as other solid-state caloric effects, such as the magnetocaloric effect (*8*–*11*). The reason for this is that although very large EC temperature cooling (>30°C) has been reported in self-supporting EC polymers and their nanocomposites, this large EC cooling is achieved under fields near the dielectric breakdown (*3*, *4*), an electric field that will cause device failure. Practical EC coolers should be operated at fields well below the dielectric breakdown for long-term reliable use of the coolers, limiting the caloric temperature change that can be used reliably in the present EC polymer films to about 10°C.

Several EC device demonstrations that use cycles similar to the Ericsson cooler cycle have been reported. One example has a basic building block of two rings in thermal contact that are composed of EC elements; the rings rotate in opposite directions, and many such units stack together to form an EC cooler (*10*). The heat released from one ring is used to heat the other to complete the regenerative process. Modeling results show a temperature lift more than ten times greater than the EC material temperature change alone. A prototype device that uses commercial multilayer ceramic capacitors demonstrated the regenerative principle, achieving a larger temperature lift (*10*). Recent system modeling on the EC polymer coolers also indicates that the EC coolers achieve greater COP and thermal capacity compared with conventional VCC systems. Preliminary module test results have been consistent with the system-level models (*12*).

Because EC coolers do not need compressors and are low-noise devices, their high efficiency can open up applications beyond household air conditioners and refrigerators that are not possible with coolers based on VCC. One could imagine wearable cooling bandages that replace ice bags for injury treatment and cooling of biologic tissues and organs; compact air conditioners and thermal management systems placed on office desks or integrated into chairs for localized climate control; and electronic devices such as labs-on-a-chip. ■

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NANOSCIENCE

DNA robots sort as they walk

Multiple DNA robots perform parallel tasks on a self-assembled DNA origami surface

By **John H. Reif**

DNA nanoscience is the science and engineering of molecular-scale devices composed of DNA. In prior work, DNA devices have been engineered to do nontrivial serial computational and robotic tasks. On page 1112 of this issue, Thubagere *et al.* (*1*) report an experimental molecular robotic system that makes parallel use of multiple DNA robotic devices to execute a defined task. The results provide evidence that the powerful technique of parallelism, previously used in macro- and micro-robot systems, can be used for molecular robotics.

The field of DNA nanoscience encompasses three main areas: the self-assembly of nanostructures from DNA strands via hybridization reactions; molecular computation executed with DNA molecules; and DNA robotics, that is, physically active molecular devices composed of DNA. In many cases, these areas are intimately intertwined. For example, a DNA robotics device may traverse a self-assembled DNA nanostructure, changing state in discrete stages during the movement and thus executing a serial computation. DNA devices typically execute a series of rationally designed chemical reactions to achieve the desired computation or robotic movement. Often, these chemical reactions are strand-displacement reactions in which an initial partially hybridized strand is displaced by another strand.

"The major advance in Thubagere et al.'s study is their methodology for designing simple DNA devices that work in parallel to solve nontrivial tasks."

DNA nanoscience is highly interdisciplinary and makes use of diverse techniques from distinct fields, such as computer software for design DNA sequences of DNA devices, chemical reaction and molecular modeling to estimate kinetics and energetics of chemical reactions undergone by DNA devices, and biochemistry techniques to conduct the experiments. Using these multiple interdisciplinary techniques, the DNA devices are rationally designed to operate as desired in biochemical environments.

In the past two decades, the scale, complexity and sophistication of experimental demonstrations of DNA nanoscience have increased rapidly. The early idea of self-assembly of simple flexible DNA nanostructures (*2*) eventually progressed to sophisticated self-assembly techniques such as DNA origami (*3*), allowing the rapid automatic design and self-assembly of highly complex DNA nanostructures with hundreds of features. The first demonstration of DNA computation (*4*) solved a small combinatorial optimization problem; subsequent work eventually led to methods for molecular-scale execution of moderate-scale digital circuits (*5*). In DNA robotics, experimental demonstrations of fully autonomous DNA walkers (*6*, *7*)—DNA devices that traverse a DNA nanostructure (*8*)—were subsequently extended to DNA walkers that execute functional tasks as they walked. For example, walkers have been shown to pickup and drop off molecular cargo (*9*, *10*) and perform DNA-templated synthesis (*11*).

Most prior studies of DNA robotics have made use of only individual devices, with minimal interaction between devices. Thubagere *et al.* now report a design that allows a group of DNA robots to collectively do a predetermined task: that of sorting cargo molecules and moving them into targeted locations.

The authors use two types of molecular cargo, each a distinct single-stranded DNA. Initially, the molecular cargo strands are attached to the surface of a 2D DNA origami at arbitrary locations. The task is to sort and transport the cargo strands into distinct separate locations on a two-dimensional DNA origami surface (see the figure). Multiple identical single-stranded DNA robots walk in parallel on the surface. Each robot has a foot domain used for walking (with two foot subdomains),

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as well as an arm and hand domain used for picking up and dropping off cargos. Each robot can perform three modular operations: a random walk step to one of its neighbors, a pickup of a cargo strand, and the drop off of a cargo strand.

The study's design is simple and elegant. It has four key features. First, the design allows for a natural parallelism; each robot executes individual sorting tasks largely independent of the other robots, except that a random walk step cannot move into the location of another robot, and two robots cannot simultaneously pickup or drop off the same identical cargo strand at the same time. Second, any given robot can be reused for multiple cargo-sorting tasks, because a random walk step by a robot to each of its four possible neighbors requires no energy expenditure. Third, the pickup and subsequent drop off of a cargo strand do not depend on the type of cargo, and the same robot can therefore be used to transport either of the two types of cargo strands, simplifying the protocol design. Finally, since all the cargo and robots remain attached to the same DNA origami, each cargo-sorting task is localized to an individual DNA origami. The authors demonstrate that multiple distinct cargo-sorting tasks can be executed simultaneously in a single test tube, each on a distinct DNA origami.

The major advance in Thubagere *et al.*'s study is their methodology for designing simple DNA devices that work in parallel to solve nontrivial tasks. Similar systems should be able to perform more complex tasks, such as executing chemical synthesis in parallel. Many exciting emerging applications, for example in nanomedicine, may make use of parallel executing DNA devices. ■

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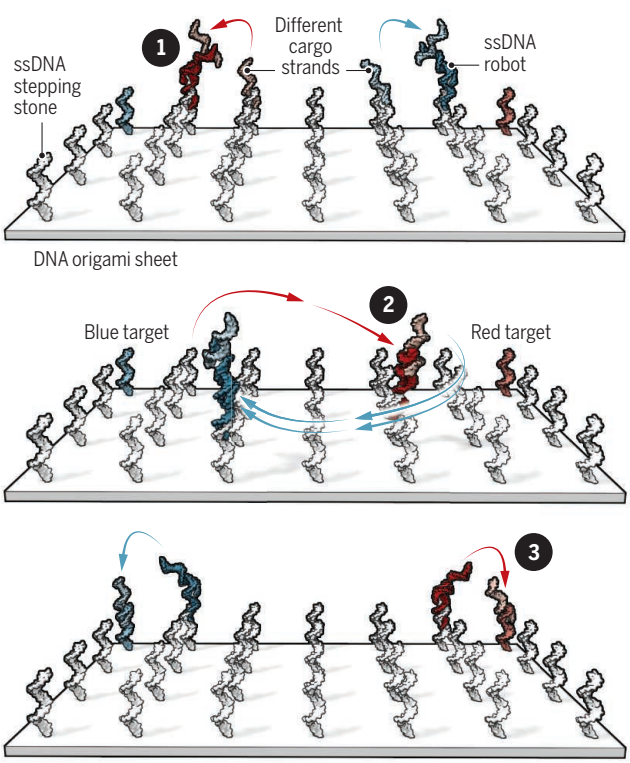
Parallel cargo transport using multiple DNA robots

DNA robots independently execute operations (cargo pickup, random movement to adjacent stepping stones, cargo drop off) via hybridization reactions.



1 The robot picks up cargo at location on DNA origami.

2 The robot randomly moves across DNA stepping stones on the origami sheet, to its target location.

3 Each transported cargo is dropped off at its target location on the DNA origami.

MICROBIOLOGY

Crystal-clear memories of a bacterium

Structures of the CRISPR memorization complex in bacteria reveal new mechanistic details

By **Rea Globus** *and* **Udi Qimron**

Information storage in DNA is the cornerstone of biology. Interestingly, prokaryotes can store information in specific loci in their DNA to remember encounters with invaders (such as bacteriophages—viruses that infect bacteria). Short samples of DNA from invaders are inserted as "spacers" into the CRISPR array. The array thus contains samples of DNA invaders in a defined locus that is recognized by Cas proteins that further process this information. This enables bacteria to adaptively and specifically respond to invading DNA that they have experienced before. Structures of the molecular machinery catalyzing this memorization process have previously been solved (*1*–*4*), but not when bound to the CRISPR array. On page 1113 of this issue, Wright *et al.* (*5*) provide structures of this molecular machinery with artificial substrates that represent the CRISPR array in different stages of spacer insertion. Better understanding of how spacers are integrated into the CRISPR array in the memorization process will assist in harnessing it for future biotechnological applications.

The study addresses one of the last unsolved steps in the CRISPR memorization process. The authors designed two DNA molecules that mimic intermediates of the integration reaction. One DNA molecule mimics the product formed after the first nucleophilic attack, which occurs when a spacer is joined to one side of the repeat sequence in the CRISPR array. The other DNA molecule mimics the product formed after the second nucleophilic attack, which joins the other end of the spacer with the other side of the CRISPR array repeat. The second DNA molecule is elegantly designed as a spacer joined to either side of the CRISPR array repeat but

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DNA robots sort as they walk

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