tablish cohesion. Double mutant yeast with mutations in both Trf4p and Trf5p (arrested in early M phase with nocodazole) show a marked increase in loss of cohesion if they are shifted to 36°C (the restrictive temperature) for 3 hours. Wang *et al.* go on to show that a site-directed substitution mutation in the Trf4p domain, which is essential for polymerase activity, resulted in a defect in sister chromatid cohesion, suggesting that proper cohesion seems to require polymerase activity of Trf4p.

It is still not clear how Trf4p is mechanistically involved in cohesion. It may establish sister chromatid cohesion during DNA replication as it sits at the replication fork. All known cohesion molecules are essential for S phase and some, such as Ctf7p, Mis4p, and Eso1p, interact with enzymes implicated in DNA replication. Mutations in Ctf7p—together with mutations in Pol30p (proliferating cell nuclear antigen) or Ctf18p (replication factor C–like protein)—are lethal for budding yeast (*5*). In fission yeast, mutation of Mis4p combined with a DNA ligase mutation is also lethal (*6*). Another fission yeast cohesion molecule, Eso1p, consists of two domains: one related to budding yeast Eco1p/Ctf7p and the other related to DNA pol η (*7*).

The finding that Trf4p (pol κ) is essential for cohesion adds another function for DNA polymerases to a list that already includes genomic DNA replication (pol α, δ, and ε), mitochondrial DNA replication (pol γ), and repair replication (pol α, β, δ, ε, ζ, η, θ, and ι) (*8*). Trf4p is the first cohesion molecule found to have enzymic activity as well. Wang *et al.* propose that cohesion may be established in such a way that when the replication fork encounters a cohesion site, there is a switch from DNA polymerase α, δ, or ε to Trf4p and Trf5p (pol κ).

If pol κ activity per se is required for maintenance of sister chromatid cohesion, then currently held notions about cohesion may have to be substantially revised. A structural model has been proposed in which the cohesin complex binds the two sister chromatids together. The cohesin complex contains heterodimeric SMC (structural maintenance of chromosome) proteins that have head and tail domains connected by rods and a central hinge region. Because the SMC complex interacts with adenosine triphosphate (ATP), the structural link may well be altered during the cell cycle in an ATP-dependent manner. The Wang *et al.* study shows that formation and maintenance of sister chromatid cohesion may require the catalytic activity of a DNA polymerase. It will be interesting to determine how passage of the replication fork results in the establishing of effective cohesion by Trf4p and whether de novo DNA replication dependent on pol κ restores broken cohesion in cells after S phase.

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PERSPECTIVES: BIOMINERALIZATION

Naturally Aligned Nanocrystals

A. P. Alivisatos

By what sequence of events does a mineral form? In traditional models, individual atoms or molecules are added or subtracted as crystals grow. But a different view is emerging. In a series of laboratory experiments, Penn and Banfield have previously shown that inorganic nanocrystals, made up of hundreds or even thousands of atoms, can be the fundamental building blocks for the creation of highly ordered extended solids. On page 751 of this issue, Banfield *et al.* (*1*) provide strong evidence that some natural minerals also grow through such a mechanism of "oriented attachment" of nanocrystals. The results will be important not only for geochemistry but also for the creation of advanced artificial materials.

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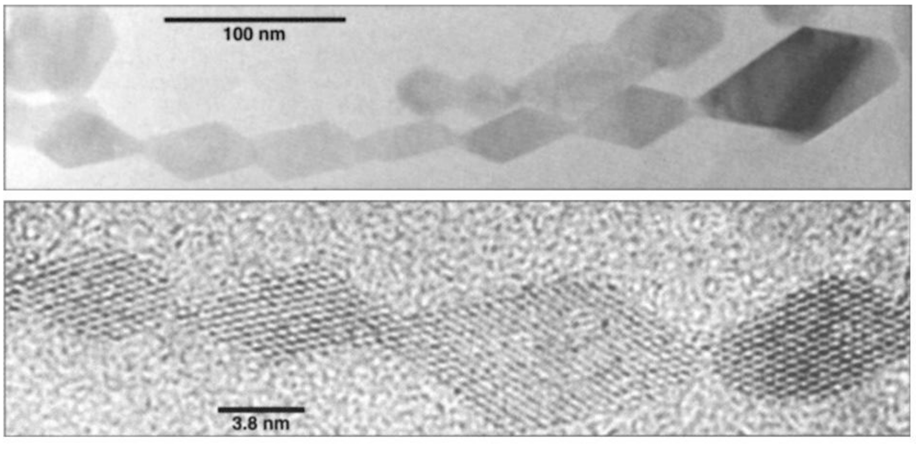
A nanocrystal typically has a diameter of between 1 and 10 nm and may contain as few as a hundred or as many as tens of thousands of atoms. Many fundamental properties of nanocrystals depend strongly on their size in smooth and predictable ways. Examples include the external field required to switch a magnetized particle [of great importance in magnetotactic bacteria (*2*) and in hard disk drives (*3*)] and the color of light emission from a semiconductor [used for the fluorescent labeling of cells (*4*) and in lasers (*5*)]. This facile tuning of properties by size variation is one reason why nanocrystals are widely viewed as promising components for new artificial optical and electrical materials.

But there is another reason why nanocrystals are particularly attractive as a building block for larger structures. Extended solids always contain a certain number of defects, which must be controlled to achieve desirable properties (*6*). If the number of atoms is large and the free energy of defect formation is finite, then a certain density of defects, such as vacancies, is inevitable even at equilibrium. However, when this same number of atoms is partitioned into nanometer-sized crystals, then each nanocrystal on average need not contain any interior defects. It is possible—even easy—to prepare nanocrystals that are highly perfect, because the time required to anneal a



An example of oriented attachment. Transmission electron micrograph of TiO_2 nanocrystal aggregates (*9*). Primary particles align, dock, and fuse to form these oriented chains.

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The author is at the Department of Chemistry and Materials Science, University of California, Berkeley, Berkeley, CA 94720, USA. E-mail: alivis@uclink4.berkeley.edu

nonequilibrium defect is short when a crystal is small. (That small perfect crystals are easier to make than large ones is confirmed by a quick check of the size dependence of prices for diamonds at a jewelry store!)

Can small but highly perfect nanocrystals be assembled into pure extended solids? Until recently, it seemed that aggregation of nanocrystals would always lead to disordered (albeit very interesting) solids. For example, Matijevic and coworkers demonstrated exquisite shape control of polycrystalline micrometer-sized particles prepared by nanocrystal aggregation (*7*). Gleiter showed that ceramics derived from the random consolidation of nanoparticles are particularly resistant to fracture (*8*). The discovery that aggregation of nanocrystals can yield an ordered crystal thus comes as a surprise.

Penn and Banfield previously showed that long chains of highly ordered titania can emerge from a solution of primary titania nanoparticles (*9*) (see the figure). This chain can only arise if each nanocrystal "docks" with the next, such that the two crystals are fully aligned, a process the authors call "oriented attachment." There is certainly a strong thermodynamic driving force for oriented attachment, because the surface energy is reduced substantially when the interface is eliminated. The surprise is that two crystals can align, dock, and fuse without first getting stuck in any one of an almost innumerable set of misoriented arrangements.

One possible explanation for this behavior comes from Averback and coworkers (*10*), who independently and simultaneously discovered the same type of nanocrystal addition process. They studied the deposition of a silver nanoparticle onto a copper substrate and observed a process they called "contact epitaxy." The Ag nanocrystals were initially randomly oriented but subsequently aligned epitaxially with the substrate. Once aligned with the substrate, the nanocrystals are also aligned with each other. In a series of simulations, Averback *et al.* showed that this could arise if, after the nanocrystal lands on the substrate, the stress between the nanocrystal and the substrate creates a dislocation within the nanoparticle. As this dislocation moves toward the nanocrystal surface, the particle "rotates," resulting in full alignment with the substrate. Similar phenomena occur in simulations studying the docking of two nanocrystals (*11*).

Three aspects of oriented attachment are of particular interest: (i) it occurs naturally, (ii) it provides a convenient explanation for certain types of defects in solids, and (iii) it may be a useful method for creating advanced artificial materials.

Banfield *et al.* present a strong case for some naturally occurring materials arising through oriented attachment (*1*). They examine iron oxyhydroxide minerals recovered from a flooded mine and find both primary particles with diameters of 2 to 3 nm and oriented nanoparticle chains and sheets. They conclude that the latter have arisen during natural biomineralization as a consequence of oriented attachment. It remains to be seen, however, how common this type of mineral growth is in nature.

Oriented attachment provides a simple set of explanations for how particular types of defects may arise in extended solids (*12*). Nanocrystals, if well formed, have facets, separated by regions where step faces are exposed. If the face of one nanocrystal docks against the steps of another, the two crystallites will naturally be oriented at a particular angle. Depending on the orientation, further oriented attachment will yield various types of dislocations or screw axes (*13*). Impurity incorporation may also be more facile under conditions where crystals grow by nanocrystal attachment rather than atom by atom.

Oriented attachment may enable the preparation of interesting artificial materials. One of the most advanced methods of crystal growth, molecular beam epitaxy, involves deposition of atomic or molecular precursors onto a hot substrate. Manipulation of the stress and strain at the interface between two solids can be used to control particle size and shape, as in the growth of quantum dots, or to create metastable materials. The use of preformed nanoparticles as precursors in molecular beam epitaxy may generate new and interesting artificial materials. Likewise, the growth of nanorods and other specially shaped nanostructures with controlled defects may be possible by exploiting and controlling oriented attachment.

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PERSPECTIVES: CHEMISTRY

New Chemical Bricks Made Through Phosphorus Tricks

Hansjörg Grützmacher

The columns of the Periodic Table help chemists systematize their thinking about chemical reactivity of groups of elements based on their valence. This approach is useful so long as one is aware of the "first-row anomaly": the very different reactivity of first-row elements such as carbon (C) and nitrogen (N) relative to silicon and phosphorus (P). The first-row elements tend to form hybrids from s and p orbitals that lead to the familiar trigonal and tetrahedral bonding geometries. Second-row elements avoid hybrization (*1*). This tendency can be seen in their elemental forms—for example, nitrogen ($N\equiv N$) contains a multiple bond, whereas phosphorus adopts P–P single bonds in the tetrahedral P_4 molecule.

For organic reactions, differences in electronegativity—the relative ability of atoms in molecules to attract electrons—is also important. Whereas N is more electronegative than C, P is slightly electropositive. These differences can be exploited to stabilize P-containing species that would be transient or unknown as the N analog. On page 754 of this issue, Kato *et al.* (*2*) show that replacing N or C centers with P can lead to versatile new reagents. Two recent related studies are also discussed below (*3*, *4*). The three studies not only help identify new reagents, but also expand our understanding of the chemical bonding and reactivity of main group elements.

Carbenium ions like amidinium ions $[CR(NR'_2)_2]^{\oplus}$ **1** play a prominent role in synthetic chemistry because a new chemical bond between the electrophilic carbon center and an electron-rich entity, or nucleophile, is easily formed. The amino

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The author is in the Laboratory of Inorganic Chemistry, ETH-Centre, Universitätstrasse 6, CH-8092 Zürich, Switzerland. E-mail: gruetzmacher@inorg.chem.ethz.ch