

Lessons from Nature—Biomimetic Approaches to Minerals with Complex Structures

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Guest Editors

Abstract

In biology, organic-inorganic hybrid materials are used for several purposes, in particular, for protection and mechanical support. These materials are generally optimized for their function through precise control over the structure, size, shape, and assembly of the component parts and can be superior to many synthetic materials. The shapes and forms of minerals encountered in nature strongly contrast with those that are generally formed in a synthetic environment. According to current understanding, this is achieved through different modes of control: their shape can be controlled by restricting their growth to a confined space or by influencing their preferred direction of growth; in addition, for crystalline materials, polymorph selection and oriented nucleation are achieved through specific interactions between a template or additive and the developing nucleus. Also, controlled arrangement of nanoparticles into superstructures can lead to a complex structure. The understanding and, ultimately, the mimicking of these processes will provide new synthetic routes to specialized organic-inorganic hybrid materials. On the other hand, transformation of existing complex hierarchical natural structures such as wood or diatom frustules into other materials using shape-preserving chemistry is another approach toward minerals with complex biomimetic structure. The theme topic in this issue will focus on recent biomimetic and bioinspired approaches used to achieve control over the shape and organization of mineral and organic-inorganic hybrid materials. The different contributions will also highlight the advantages of these methods for advanced materials synthesis, and possible applications will be discussed.

Introduction

Living organisms use a whole range of organic-inorganic hybrid materials for a variety of purposes, including mechanical support, navigation, protection, and defense. These biominerals often have remarkable mechanical, optical, and magnetic properties related to the precise hierarchical assembly of nanoscale building blocks.¹⁻⁵ Moreover, in many cases, these biominerals have fascinating shapes that are seldom found in geological or syn-

thetic minerals and which are adjusted to their specific functions (Figure 1). These beautiful morphologies have been the source of inspiration for many scientists for more than a century.⁶ The formation of biominerals is strictly regulated by the interaction of the mineral with ordered assemblies of biomolecules that dictate the shape, size, orientation, polymorphism, and assembly of the constituting building blocks. Through this intimate

interaction between the organic and inorganic phases, biominerals obtain their unique characteristics.^{2,5,7,8}

Aiming at mimicking these inspiring biological structures and their properties, efforts in the fields of chemistry, physics, and materials science over the years have led to a large variety of inorganic and hybrid materials, targeting several applications. Nevertheless, to date, designing organic-inorganic composite materials with controlled structure and morphology is still a major challenge.⁹ To achieve this, it is of paramount importance to gain a deep fundamental understanding of the processes involved in biomineralization and of the possible ways to apply them in materials synthesis. On the other hand, it is equally important from the viewpoint of materials science to learn how nature's hierarchical complex structures can be transformed into other materials using shape-preserving chemistry, as this will enhance the materials toolbox of minerals with complex structures.

In this issue, we will highlight several different approaches to achieve control over mineral structure through the application of bioinspired synthetic methods. First we wish to give a general introduction to the principles and pathways in biological and biomimetic mineral formation, with a particular focus on recent new developments that have drastically changed the classical view of mineral growth.

Controlling Morphology Using Organic (Macro)Molecules

While most biominerals are crystalline, some organisms (e.g., diatoms, radiolaria) use amorphous silica for the construction of often complex and beautiful morphologies. Because silica is an amorphous solid that has no preferred morphology, it can be easily molded into many shapes, as is shown in the large variety of species-specific morphologies in biology¹⁰ and in the successful mimicking of these structures by chemical approaches.¹¹ Silica also differs from most other minerals in that its formation relies on the generation of covalent (Si–O–Si) bonds, rather than on ionic interactions. Silica nucleation and growth in solution have been investigated for many decades and proceed through the formation of small oligomers that condense to larger particles and gels. It was recently demonstrated that the same classical silica chemistry also rules the formation of biosilica formation in diatoms.¹² Morphological control in these organisms occurs through the confinement of the mineralization process to the so-called silica deposition vesicles, in which dedicated macromolecules are responsible for

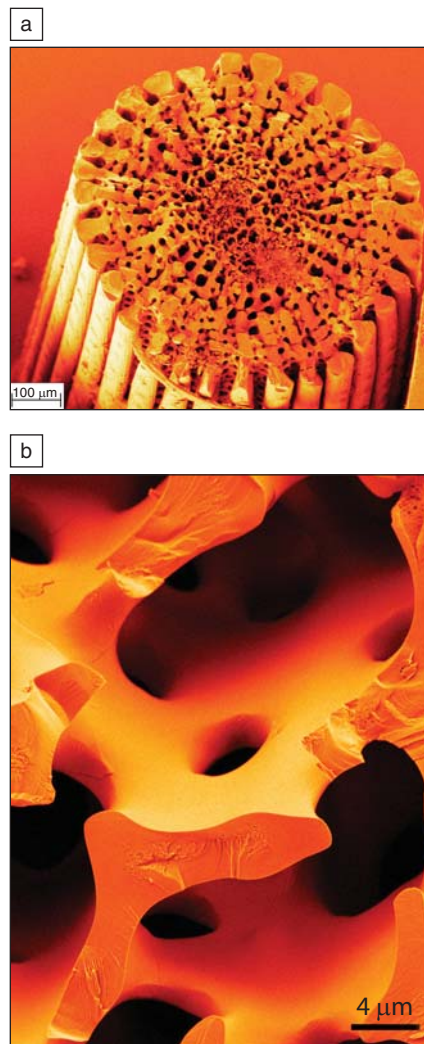


Figure 1. Scanning electron microscopy images of a sea urchin spine with its spongy hierarchical structure made from calcite (CaCO_3) in the stable calcite polymorph. (a) Whole spine overview and (b) a magnified view of the spongy spine structure, which has properties of a single crystal. Adapted with permission.

shaping the detailed multi-length scale pore structure.¹³ In this issue, Kröger and Sandhage discuss the design and development of biomimetic proteins capable of directing the *in vitro* formation of silica and other inorganic materials from aqueous precursor solutions under ambient conditions.

Most other biominerals consist of intrinsically crystalline materials. According to classical nucleation theory, the crystallization of inorganic minerals starts from the stochastic association of the constituting ions into dynamic clusters. Above a criti-

cal size, where the unfavorable surface energy is counterbalanced by the gain in bulk energy, these clusters are thought to form the critical crystal nuclei that are the basis of further growth.¹⁴ In the traditional view of biomineralization, the formation of biominerals proceeds via the ordered assembly of ions on an organic matrix with associated macromolecules (structural or insoluble matrix), guided by additives present in solution (functional or soluble matrix). Indeed, a vast number of biomimetic laboratory experiments has demonstrated that polymorphism, crystal habit, and crystal orientation can be controlled using (a combination of) synthetic templating surfaces and solution additives.^{9,15–17} In this issue, Kato et al. describe the use of synthetic and semi-synthetic macromolecules for the preparation of inorganic-organic hybrids having oriented, patterned, and 3D complex structures as well as thin-film structures with smooth surfaces.

Most biominerals grow in confined spaces and often inside a gel-like medium.¹⁸ During mineral formation, these organic components can undergo significant conformational and structural changes. In fact, it was demonstrated that the presence of a gel-like medium can drastically influence the nucleation behavior of a templating surface.¹⁹ Similarly, it was shown that the nucleation activity of an organic template is strongly affected by its ability to adapt to the demands of the developing mineral phase.^{20,21}

Although these experiments demonstrated how organic molecules and surfaces can influence the nucleation and growth of minerals, they did not provide the answer to the question of how nature is able to sculpt crystalline minerals into the often-observed nonequilibrium morphologies. Even though in some examples the use of low temperatures and low ionic strengths allows the detailed replication of polymeric templates yielding single crystals with nonequilibrium morphologies,^{22–24} we cannot assume that nature uses this approach to fabricate precisely shaped biocrystals on a large scale. Instead, recent research revealed that in many biological systems, the formation of the crystalline mineral phase is preceded by amorphous solid precursors,^{25–27} which are intrinsically labile but temporarily stabilized by the presence of acidic biomacromolecules. This seems to be an important step in the formation of crystalline biominerals with complex morphologies; in this case (cf. silica), the amorphous state allows the mineral to be molded into the shape of a scaffold, as demonstrated for synthetic nacre,²⁸ or nonequilibrium

shapes prior to their transformation into a crystalline form.²⁹ Similarly, in laboratory experiments, amorphous mineral phases can be kinetically stabilized by highly charged synthetic polymer molecules (“polyelectrolytes”),²⁹ as well as by polar/charged surfaces,³⁰ which allow for the formation of complex-shaped crystals and hierarchical structures similar to their biogenic counterparts.²⁷

Although it had long been suspected that the formation of small clusters of ions would form the first stage in the nucleation of the amorphous mineral phases,^{31,32} only recently the existence of pre-nucleation clusters was unambiguously demonstrated.^{33–35} In contrast to what classical nucleation theory describes, these nanometer-sized clusters were found to be stable and to exist in thermodynamic equilibrium with the ions in solution.³³ Their subsequent aggregation was shown to be the onset of the formation of amorphous nanoparticles that nucleated in solution rather than on the organic template present.³⁴ These nanoparticles were rather homogeneous in size and only developed to larger sizes that allowed the nucleation of crystalline domains when attached to the template. The presence of charged polymeric additives was shown to have multiple functions, such as delaying the onset of nucleation of the amorphous phase,³⁶ underlining the importance of a fundamental understanding of these basic species for the development of complex morphologies through the use of amorphous mineral phases. These findings imply that controlled aggregation over multiple length scales can facilitate the formation of complex hierarchical crystalline structures.

Hierarchical Complexity in Crystals

For many biological crystals, it has been demonstrated that they diffract as single crystals, despite the fact that they clearly are built from a large collection of small crystallites.^{37,38} Evidently, the formation mechanism involves the very precise assembly of premade building blocks into a perfect registry, as was observed for purely inorganic systems in the process of oriented attachment (i.e., the crystallographically oriented fusion of crystallites into larger single crystals),³⁹ which also can lead to complex mineral structures.⁴⁰ In this issue, Burrows et al. give a detailed description of the methods for characterizing crystal growth by oriented aggregation and the current models that describe the process. Under most conditions, the assembly of pre-formed crystalline building blocks in a synthetic

environment leads to the formation of polycrystalline materials. Nevertheless, highly ordered polycrystalline structures were demonstrated by the polymer-controlled helical assembly of well-defined building blocks.⁴¹ Even single crystalline structures can be obtained at a high temperature by the hydrothermal fusion of small crystallites, as discussed by Penn and Banfield,³⁹ or at room temperature if directed by a polymer.⁴² In addition, under careful control of mineral and additive concentrations, the formation of crystalline structures that diffract as single crystals from the polymer-directed assembly of mesoscale crystalline building blocks has recently been successfully accomplished.⁴³ In fact, the formation of these types of crystals, which are now termed “mesocrystals,” has been found to be much more widespread than initially realized and forms an important pathway for the controlled fabrication of complex mineral structures.^{37,44} In this issue, Imai and Oaki describe the application of gels and polyelectrolytes to construct a variety of hierarchical structures from ordered inorganic building blocks.

Templating by Preformed Precursor Materials

Where nature uses the amorphous-to-crystal transformation for the generation of complex crystalline forms from a preformed precursor, an intriguing and complementary approach comprises the synthesis of objects with similar complexity through a mineral-to-mineral or an organic-to-mineral transformation. In this approach, a chemical transformation of a precursor material, such as biosilica⁴⁵ or wood,⁴⁶ leads to the generation of new mineral forms that perfectly copy the morphology of the original template. This shape-preserving chemistry, including topotactic solid-state reactions (i.e., solid-state transformations in which the morphology of the starting material and product are in coherence), provides a new approach to materials design where materials properties are imposed onto existing shapes. In this issue, Greil describes different routes to the conversion of natural materials into biomorphous ceramics with structures and properties.

A further understanding of the processes outlined here will provide new routes for the fabrication of specialized organic-inorganic hybrid materials, such as tissue engineering scaffolds (Figure 2),⁴⁷ reinforced polymers,⁴⁸ catalyst supports,⁴⁹ sensors and optoelectronic devices,⁴⁵ tough mechanical materials,⁵⁰ and biosculpting and peptide-induced room-temperature synthesis of materials that are

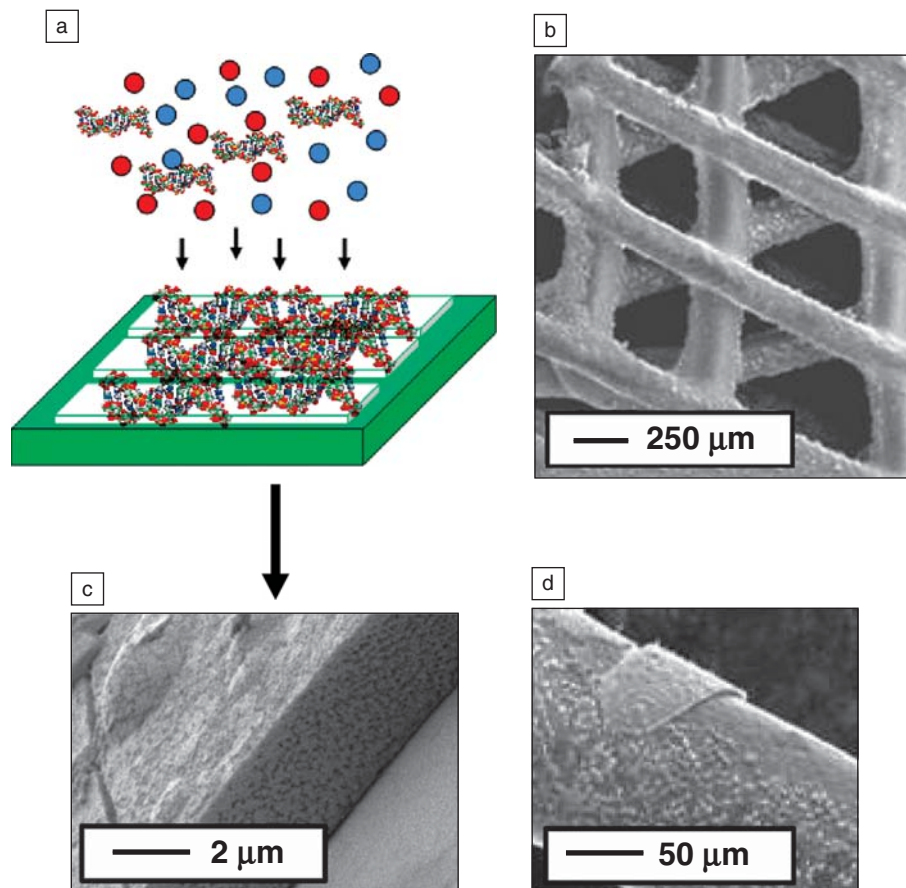


Figure 2. CaCO_3 films grown in the presence of 2.5×10^{-3} wt% DNA on a scaffold with a DNA/surfactant double layer coating. (a) Schematic representation of the DNA-controlled process; (b) scanning electron microscopic (SEM) image of a film on a glass substrate five days after formation; and (c–d) SEM images of a two-day film deposited on a poly(caprolactone) highlighting the ability of the inorganic coating to follow the contours of the scaffold. Adapted with permission from Reference 52.

usually only available at high temperatures.⁵¹ The accurate prediction of the outcome of synthetic efforts would make targeted experimentation possible and take the current methodology of hybrid materials synthesis out of the realm of trial and error. The implementation of this knowledge in a production environment for the controlled and programmed biomimetic synthesis of hybrid and/or hierarchical materials also should lead to a new and environmentally friendly approach to biologically benign structural materials with tunable material properties.

References

1. J. Aizenberg, J.C. Weaver, M.S. Thanawala, V.C. Sundar, D.E. Morse, P. Fratzl, *Science* **309**, 275 (2005).
2. B.L. Smith, T.E. Schaffer, M. Viani, J.B. Thompson, N.A. Frederick, J. Kindt, A. Belcher, G.D. Stucky, D.E. Morse, P.K. Hansma, *Nature* **399**, 761 (1999).
3. E. Bäuerlein, *Handbook of Biomineralization* (Wiley-VCH, Weinheim, 2007).
4. S. Mann, *Nature* **365**, 499 (1993).
5. H. Cölfen, S. Mann, *Angew. Chem. Int. Ed.* **42**, 2350 (2003).
6. P.Q. Harting, *J. Microsc. Sci.* **12**, 118 (1872).
7. A. Berman, L. Addadi, S. Weiner, *Nature* **331**, 546 (1988).
8. F. Nudelman, H.H. Chen, H.A. Goldberg, S. Weiner, L. Addadi, *Faraday Discuss.* **136**, 9 (2007).
9. F.C. Meldrum, H. Cölfen, *Chem. Rev.* **108**, 4332 (2008).
10. E. Haeckel, *Kunstformen der Natur* (Prestel Verlag, New York, 1904, reprinted 1998), <http://caliban.mpiz-koeln.mpg.de/~stueber/haeckel/kunstformen/natur.html>.
11. Q.Y. Sun, E.G. Vrieling, R.A. van Santen, N.A.J.M. Sommerdijk, *Curr. Opin. Solid State Mater. Sci.* **8**, 111 (2004).
12. E.G. Vrieling, Q.Y. Sun, M. Tian, P.J. Kooyman, W.W.C. Gieskes, R.A. van Santen, N.A.J.M. Sommerdijk, *Proc. Nat. Acad. Sci. U.S.A.* **104**, 10441 (2007).
13. M. Sumpster, N. Kröger, *J. Mater. Chem.* **14**, 2059 (2004).

14. M. Volmer, *Kinetik der Phasenbildung* (Steinkopff Verlag, Dresden, 1939), p. 220.
15. A.W. Xu, Y.R. Ma, H. Cölfen, *J. Mater. Chem.* **17**, 415 (2007).
16. N.A.J.M. Sommerdijk, G. de With, *Chem. Rev.* **108**, 4499 (2008).
17. T. Nishimura, T. Ito, Y. Yamamoto, M. Yoshio, T. Kato, *Angew. Chem. Int. Ed.* **47**, 2800 (2008).
18. L. Addadi, D. Joester, F. Nudelman, S. Weiner, *Chem. Eur. J.* **12**, 981 (2006).
19. H.Y. Li, L.A. Estroff, *J. Am. Chem. Soc.* **129**, 5480 (2007).
20. D.C. Popescu, M.M.J. Smulders, B.P. Pichon, N. Chebotareva, S.Y. Kwak, O.L.J. van Asselen, R.P. Sijbesma, E. DiMasi, N.A.J.M. Sommerdijk, *J. Am. Chem. Soc.* **129**, 14058 (2007).
21. S. Cavalli, D.C. Popescu, E.E. Tellers, M.R.J. Vos, B.P. Pichon, M. Overhand, H. Rapaport, N.A.J.M. Sommerdijk, A. Kros, *Angew. Chem. Int. Ed.* **45**, 739 (2006).
22. R.J. Park, F.C. Meldrum, *Advanced Materials* **14**, 1167 (2002).
23. R.J. Park, F.C. Meldrum, *Journal of Materials Chemistry* **14**, 2291 (2004).
24. B. Wucher, W.B. Yue, A.N. Kulak, F.C. Meldrum, *Chem. Mater.* **19**, 1111 (2007).
25. S. Weiner, I. Sagi, L. Addadi, *Science* **309**, 1027 (2005).
26. Y. Politi, T. Arad, E. Klein, S. Weiner, L. Addadi, *Science* **306**, 1161 (2004).
27. J. Mahamid, A. Sharir, L. Addadi, S. Weiner, *Proc. Nat. Acad. Sci. U.S.A.* **105**, 12748 (2008).
28. N. Gehrke, N. Nassif, N. Pinna, M. Antonietti, H.S. Gupta, H. Cölfen, *Chem. Mater.* **17**, 6514 (2005).
29. L.B. Gower, *Chem. Rev.* **108**, 4551 (2008).
30. J. Aizenberg, D.A. Muller, J.L. Grazul, D.R. Hamann, *Science* **299**, 1205 (2003).
31. E.D. Eanes, I.H. Gillesse, A.S. Gosner, *Nature* **208**, 365 (1965).
32. A. Navrotsky, *Proc. Nat. Acad. Sci. U.S.A.* **101**, 12096 (2004).
33. D. Gebauer, A. Völkel, H. Cölfen, *Science* **322**, 1819 (2008).
34. E.M. Pouget, P.H.H. Bomans, J. Goos, P.M. Frederik, G. de With, N.A.J.M. Sommerdijk, *Science* **323**, 1555 (2009).
35. F.C. Meldrum, R.P. Sear, *Science* **322**, 1802 (2008).
36. D. Gebauer, H. Cölfen, A. Verch, M. Antonietti, *Adv. Mater.* **21**, 435 (2009).
37. H. Cölfen, M. Antonietti, *Mesocrystals and Nonclassical Crystallization* (Wiley, New York, 2008).
38. Y. Oaki, A. Kotachi, T. Miura, H. Imai, *Adv. Funct. Mater.* **16**, 1633 (2006).
39. R.L. Penn, J.F. Banfield, *Geochim. Cosmochim. Acta* **63**, 1549 (1999).
40. J.F. Banfield, S.A. Welch, H.Z. Zhang, T.T. Ebert, R.L. Penn, *Science* **289**, 751 (2000).
41. S.H. Yu, H. Cölfen, K. Tauer, M. Antonietti, *Nat. Mater.* **4**, 51 (2005).
42. T.X. Wang, A. Reinecke, H. Cölfen, *Langmuir* **22**, 8986 (2006).
43. A.N. Kulak, P. Iddon, Y.T. Li, S.P. Armes, H. Cölfen, O. Paris, R.M. Wilson, F.C. Meldrum, *J. Am. Chem. Soc.* **129**, 3729 (2007).
44. H. Cölfen, M. Antonietti, *Angew. Chem. Int. Ed.* **44**, 5576 (2005).
45. Z.H. Bao, M.R. Weatherspoon, S. Shian, Y. Cai, P.D. Graham, S.M. Allan, G. Ahmad, M.B. Dickerson, B.C. Church, Z.T. Kang, H.W. Abernathy, C.J. Summers, M.L. Liu, K.H. Sandhage, *Nature* **446**, 172 (2007).
46. P. Greil, T. Lifka, A. Kaindl, *J. Eur. Ceram. Soc.* **18**, 1961 (1998).
47. D.C. Popescu, E.N.M. van Leeuwen, N.A.A. Rossi, S.J. Holder, J.A. Jansen, N.A.J.M. Sommerdijk, *Angew. Chem. Int. Ed.* **45**, 1762 (2006).
48. H. Peterlik, P. Roschger, K. Klaushofer, P. Fratzl, *Nat. Mater.* **5**, 52 (2006).
49. M.E. Davis, *Nature* **417**, 813 (2002).
50. L.J. Bonderer, A.R. Studart, L.J. Gauckler, *Science* **319**, 1069 (2008).
51. G. Ahmad, M.B. Dickerson, B.C. Church, Y. Cai, S.E. Jones, R.R. Naik, J.S. King, C.J. Summers, N. Kröger, K.H. Sandhage, *Adv. Mater.* **18**, 1759 (2006).
52. N.A.J.M. Sommerdijk, E.N.M. van Leeuwen, M.R.J. Vos, J.A. Jansen, Calcium carbonate thin films as biomaterials coatings using DNA as crystallization inhibitor, *Cryst. Eng. Comm.* **1209** (2007). □



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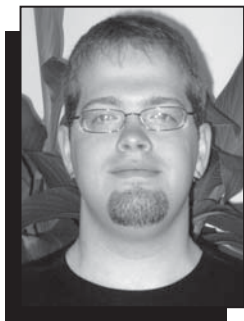
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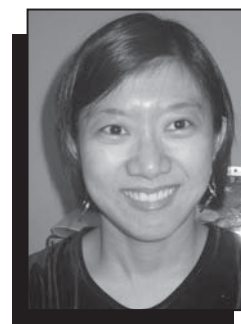
materials and recently included the shape-preserving conversion of nanostructured biomineral templates into new functional chemistries and the use of biomolecules to synthesize functional oxide powders or conformal coatings.

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University in 2008 under the supervision of Professor Jeffrey Hartgerink. Her current research is focused on studying the mechanisms of nanocrystal growth with Professors R. Lee Penn, Michael Tsapatsism, and Alon McCormick at the University of Minnesota–Twin Cities. In general, she is interested in controlled assembly of organic and inorganic nanostructures and electron microscopy. □

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