disproportionately more beneficial for females, offsetting the physical disadvantage of lower bite force, compared with that of males, due to their smaller body size.

The study by Law *et al.* introduces a new measure of fitness benefits in tool use and highlights the importance of considering the local resource landscape when making inferences about the adaptive value of tool use. However, it remains unclear how the high interindividual variation in the reliance on tool use is maintained in these populations. Sea otters become more proficient at using tools with experience (*13*). Although the acquisition of stone tool use to access prey items does not need to be learned socially in this species (*9*), there is some evidence that pups learn how to use tools from their mothers, resulting in them adopting the same diet (*13*, *14*). Because prey specialization and tool-use frequency are closely linked (*10*), the finding by Law *et al.* that reliance on tool use has fitness consequences in terms of dental health opens exciting avenues for future research. For example, it will be important to determine whether dental health is transmitted from mothers to pups through the "social inheritance" of diet specialization and whether the fitness costs incurred by infrequent tool use—which leads to poor dental health—result in lower reproductive success. More generally, the study by Law *et al.* emphasizes the importance of investigating the physical impacts of tool use on the body of the tool user to understand and quantify the fitness consequences of tool use across a broad range of species. ■

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PHYSICS

Engineering colloidal crystals molecule by molecule

DNA particles are programmed to assemble with precision into complex lattices

By **Zhe Li**[1] and **Chengde Mao**[2]

Engineering crystalline materials by molecular design (*1*–*4*) has led to numerous technological and scientific advancements in medicine, catalysis, optics, and electronics. Colloidal crystals (*5*) are often considered to be the structural analogs of molecular crystals, wherein microscopic particles rather than molecules are arranged into highly ordered architectures. Despite substantial progress, engineering colloidal crystals with precise structures and properties remains a challenging task, especially when compared to the level of control achieved in molecular crystals. On page 781 and 776 of this issue, Posnjak *et al.* (*6*) and Liu *et al.* (*7*), respectively, report the design of DNA molecules that are engineered to self-assemble across multiple length scales into colloidal crystals with unprecedented control and programmability. This advance opens up tremendous engineering opportunities for creating new crystalline materials in optics, sensing, and separation applications.

Conventional colloidal particles can be composed of a wide range of materials and vary in size from nanometers to micrometers in diameter. They also often have limitations in terms of size uniformity, shape control, polydispersity, and the ability to finely tune interactions between particles. By contrast, DNA origami particles (*8*) overcome these limitations because such properties can be programmed into DNA with nanometer precision. Assembled from hundreds of DNA single strands, DNA origami particles can be designed to take on almost any conceivable microscopic shape and size. Although the potential of DNA origami for colloidal assembly was realized more than a decade ago (*9*), it has been a long journey of trial and error (*10*, *11*) to achieve the programmability described by Posnjak *et al.* and Liu *et al.* Many things can go wrong when DNA origami particles assemble in three dimensions. For example, the structural flexibilities of particles or interparticle interactions can result in collapsed or distorted assembly. Nonspecific interactions between particles can lead to alternative architectures. Also, tight interactions can randomly aggregate DNA particles into kinetic traps that hinder the formation of a thermodynamically stable ordered state.

Posnjak *et al.* created a cubic diamond lattice, one of the most demanding colloidal crystal geometries, in which the particles are arranged in the same way as carbon atoms in diamond. Such packing has large, open spaces and is not favored energetically. As such, the structure has had limited success in colloidal crystals (*12*). To overcome this problem, the authors designed a DNA origami tetrapod. Each tetrapod consists of four arms of parallel, double-stranded DNA (24 duplexes). At the tip of each arm are single-stranded DNA tails bearing complementary sequences that allow the tails to hybridize. Because the tetrapods associate with each other by connecting their arms through DNA hybridization, the sequences must be carefully designed for the correct assembly to emerge. The formation of multiple DNA hybridizations between two neighboring tetrapods is required to achieve a uniform, staggered conformation rather than an eclipsed conformation. At the same time, DNA hybridizations have to be sufficiently weak for the assembly of well-ordered, colloidal crystals with clear facets.

Liu *et al.* established a powerful computational-experimental framework for designing colloidal crystals based on DNA origami. In their simulation, the authors treated DNA origami as spherical particles with multiple interaction patches on the surface and used a feedback loop to promote designs that facilitated lattice formation and exclude designs that led to undesired, competing assemblies. After certain iterations, the authors obtained a pyrochlore lattice—an arrangement of tetrahedral shapes joined at each corner—with high yield in silico. Liu *et al.* further experimentally confirmed the simulation results by assembling pyrochlore lattices from DNA octahedra or icosahedra. The interaction patches on the surface of each spherical DNA particle are clusters of multiple, flexible DNA single strands without any orientation control. They designed four different particles,

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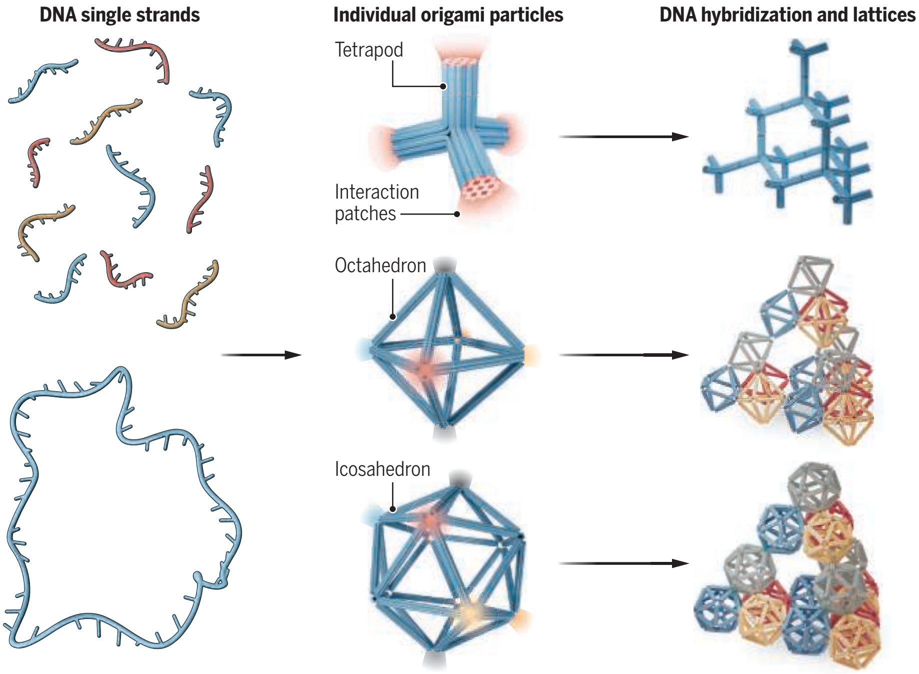
[1] Department of Biomedical Engineering, Southern University of Science and Technology, Shenzhen, China. [2] Department of Chemistry, Purdue University, West Lafayette, Indiana, USA. Email: liz8@sustech.edu.cn; mao@purdue.edu

Engineering DNA colloidal crystals

On the basis of preknowledge or computational simulation, DNA single strands can be designed to assemble into individual origami particles and then to associate further with each other into three-dimensional lattices by specific patches of DNA hybridization.



GRAPHIC: LI *ET AL.* AND A. MASTIN/*SCIENCE*

and each particle had six different patches. In total, there were 24 different patches, grouped into 12 pairs of complementary DNA sequences (each patch contains three DNA strands with an identical sequence) that guided the systems of multiple, different species of DNA origami particles to coassemble into the desired crystals.

Although individual DNA origami particles can be readily created, the key to successful assembly of DNA colloidal crystals lies in the design of interparticle interactions (see the figure). In the approach of Posnjak *et al.*, each tetrapod has an interaction patch located on the tip of each arm. Between neighboring tetrapods, multiple molecular interactions across patches constrain and orient their association in the desired direction and, consequently, promote lattice assembly. In the approach of Liu *et al.*, simulation methods extensively search and identify the best combination for 12 interacting patch pairs to work in synergy. Although these interaction patches are flexible, the multivalency and specificity freeze and pack the DNA origami particles at the desired lattice positions.

It is currently possible to engineer particle interactions for successful crystal assembly, but further experimental tweaks and modifications across various design parameters are needed to generate crystals with larger size and more precise structural order (which affects their properties). A vast variety of sophisticated crystal architectures are within reach by engineering individual DNA origami particles and their interactions with the approach described by Liu *et al.* Colloidal crystals are also promising scaffolds for spacing materials at a length scale comparable to the wavelength of ultraviolet and visible light as optical metamaterials (*13*). For example, Posnjak *et al.* coated diamond lattices with inorganic materials to create photonic crystals with tunable band gaps. Combined with the dynamic aspect of DNA nanotechnology (*14*), these highly programmable colloidal crystals could be further engineered into responsive and reconfigurable optical devices and enable the manipulation of light with a level of accuracy that could not be reached before. ■

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MEDICINE

The complexity of physician power

Inequitable variation in physician effort and resource use is revealed

By **Laura Nimmon**[1,2]

Power is present in all human relationships. Thus, there is no interaction in which power and its potential to exert influence is not relevant in medicine (*1*). Although the role of power in medical interactions is important, few studies investigate how physicians allocate effort and execute their power when interacting with patients. The ephemeral and unobservable nature of power has made it profoundly difficult to study empirically. On page 802 of this issue, Schwab and Singh (*2*) investigate how physician power in the US Military Health System interfaces with sociological phenomena such as hierarchy, status, and authority. Their findings reveal the variability and complex mechanisms through which physician power is exerted, ultimately providing nuance about how the ethics of physician power is understood as it interfaces with other hierarchical systems of power.

A widely held assumption is that there is an inherent power imbalance in the physician-patient dyad. The nature of physicians' relationships with patients is characterized as top down and asymmetrical (*1*). This unequal relationship is thought to be a product of physicians possessing legitimized expert knowledge and legal decision-making authority and patients who are reliant on care and services (*1*). Underpinning this power afforded to physicians is societal trust that physicians will always act altruistically and ethically toward patients.

Drawing on data from the US Military Health System, Schwab and Singh examined power differentials (measured by using differences in military ranks) between physician and patient to estimate the effect on patient care and outcomes. The authors'

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[1] Centre for Health Education Scholarship, Faculty of Medicine, University of British Columbia, Canada.
[2] Department of Occupational Science and Occupational Therapy, Faculty of Medicine, University of British Columbia, Canada. Email: laura.nimmon@ubc.ca