do not affect either of the two steps of the nucleation process, and that they only serve as hooks to which the liquid clusters attach so that they and the process of nucleation occurring inside them can be monitored with SMRT-TEM.

Harano and colleagues' work leaves open questions about the mechanism underlying the formation of the dense liquid clusters, about the properties of the clusters and the parameters determining which clusters will support crystal nucleation, and about the generality of the two-step mechanism. Also, how can the gained insight on the two-step mechanism be used to design nucleation control strategies? Answering these questions will require additional theoretical understanding and the accumulation of further experimental data, both structural and kinetic, on nucleation in solution. ❐

*Peter G. Vekilov is in the Department of Chemical and Biomolecular Engineering, and the Department of Chemistry, University of Houston, 4800 Calhoun Boulevard, Houston, Texas 77204-4004, USA.*
*e-mail: vekilov@uh.edu*

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MATERIAL WITNESS

# BRINGING CRYSTALS TO LIFE

PHILIP BALL

Attempts to connect crystals to the life sciences have a long history, much of it tinged with mysticism. Kepler invoked a mysterious 'formative principle' to account for the vegetative intricacy of snowflakes; Newton attributed to something like organic growth the 'treelike' salt precipitates of silica gardens. In the mid-eighteenth century a Swedish mineralogist could write that "there are naturalists who maintain that minerals have a life like that which vegetation enjoys". The discovery of liquid crystals in the late nineteenth century was interpreted by Ernst Haeckel as the missing link between crystalline order and organic plasticity of form, and in some ways he was not wrong: liquid crystalline and other mesophases abound in living organisms, from the reflective pigmented stacks of animal 'structural colours' to the fibrous alignment of silk and the membranes that template complex biominerals.

Meanwhile, the connection between quasi-regular structures and the encoding of information was introduced with Schrödinger's famous invocation of an 'aperiodic crystal' as the material basis of genetics — an insight validated by the discovery of the structure of DNA. It is increasingly apparent that DNA in fact has a hierarchy of structural ordering *in vivo*, including liquid crystal phases, and that important information is encoded at higher levels than the primary sequence, for example in the condensed phases of chromatin. The possibility that inorganic crystals might enable the storage, transmission and mutation of 'genetic' information — for example in the stacking sequences of clays — was introduced to prebiotic chemistry by Graham Cairns-Smith in the 1960s.

So it is surprising in retrospect that a collection like that provided in a special issue of *Philosophical Transactions of the Royal Society A* entitled 'Beyond crystals: the dialectic of materials and information'[1] has not appeared sooner. It is in effect a Festschrift for Alan Mackay, who has thought perhaps more deeply than anyone else about the relationships between crystal structure, periodicity and information. Mackay predicted quasicrystals before their discovery in 1984, and in the introduction to his 1999 translation of Haeckel's book *Crystal Souls* he foreshadows some of the concepts in the present volume[2].

The *Philosophical Transactions* collection, which Mackay co-edits with Julyan Cartwright, shows that even the oldest themes remain relevant. 'Crystal gardens' like those that fascinated Newton remain imperfectly understood: the morphologies are varied and complex, and seem to involve the formation of membranes, compartments and chemical gradients that could indeed provide a bridge from the inorganic to the organic on the early Earth. Russell and co-workers consider whether iron sulphide chimneys at hydrothermal vents could have provided electron sources and catalytic structures that seeded the development of protein/nucleic acid biochemistry[3].

The 'materials/information dialectic' is perhaps most apparent today in supramolecular chemistry, described by Jean-Marie Lehn as a "science of informed matter"[4]. Crystal engineering can be profitably regarded as the navigation of an energy landscape akin to that of protein folding[5], with attendant possibilities for obtaining function from dynamical transitions between metastable conformations[6]. And just as in biological structures the interaction of 'primary sequence' information with environment, self-assembly and defects can give rise to complex hierarchical structures and shapes such as multi-protein devices or biominerals such as nacre, so may similar considerations open opportunities at the nano- and mesoscales in synthetic materials[7]. ❐

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