Templating a Molecular Tug-of-War

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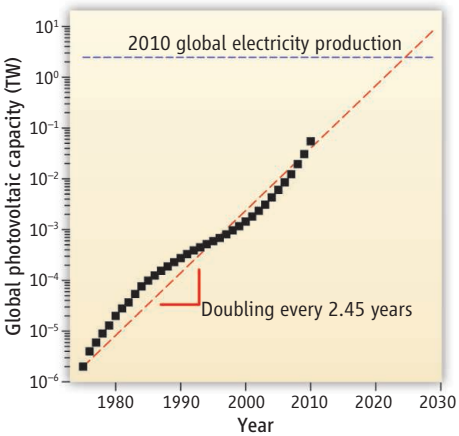

Moore's law for solar cells. The accumulated amount of photovoltaic solar cells manufactured from 1975 to 2010, in terawatts (*13*). The red dashed line is a linear fit to the data and represents a doubling of the global capacity every 2.45 years since 1975. The blue dashed line is the gross electricity produced globally from all sources in 2010 (*14*) for comparison.

nanoparticles with alumina nanoparticles, the dye with a thin layer of an organic-inorganic perovskite (*12*), and the liquid electrolyte with a solid organic conductor. The outcome was a device that converted full sunlight with an efficiency of 10.9%, a truly impressive number, especially for a combination one might not expect to perform at all.

In particular, alumina is nonconductive and cannot transport the light-generated electrons to the electrode. Consequently, the alumina performs only one of the three required functions—a high-surface-area scaffold upon which the light-absorbing perovskite is placed. But then how does the device work? The other functions are apparently assumed by the perovskite, which is a hybrid solid consisting of an inorganic framework (a metal halide) with small organic molecules in its voids. Although this sounds exotic, these materials are known to behave like semiconductors, allowing them to absorb the sunlight and create electrons. Without the titania, the perovskite also has to transport this charge to the electrode. Because the overall device performance is high, the perovskite apparently accomplishes all of these tasks surprisingly well.

Replacing the simple organic dye with the perovskite also sounds complicated (and expensive). However, Lee *et al*. show that highly crystalline layers of these materials can be grown simply by coating the surfaces of the alumina particles with a solution of low-cost molecular precursors followed by mild heating. The high structural quality of the resulting films is presumably one reason the perovskite can collect and transport the electrons so efficiently. Because the absorbing layer is produced by simple and inexpensive solution processing, the Lee *et al*. device also maintains a primary advantage of the conventional dye-sensitized solar cell: low cost.

On the basis of this first report, researchers can now evolve the new device and search for further improvements. An obvious target is the organic-inorganic perovskite. The specific lead halide used is only one example of a large class of possible perovskites (*12*). Exploring related materials can also provide an opportunity to eliminate the lead, a worthwhile goal for environmental protection.

These and other "mutants" are intended to help photovoltaic solar cells make an impact on the world's electricity production (see the figure). Global photovoltaic solar cell capacity has doubled every 2.5 years between 1975 and 2010. Such exponential growth is reminiscent of the famous Moore's law in integrated circuits, which states that the number of transistors on a computer chip doubles every 2 years. Although not a physical law, it has provided a self-fulfilling prophecy for the computer industry for several decades. Will solar cell manufacturers be able to maintain their Moore-like growth? In particular, recent increases have occurred during a period of government subsidies. If the political or economic environment changes, then technological improvements in performance and cost will be needed more than ever to stay on track. Research on mutant solar cells, which can lead to improvements in both efficiency and cost, has an important role to play in achieving this goal.

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BIOCHEMISTRY

Templating a Molecular Tug-of-War

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Tying cytoskeletal motors together on a DNA rope reveals how opposing motors compete to determine the direction of cargo transport.

The activated transport of organelles, vesicles, and many other subcellular commodities along cytoskeletal filaments is central to mechanisms that regulate the internal organization of eukaryotic cells (*1*). The motions of these cargos are driven by several classes of ATP–dependent enzymes called motor proteins that are capable of converting chemical energy into mechanical work. A variety of bulk biochemical and single-molecule techniques have been developed over the past decade to characterize the principles that allow these enzymes to function effectively as molecular machines (*2*, *3*). Yet most cargos are transported by multicomponent motor systems containing multiple copies of the same motor, or even by mixtures of different classes of motors that move with different velocities, in opposite directions, and along different types of cytoskeletal filaments (*4*, *5*). Understanding how motors cooperate productively and compete antagonistically has therefore become increasingly important for dissecting mechanisms that regulate intracellular transport as well as the impact of motor mutations in diseases. On page 662 of this issue, Derr *et al*. (*6*) demonstrate a new materials approach to these problems that allows the characterization of key relationships among the structural organization of multiple motor systems, the

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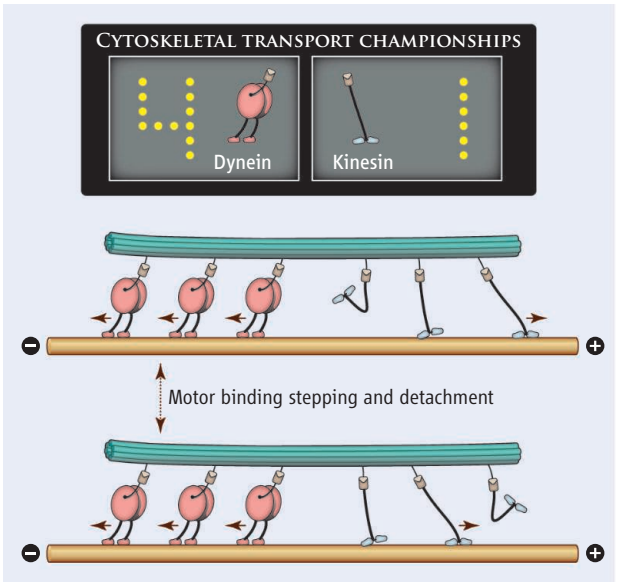
properties of motors within these complexes, and their collective dynamic behaviors.

Current studies of collective motor functions have been confounded by the fact that the number and spatial arrangement of motors on a cargo are unknown in most assays and must be inferred from analyses of cargo motions. The combination of these experimental deficiencies and the inherent complexities of collective motor behaviors have left many aspects of multiple motor dynamics poorly defined and controversial. To address these challenges, several groups have developed methods to generate organized motor complexes using molecular scaffolds composed of protein-based polymers, linear DNA duplexes, and other biomacromolecules (*7*–*9*). These approaches provide important abilities to quantify differences between single and multiple motor run lengths, velocities, and force production. However, they have allowed small motor complexes to be prepared that typically only contain two identical motors. Derr *et al*. have overcome this limitation by engineering DNA scaffolds, called DNA origami, in order to create motor complexes that better reflect the size and complexity of the motor systems responsible for the transport of natural cargos. The DNA origami is formed by folding a long viral single-stranded DNA strand into an organized structure by annealing this strand with collections of small oligonucleotides called "staple strands," which hybridize to different regions of the viral DNA (*10*). This method allows long molecular scaffolds to be synthesized whose persistence length can far exceed that of a single DNA duplex because multiple duplexes can be tied together. The staple strands can also be extended from the structure and used to specify sites where DNA-tagged motors and fluorescent labeling strands are linked to the scaffold. The resulting ability to program the number, sequence, and spatial presentation of these handles allows near-arbitrarily complex, three-dimensional scaffolds to be prepared that can template the self-assembly of multiple protein systems containing collections of different proteins.

The development of recombinant yeast dynein expression constructs that can be outfitted with oligonucleotides also provided Derr *et al*. with new opportunities to engineer motor complexes containing oppositely directed kinesin and dynein motors and then examine how these microtubule motors compete to control the direction of cargo motion. Single kinesin motors move processively toward the plus end of microtubules and can produce forces up to 7 pN. Yeast dynein is a minus end–directed motor and has been found to stall at somewhat smaller forces (5 pN) (*11*). One may therefore expect that teams of kinesins would prevail over similar-sized teams of dyneins during a molecular tug-of-war. However, Derr *et al*. found that collections of dyneins tended to win this competition, except in extreme cases where the number of kinesins far outweighed the number of dyneins in a complex. These results show that factors other than a motor's stalling force can play key roles determining how motors cooperate in groups. They are also consistent with recent optical trapping studies that have suggested that teams of kinesins use only a small fraction of their motors at a time when transporting cargos against opposing loads on average (*9*, *12*). This weak cooperative response has been attributed to kinesin's relatively high stepping rate under load and large stalling force relative to its critical detachment force (*8*, *13*). Although these properties allow kinesin to function efficiently as single motor molecules, they can produce kinetic constraints that limit the ability of multiple kinesins to cooperate productively by sharing their applied loads (see the figure). The present dynein motors possess much higher filament affinities than kinesin and advance at much lower rates, which appears to relieve these constraints, yielding net minus end–directed motions even at low dynein-to-kinesin ratios.



Oppositely directed motors compete in a tug-of-war. Many cargos are outfitted with different types of antagonistic cytoskeletal motors in cells and move bidirectionally along cytoskeletal filaments. Using molecular scaffolds call DNA origami to generate organized multiple motor complexes, Derr *et al*. show that teams of yeast dyneins tend to win tug-of-war competitions with multiple kinesins. Despite its lower stalling force, dynein's high microtubule affinity tips the scale in the dynein team's favor because this property allows more dyneins to remain engaged during a tug-of-war against a team of kinesins, which tend to use only a small fraction of their motors during the competition.

The ability to controllably tune the motor ratios will likely shed light on intracellular transport regulatory mechanisms. The dominant role of high-affinity motors in the present ensembles suggests that controlling their number and activities will be particularly influential to tug-of-war competitions. Nevertheless, the mechanochemical properties of motors can vary appreciably depending on their structure and association with specific accessory factors, indicating that characteristically different collective responses can potentially be produced by other motor systems. Analogously rich collective behaviors are known to occur when nonmotile proteins interact in groups and operate as integrated biosynthetic factories and signaling complexes (*14*, *15*). Consequently, the ability to make use of DNA self-assembly techniques to engineer organized multiple protein assemblies and deterministically modulate their composition will likely constitute an important new approach to dissecting the functions of various integrated macromolecular systems of proteins.

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