The Ecology of Technology and Nanomotors

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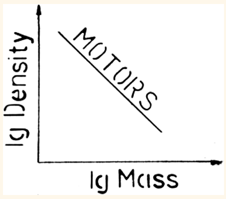
ABSTRACT Ecosystems are characterized by particular scaling laws describing, for example, the relationship between animal abundance and species body weight. It is hypothesized that technological systems follow similar scaling laws, where the abundance of a type of machine correlates with its size. Human progress continuously expands the range of accessible machine sizes, creating a technology trend toward vast numbers of microscopic machines. Current research related to nanomotors, such as the report by Kumar *et al.* in this issue of *ACS Nano* describing advances in controlling biomolecular motors, lays the scientific foundation for this trend.



Where does technological progress lead us? Are there discernible patterns to technical systems enabling us to predict the evolution of the technosphere and, in particular, nanotechnology? These questions have striking similarities to those investigated in ecology with respect to biological systems.[1] Scaling laws, relating, for example, body size and basal metabolic rate[2,3] or body size and population density,[4] are hotly debated discoveries regarding the organization of ecosystems. Similar to synthetic biology, where the investigation of engineered systems provides insights into biological design principles and *vice versa*,[5] the "ecology of technology" may yield surprising perspectives and generalizations.

Consider, for example, the roughly inverse proportionality between body mass and population density observed for various species (Figure 1a). While other factors, such as geographic location[6] and metabolic group,[6−10] contribute to the observed population density, the variation in body weight most consistently predicts animal population density.[4] A surprising consequence of the relationships between body mass, population density, and metabolic rate is the energetic equivalence rule,[7,11] which states that different species consume similar portions of the total energy budget.

Motors and engines are one category of machines that vary in mass by several orders of magnitude from less than a gram to hundreds of tons. Marden and Allen investigated the dependence of force output on motor mass and discovered new scaling laws shared by biological and man-made force-generating systems.[12] But, surprisingly, the classic dependence of population density on mass can also be found for motors and engines (Figure 1b). Here, each type of motor or engine is considered a "species" and the order of magnitude of their abundance is estimated (see Supporting Information). Similar to the observations from biology, the abundance of each motor is affected by additional factors, such as its "family," *e.g.*, electric motor or steam engine.

> Improved understanding of the global organization of technological systems, or the "technosphere", may improve our forecasts of technological change and guide research and development efforts.

A historical perspective on the development of the abundance-weight distribution illustrates how technological progress since the invention of the steam engine in the 18th century broadened the range of engine sizes and increased their abundance to the current state. In particular, the invention of the electric motor gave rise to billions of small electric motors in consumer products weighing about 20 g as well as only a few of the huge turbines for pumped-storage hydroelectric power stations weighing

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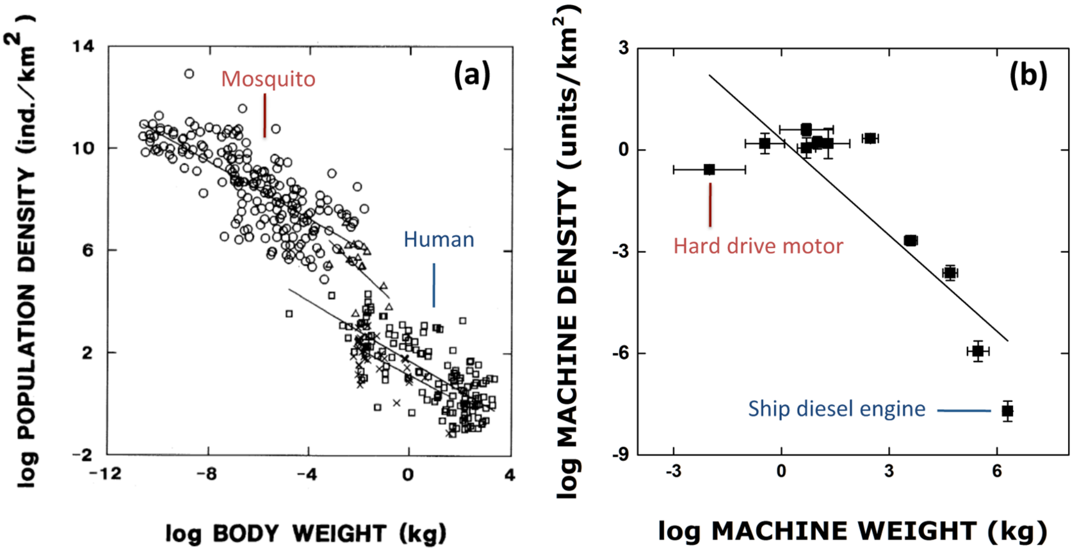

Figure 1. (a) In the global ecosystem, the population density of animal species is roughly inversely proportional to the body mass of the individuals. Reprinted with permission from ref 4. Copyright 1993 Wiley. (b) The technosphere exhibits a similar scaling of density to machine mass, where machine density is calculated by dividing the estimated number of machines of a given type in the world by the surface area of the earth. Data are estimated for the year 2000.

hundreds of tons and producing hundreds of megawatts of power.

In the context of nanotechnology, the main question is how technological progress will create smaller and smaller engines and motors. Incremental progress may progressively reduce the size of electric motors, engines, and actuators while simultaneously increasing their numbers. The tens of millions of digital micromirror devices weighing about a gram, each incorporating a million independent actuators, illustrate the potential of this route. Alternatively, molecular motors and related nanodevices may be integrated into mechanically active systems in numbers approaching a mole (6×10^{23}) through bottom-up designs.

The insights of ecology into the organization of biological systems have practical utility in the development of conservation strategies and international development policies.[13] Improved understanding of the global organization of technological systems, or the "technosphere", may improve our forecasts of technological change and guide research and development efforts. For example, does the energetic equivalence rule hold for technological systems as well, implying that future nanomotors will consume significant amounts of energy and contribute to environmental problems on scales comparable to the Diesel engine? If so, the efficiency of molecular motors will become a primary consideration and will need to be on par or better than those of macroscale engines.[14] In summary, the "ecology of technology" may be a valuable addition to other efforts aimed at predicting the societal implications of nanotechnology.[15]

A review of the current state of research related to molecular motors and nanomotors is beyond the scope of this Perspective. However, we would like to highlight two recent significant advances in the engineering of nanosystems using biomolecular motors, such as dynein or kinesin motor proteins.

> In this issue of *ACS Nano*, Kumar *et al.* describe a new solution to a problem that has occupied researchers for more than a decade: how do we switch motor activity on and off?

Aoyama, Shimoike, and Hiratsuka accomplished the design of an optical device driven by dynein motors, which mimics the mechanism responsible for color changes in the skin of certain fish.[16] The device is a 100 × 100 pixel array, where each pixel consists of a self-assembled "melanophore" capable of a stimulus-dependent change in coloration (Figure 2). Upon exposure to UV light, caged ATP is photolyzed and activates kinesin motors, which in turn aggregate 1000 initially dispersed pigment granules at the center of the pixel by active movement along an aster-like array of microtubules. The collective action of the device faintly resembles a digital micromirror device; however, the number of individually acting motors is several orders of magnitude larger and potentially enables the ability to address many intensity levels for each pixel. Imagine an automobile covered in a paint that is composed of such devices: the main engine and the hundred smaller motors currently employed in a car would be complemented by a mole of molecular motors dynamically changing the car's color!

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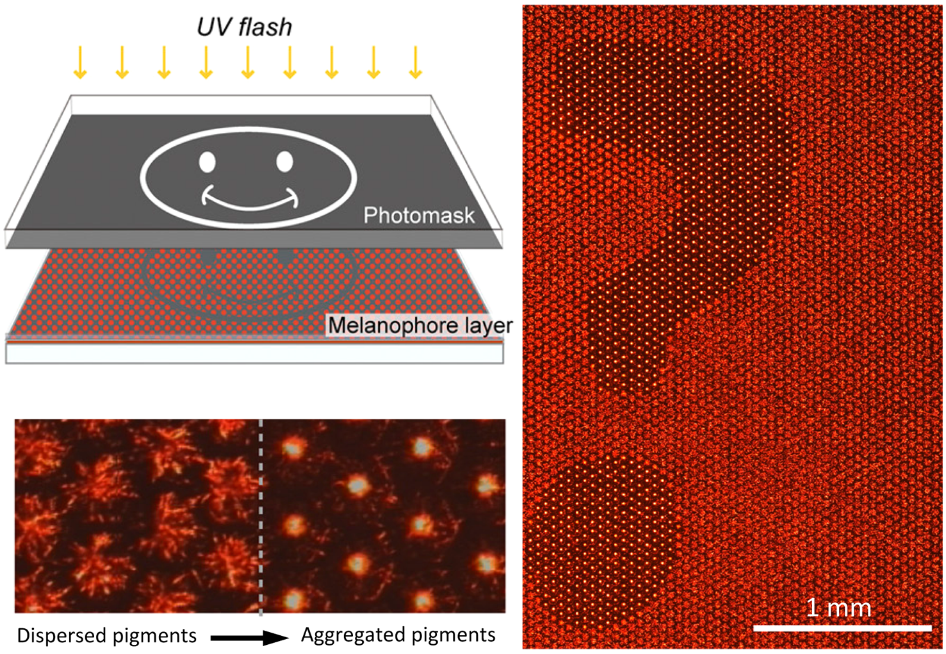

Figure 2. Motor protein-driven device of Aoyama *et al.*[16] Dynein motor proteins aggregate pigment granules upon a stimulus of UV light in an array of artificial melanophores. The system is inspired by the camouflage mechanism used in the skin cells of certain fish. Adapted with permission from ref 16. Copyright 2013 National Academy of Sciences.

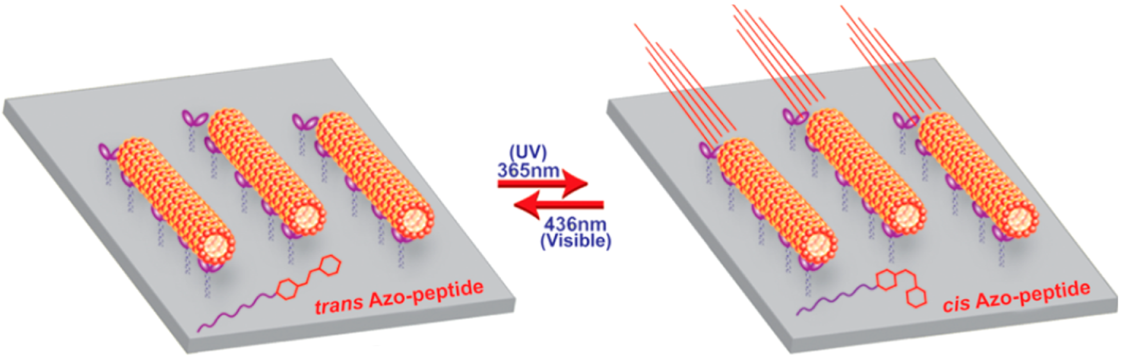

Figure 3. Kumar *et al.* describe how an azobenzene-tethered peptide can switch the activity of surface-adhered kinesin motor proteins on and off, which in turn controls the gliding velocity of microtubules propelled by these kinesin motors. The microtubules can serve as cargo-carrying elements in nanoshuttle systems. Adapted from ref 17. Copyright 2014 American Chemical Society.

problem that has occupied researchers for more than a decade: how do we switch motor activity on and off? Controlling activity was already a challenge in the development of the steam engine, solved by James Watt with the invention of the centrifugal "flyball" governor that maintains the speed of the engine at a constant level. For nanosystems driven by motor proteins, an initial approach was to control the supply of ATP molecules to the motors. Because exchanging the solution surrounding the motor proteins in order to adjust the ATP concentration relies on the fluid flow that the motor proteins are often supposed to replace, the preferred approach is to rely on UV light as a trigger which photolyzes "caged" ATP. While this is an elegant "on" switch, the "off" switching requires the sequestration of the released ATP, essentially dumping most of the fuel. Motor activity can also be altered by temperature, surface state, and electric fields; howevers these approaches do not enable simple "on/off" switching with high contrast ratios. Kumar *et al.* used a combination of design and discovery to create a photoaddressable molecular switch, an azobenzene-tethered peptide that in the *trans*-rich state completely inhibits the activity of kinesin motor proteins and in the *cis*-rich state hardly interferes at all (Figure 3). From our point-of-view, this is a major step forward, which is likely to displace completely other approaches to switching the activity of biomolecular motors.

In summary, engineering experimentation with biomolecular motors continues with notable successes. The purpose of these systems is currently four-fold: to demonstrate potential applications, to inspire the development of synthetic molecular motors, to elucidate general nanoscale engineering principles,[18] and to hone our understanding of design decisions by natural evolution as observed in biological systems. In the long term, we aim to fill Feynman's "room at the bottom" with moles of nanomotors.

Conflict of Interest: The authors declare no competing financial interest.

Supporting Information Available: The abundance of machine units per square kilometer as a function of machine weight. This material is available free of charge *via* the Internet at http://pubs.acs.org.

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