Actuating macroscopic machines with nanoscopic engines

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Summary

Can we harness the power of nanoscopic enzymes to actuate macroscopic machines? In this issue of Matter, Laskar *et al.* present an in silico design of deformable, enzyme-powered millimeter scale gears that can potentially perform mechanical work through chemo-fluidic-mechanical coupling.

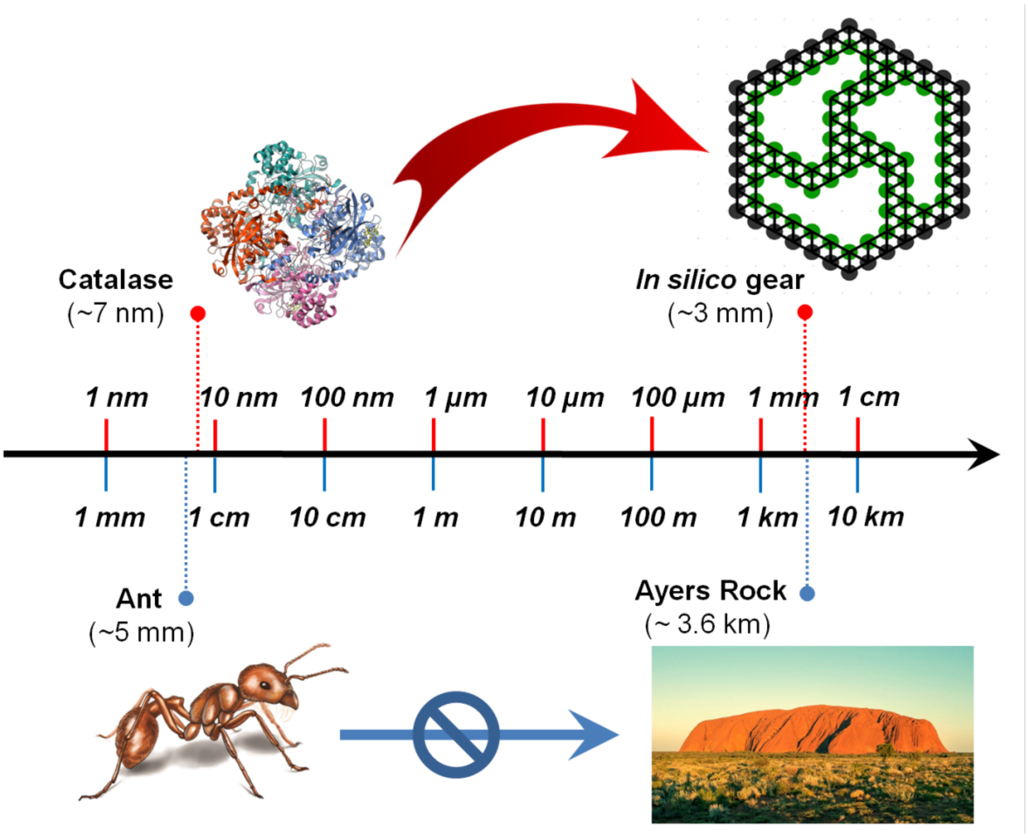

Figure 1. A scale comparison indicates that actuating millimeter gears by enzymes is a challenge comparable to moving the Ayers Rock with ants.

Main Text

Assembling biological building blocks (e.g. metabolites, genes, proteins, cells, or even tissues) and artificial parts (e.g. xeno-nucleic acids, unnatural amino acids, synthetic materials and structures) into functional structures is a central goal of synthetic biology and bionanotechnology. The construction of a motile unit that can convert chemical energy into motion is of particular interest as this unit can power a machine capable of executing specific tasks. In biological systems, the chemo-mechanical conversion is often performed by motor proteins, a class of enzymes catalyzing the hydrolysis of adenosine triphosphate (ATP) to produce mechanical forces and torques, which have been widely adopted and engineered to serve as actuators in synthetic devices.[1] However, the availability of biomolecular motors and their associated filaments is still limited, precluding widespread application.

Recent reports have suggested that common enzymes produce microscopic propulsion during enzymatic conversion of substrates into products, extending chemo-mechanical conversion to general enzymes and broadening the palette of fuel molecules from ATP only to various enzyme substrates. While the claim that enzymes can diffuse faster as a result of substrate conversion is still controversial,[2,3] several enzymes have served successfully as nanoengines attached to artificial micro/nanoobjects to power their motion. For example, enzyme-coated or enzyme-encapsulated liposomes, polymersomes, nano-/micro-particles, hollow tubes, and Janus structures with body sizes ranging from tens of nanometer to a few micrometers have exhibited enhanced diffusion or directional locomotion in a reaction velocity-dependent manner.[4] The propulsion is attributed to mechanisms such as electrophoresis, diffusiophoresis or bubble ejection depending on the reactions and solution conditions.

Can enzymes drive motions at the macroscopic scale? The answer is not obvious, since the size difference between an enzyme and a millimeter size machine part is similar to the size difference between an ant and Ayers Rock (Figure 1). The pioneering work of Ismagilov et al.[5] has shown that a millimeter-size PDMS floating plate with a small platinum-covered area can swim at the liquid–air interface by ejecting bubbles generated from the platinum-catalyzed decomposition of H_2O_2. It can be anticipated that the same structure can be powered by the enzyme catalase, the biological equivalent of platinum with even higher specific activity for H_2O_2 decomposition. Similarly, Mano and Heller[6] developed a centimeter-long carbon fiber (7 μm in diameter) with two terminals coated respectively with glucose oxidase and bilirubin oxidase, achieving self-electrophoretic motion at the water–air interface with a velocity of 1 cm/s.

Reactions of immobilized enzymes can also couple with fluid flow and mechanical motion, resulting in unexpected dynamics. Sen and colleagues[7] showed that enzymes attached to patches on a surface can serve as microscale pumps to drive large-scale fluid flows triggered by a reaction-induced gradient of solutal density. The typical pumping velocity is on the order of μm/s and is reaction velocity-dependent. A self-organized implementation of fluid flows driven by density changes caused by enzymatic reactions was realized by Zhang et al.[8], who observed Rayleigh–Bénard type convection with mm/s velocities in a Petri dish using a two-enzyme reaction network.

The latest advance in the quest to design enzyme-driven chemo-mechanical conversion is the work by Laskar et al. in the current issue of Matter.[9] The team led by Prof. Balazs from the University of Pittsburgh studied in silico a microfluidic gearbox, where the gears are moved by self-generated convective flows induced by enzymatic catalysis. Each active gear is coated with catalytic enzymes and possesses two unique features, a flexible frame and chiral internal structures. The flexibility enables it to self-morph into a three-dimensional umbrella-like configuration in response to the reaction-induced solutal buoyancy, and the asymmetry ensures that it rotates unidirectionally. By introducing cogs on the outer rims, the active gears can transmit rotational motion to passive gears via physical contacts, resembling the conventional configuration of gear or cogwheel systems. Although this computational design has not yet been experimentally realized, the track record of Balazs and colleagues in successfully replicating *in silico* less sophisticated systems relying on enzymatically driven fluid flow inspires confidence that an experimental implementation will perform as anticipated.[10]

This computational modeling project highlights two key aspects of harnessing the power of enzymes for driving macroscopic machines, i.e., unidirectional motion and the engagement of hierarchical components. The unidirectional motion rooted in the structural chirality enables a machine to perform useful work, and the engagement of hierarchical components carries out the transmission of mechanical power from a prime mover to the point of operation. A well-designed spatial arrangement of enzymes and the associated synthetic components is critical for maximizing the mechanical power output.

In comparison to their biological “role models”, such as muscles hierarchically assembled from myosin and actin filaments, current designs of artificial enzyme-powered machines are several orders of magnitude less efficient in chemical-to-mechanical energy conversion. This is due largely to the indirect chemo-mechanical coupling. For example, the convective flow-induced motion is driven by the potential energy of concentration gradients produced by the small density difference between substrates and products, while a large fraction of the chemical energy released during the reaction is dissipated as heat into the environment. Subsequently, a large fraction of the kinetic energy of the fluid flow is lost without driving a targeted machine. In contrast, biological motors such as kinesin couple chemical reactions with conformational changes such that the force is generated through a power-stroke mechanism with an energy efficiency exceeding 50%. It is still a challenge for the future to replicate the efficiency of biological chemo-mechanical coupling in artificial constructions, and also maintain the efficiency as mechanical force is produced, transmitted, and applied in enzyme-actuated machines.

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