be entirely stopped. Another method exploits thermo-responsive polymers on a surface to control the motility of microtubules (*35*). The polymers, absorbed between the kinesin molecules, are in an extended configuration at low temperatures, which then sterically prevent gliding of the microtubules (Fig. 3D). Increasing the temperature shrinks the polymers and allows the microtubules to interact with the motors. By spatial patterning of these polymers, this technique can be of use for gating the density of motile microtubules. Another method of locally gating the microtubule density has exploited electric fields to attract microtubules onto a kinesin-coated gold surface (*36*).

Control of the direction of individual microtubules has recently become possible through the use of electric or magnetic forces. By using enclosed fluidic channels, one can apply strong electric fields very locally that act on the leading tip of a microtubule (which is electrically charged). In this way, individual microtubules approaching a Y junction can be steered into the desired direction by an electric field that is applied through a channel perpendicular to the junction (Fig. 3E) (*21*). The combination of electric and fluidic technologies is advantageous for on-chip integration. Magnetic fields have been used to direct the motility of microtubules that were functionalized with small magnetic particles (*23*).

The latest advances in the field of biomolecular motors in nanotechnology have made it clear that we can use motor proteins to drive nanoscale components and that we can interface proteins selectively to different materials. We can control the placement of motor proteins through self-assembly, confine their motion, and exert electrical, chemical, or physical control, sometimes even over single proteins. These isolated demonstrations have, however, not yet been integrated into functional and useful devices. Currently, denaturation of proteins limits the lifetime of a regular gliding assay to several days, although separation between fabrication and use of assembled devices can be achieved through freezing and lyophilization (*37*).

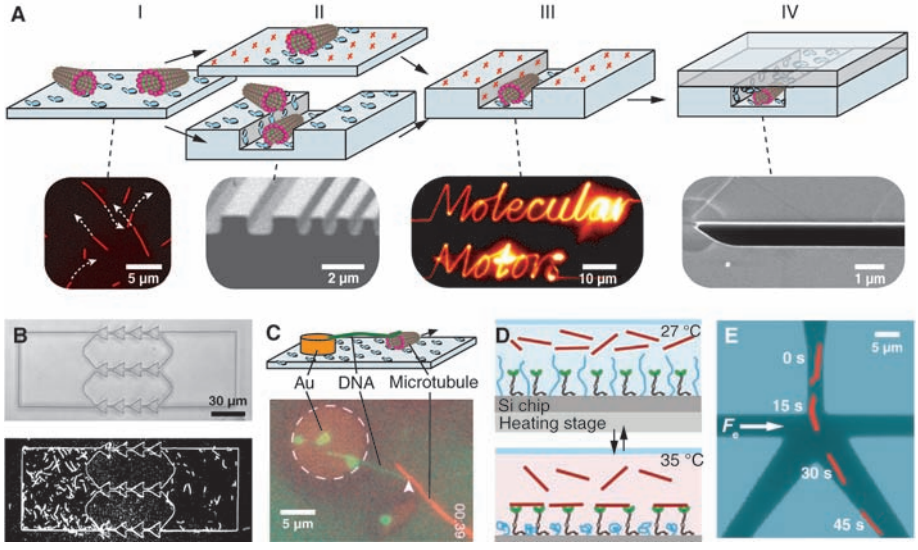

Fig. 3. Biomotor-driven transport. (**A**) Evolution in the confinement of motility. (I) On flat surfaces, the motion of filaments is in random directions (fluorescence image at bottom). (II) To confine the motion, people initially used (top) chemical patterning of motors (as indicated by red x's) or (middle) topographical structuring of the substrates. (Bottom) Scanning electron microscopy (SEM) image shows microfabricated channels in SiO_2. (III) A combination of both methods proved more effective. Bottom image shows time-integrated fluorescence of actin filaments, which are mobile exclusively in the letter-shaped tracks [reprinted with permission from (*19*); copyright 2004, Institute of Physics Publishing]. (IV) The use of submicrometer fluidic channels offers three-dimensional (3D) confinement. (Bottom) SEM image of a closed channel. (**B**) Arrow-shaped structures rectify the motility. Initially, the amount of microtubules is equal in both reservoirs, but after 18 min most microtubules have collected in the left reservoir [reprinted with permission from (*17*); copyright 2001, Biophysical Society]. (**C**) A kinesin-propelled microtubule binds to and stretches a DNA molecule attached to a gold post [reprinted with permission from (*27*); copyright 2006, Wiley-VCH]. (**D**) Thermoresponsive polymers form a clever way of switching the motility on and off [reprinted with permission from (*35*); copyright 2006, ACS] (**E**) An electric force is used to steer individual kinesin-propelled microtubules within an enclosed fluidic channel.

Outlook: Will Biomotors Make Their Way?

When people think of molecular motors and areas for their applications, they initially come up with scaled-down extensions of macroscopic systems: rotary motors to drive a propeller, and linear motors as locomotives pulling cargo. A recurring theme is the building of a molecular transport system or assembly line using kinesin or myosin motors (Fig. 4A). Indeed, applications can be imagined along these lines, where antibody-functionalized shuttles capture and separate target molecules that are present in otherwise undetectably low quantities in an analyte. Such a motor-assisted nanotechnology can be used for concentration of molecules and more sensitive detection.

Other areas where a role for motor proteins is envisioned include the use of motors to drive and accelerate self-assembly processes of nano-

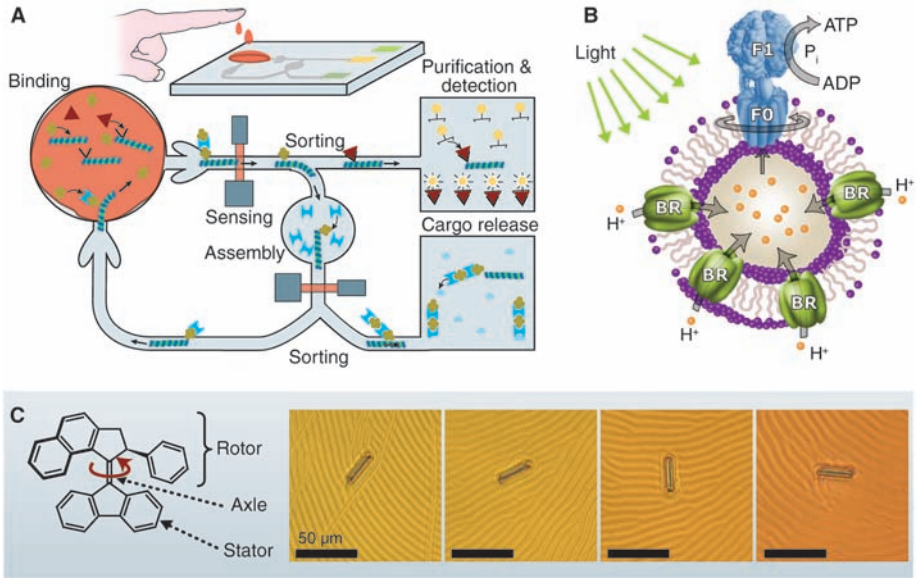

Fig. 4. Prospects and future directions. (**A**) Fictitious motor-protein–powered device that performs on-chip sorting of materials, assembly of different components, and concentrating another component for enhanced detection. (**B**) Polymer vesicles containing bacteriorhodopsin and F_OF_1-ATP synthase create ATP from the light-driven proton gradient established over the membrane [reprinted with permission from (*48*); copyright 2005, ACS]. (**C**) Artificial molecular motors are a new development. Upon illumination with UV light, organic molecules embedded in a liquid-crystal film induce a reorganization of the film texture, driving the rotation of a glass particle. Photo images taken with 15-s intervals [adapted with permission from (*44*); copyright 2006, Macmillan Publishers Ltd: Nature].

structures (*13*), to power nanoscale mechanical elements [e.g, a nanoscale version of the bacteria-powered cogwheel (Fig. 2B)], or to drive small fluidic pumps (*38*). Ideas for applications that employ the massively parallel nature of autonomous molecular motors include the use of kinesin-propelled microtubules as a probe for surface topography (*39*) or for biocomputational maze-solving, where a large number of motile probes find different ways through a microfabricated maze (*40*).

Many of these applications are little more than proof-of-principle examples, for which more developed alternative technologies exist. For example, a biomolecular transport system should be gauged against lab-on-a-chip or micro-total-analysis systems, which are fairly well established technologies. Perhaps, though, the applicability of biomotors is merely limited by the imagination and creativity of researchers (including us). Progress in the field will likely come from integration of achievements of the past few years into more complete and functional devices. Promising in this respect is the sol-gel packaging of vesicles containing bacteriorhodopsin, a light-driven proton pump, and F_OF_1-ATP synthase (*41*) (Fig. 4B). Upon illumination of these sol gels, protons are pumped into the vesicles and ATP is created outside the vesicle by the ATP synthase. Besides the excellent stability of these gels (bacteriorhodopsin continued functioning for a month), this technology provides a convenient packaging method and a way to use light energy for fueling devices. Another interesting development is the engineering of polypeptides that can specifically bind to inorganic materials (*42*). When engineered into motor proteins, this technology could provide new opportunities for motor-driven nanoscale assembly of different materials.

A related but even more futuristic field is the development of artificial molecular machines by bottom-up organic chemistry (*43*). Artificial molecular machines are synthesized molecules that can switch between different shapes upon illumination with light or through electrochemical reactions. An illustrative example is shown in Fig. 4C. The molecular motor molecules, embedded within the surface of a textured liquid crystal film, induce the rotation of a macroscopic glass particle through a continuous reorganization of the film texture (*44*). Although the stability of these molecular machines is probably superior to proteins, their control, directionality, and interface to the outside world are yet far less developed (*43*).

The small size and force-exerting capabilities of motor proteins and the range of opportunities for specific engineering give them unique advantages over current human-made motors. Upon studying and using biomotors, we will gather a lot of knowledge that is of interest to biology, material science, and chemistry, and it is reasonable to expect spin-offs for medicine, sensors, electronics, or engineering. The exploration of biomotors in technology will thus remain an interdisciplinary playground for many years to come.

References and Notes

1. B. Alberts, *Cell* **92**, 291 (1998).
2. H. Hess, G. D. Bachand, V. Vogel, *Chem. Eur. J.* **10**, 2110 (2004).
3. K. Kinbara, T. Aida, *Chem. Rev.* **105**, 1377 (2005).
4. M. Yoshida, E. Muneyuki, T. Hisabori, *Nat. Rev. Mol. Cell Biol.* **2**, 669 (2001).
5. H. C. Berg, *Annu. Rev. Biochem.* **72**, 19 (2003).
6. R. D. Vale, R. A. Milligan, *Science* **288**, 88 (2000).
7. R. D. Vale, *Cell* **112**, 467 (2003).
8. R. K. Soong *et al.*, *Science* **290**, 1555 (2000).
9. H. Liu *et al.*, *Nat. Mater.* **1**, 173 (2002).
10. Y. Hiratsuka, M. Miyata, T. Tada, T. Q. P. Uyeda, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 13618 (2006).
11. J. Xi, J. J. Schmidt, C. D. Montemagno, *Nat. Mater.* **4**, 180 (2005).
12. S. Diez *et al.*, *Nano Lett.* **3**, 1251 (2003).
13. H. Hess, *Soft Matter* **2**, 669 (2006).
14. H. Suzuki, A. Yamada, K. Oiwa, H. Nakayama, S. Mashiko, *Biophys. J.* **72**, 1997 (1997).
15. D. Riveline *et al.*, *Eur. Biophys. J.* **27**, 403 (1998).
16. H. Hess, J. Clemmens, D. Qin, J. Howard, V. Vogel, *Nano Lett.* **1**, 235 (2001).
17. Y. Hiratsuka, T. Tada, K. Oiwa, T. Kanayama, T. Q. P. Uyeda, *Biophys. J.* **81**, 1555 (2001).
18. J. Clemmens *et al.*, *Langmuir* **19**, 10967 (2003).
19. R. Bunk *et al.*, *Nanotechnology* **16**, 710 (2005).
20. Y. M. Huang, M. Uppalapati, W. O. Hancock, T. N. Jackson, *IEEE Trans. Adv. Packag.* **28**, 564 (2005).
21. M. G. L. van den Heuvel, M. P. de Graaff, C. Dekker, *Science* **312**, 910 (2006).
22. M. G. L. van den Heuvel, C. T. Butcher, R. M. M. Smeets, S. Diez, C. Dekker, *Nano Lett.* **5**, 1117 (2005).
23. B. M. Hutchins, M. Platt, W. O. Hancock, M. E. Williams, *Small* **3**, 126 (2007).
24. R. Stracke, K. J. Bohm, J. Burgold, H. J. Schacht, E. Unger, *Nanotechnology* **11**, 52 (2000).
25. K. J. Bohm, R. Stracke, P. Muhlig, E. Unger, *Nanotechnology* **12**, 238 (2001).
26. L. Limberis, J. J. Magda, R. J. Stewart, *Nano Lett.* **1**, 277 (2001).
27. C. Z. Dinu *et al.*, *Small* **2**, 1090 (2006).
28. G. D. Bachand *et al.*, *Nano Lett.* **4**, 817 (2004).
29. G. D. Bachand, S. B. Rivera, A. Carroll-Portillo, H. Hess, M. Bachand, *Small* **2**, 381 (2006).
30. S. Ramachandran, K. H. Ernst, G. D. Bachand, V. Vogel, H. Hess, *Small* **2**, 330 (2006).
31. S. Taira *et al.*, *Biotechnol. Bioeng.* **95**, 533 (2006).
32. F. Patolsky, Y. Weizmann, I. Willner, *Nat. Mater.* **3**, 692 (2004).
33. R. Yokokawa *et al.*, *J. Microelectromech. Syst.* **13**, 612 (2004).
34. G. Mihajlovic *et al.*, *Appl. Phys. Lett.* **85**, 1060 (2004).
35. L. Ionov, M. Stamm, S. Diez, *Nano Lett.* **6**, 1982 (2006).
36. M. G. L. van den Heuvel, C. T. Butcher, S. G. Lemay, S. Diez, C. Dekker, *Nano Lett.* **5**, 235 (2005).
37. R. Seetharam, Y. Wada, S. Ramachandran, H. Hess, P. Satir, *Lab Chip* **6**, 1239 (2006).
38. J. L. Bull, A. J. Hunt, E. Meyhofer, *Biomed. Microdev.* **7**, 21 (2005).
39. H. Hess, J. Clemmens, J. Howard, V. Vogel, *Nano Lett.* **2**, 113 (2002).
40. D. V. Nicolau *et al.*, *Microelectron. Eng.* **83**, 1582 (2006).
41. T. J. M. Luo, R. Soong, E. Lan, B. Dunn, C. Montemagno, *Nat. Mater.* **4**, 220 (2005).
42. M. Sarikaya, C. Tamerler, A. K. Y. Jen, K. Schulten, F. Baneyx, *Nat. Mater.* **2**, 577 (2003).
43. W. R. Browne, B. L. Feringa, *Nat. Nanotechnol.* **1**, 25 (2006).
44. R. Eelkema *et al.*, *Nature* **440**, 163 (2006).
45. D. W. Wendell, J. Patti, C. D. Montemagno, *Small* **2**, 1324 (2006).
46. D. Thomas, D. G. Morgan, D. J. DeRosier, *J. Bacteriol.* **183**, 6404 (2001).
47. H. Noji, R. Yasuda, M. Yoshida, K. Kinosita, *Nature* **386**, 299 (1997).
48. H. J. Choi, C. D. Montemagno, *Nano Lett.* **5**, 2538 (2005).

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