

Colloidal nanocrystal synthesis and the organic–inorganic interface

Yadong Yin¹ & A. Paul Alivisatos¹

Colloidal nanocrystals are solution-grown, nanometre-sized, inorganic particles that are stabilized by a layer of surfactants attached to their surface. The inorganic cores possess useful properties that are controlled by their composition, size and shape, and the surfactant coating ensures that these structures are easy to fabricate and process further into more complex structures. This combination of features makes colloidal nanocrystals attractive and promising building blocks for advanced materials and devices. Chemists are achieving ever more exquisite control over the composition, size, shape, crystal structure and surface properties of nanocrystals, thus setting the stage for fully exploiting the potential of these remarkable materials.

Colloidal nanocrystals are sometimes referred to as ‘artificial atoms’ because the density of their electronic states — which controls many physical properties — can be widely and easily tuned by adjusting the crystal’s composition, size and shape. The combination of size- and shape-dependent physical properties and ease of fabrication and processing makes nanocrystals promising building blocks for materials with designed functions^{1,2}, for example, as inorganic fluorophores in biomedical assays. But the ability to control the uniformity of the size, shape, composition, crystal structure and surface properties of the nanocrystals is not only of technological interest: access to defined nanoscale structures is essential for uncovering their intrinsic properties unaffected by sample heterogeneity. Rigorous understanding of the properties of individual nanocrystals will enable us to exploit them, making it possible to design and build novel electronic, magnetic and photonic devices and other functional materials based on these nanostructures.

Colloidal nanocrystals have an inorganic core that is stabilized by a layer of surface surfactants. Nanocrystals with a semiconductor as the inorganic material — so-called quantum dots — exhibit size-tunable band gaps and luminescence energies owing to the quantum-size effect³. These colloidal quantum dots are now widely employed as targeted fluorescent labels in biomedical research applications^{4–6}. Compared with the organic fluorophores that were previously used as biological labels, quantum dots are much brighter and do not photobleach. They also provide a readily accessible range of colours. Other applications that could benefit from the combination of low-cost processing and solid-state performance include the use of colloidal quantum dots and rods as alternatives to semiconductor polymers in light emitting diodes⁷, lasers⁸ and solar cells⁹. The scope for these applications has prompted intensive study of the synthesis of these materials to optimize colloidal semiconductor nanocrystal fabrication. As a result, many new concepts for controlling the size, shape and connectivity or coupling of colloidal nanocrystals have been developed first for these materials, but a unified set of synthesis control concepts is now also being applied to other classes of material, such as metals and metal oxides. These materials will extend the range of applications for colloidal nanocrystals to many other areas, including catalysis.

Over the past decade, chemists have come to appreciate that, from

the point of view of synthesis, colloidal inorganic nanocrystals can be thought of as a class of macromolecule, with preparative strategies that are similar in many ways to those employed with artificial organic polymers. For nanocrystals of 1–100 nm diameter, it is possible to define the average and the dispersion of the diameter, as well as the aspect ratio. The degree of precision with which the desired structure is synthesized is similar to that achieved with synthetic polymers, where the preparative methods at our disposal allow us to define the mean number of monomer units in a polymer and the variance of this number, and to build complex topologies through joining or branching of simpler macromolecules. As with artificial polymers, some principles have now emerged that give us the ability to control the size and shape of colloidal nanocrystals. After more than two decades, impressive progress has been made towards the tailored synthesis of colloidal nanocrystals that have well-defined structures. A wide variety can now be successfully produced using a number of methods, such as coprecipitation in aqueous phase, using reverse micelles as templates, hydrothermal/solvothermal synthesis and surfactant-controlled growth in a hot organic solvent^{10,11}.

In this review we outline a set of concepts for controlling the growth of colloidal inorganic nanocrystals in a hot organic surfactant (see also Fig. 1). A general approach to their fabrication in a precisely controlled manner is not yet available, but it is widely accepted that organic surfactants have a key role in determining not only the size but also the shape of the products. Because successful control depends on using organic surfactants to judiciously manipulate the nanocrystal surfaces, we will start with a discussion of the organic–inorganic interface and the possibilities offered by dynamic surface solvation with surfactant molecules. We then introduce the concepts underpinning kinetic control, which allows narrow nanocrystal-size distributions and some control over particle shape. If kinetic control is used in conjunction with selective adhesion effects, it offers even finer control over nanocrystal growth, as illustrated by the strategies used to produce more complex shapes. We conclude this review by outlining the crucial issues that need to be addressed to take colloidal nanocrystal synthesis to the next stage, which will allow the controlled fabrication and processing of ever more complex structures with exciting properties.

¹Department of Chemistry, University of California, Berkeley, and the Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA.

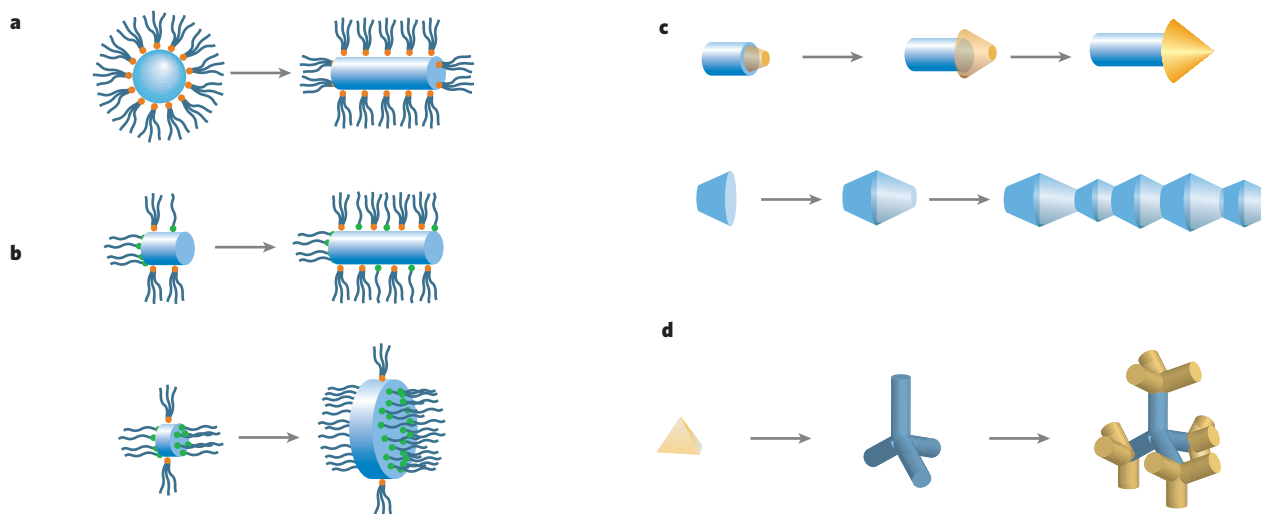


Figure 1 | Shape control of colloidal nanocrystals. **a**, Kinetic shape control at high growth rate. The high-energy facets grow more quickly than low-energy facets in a kinetic regime. **b**, Kinetic shape control through selective adhesion. The introduction of an organic molecule that selectively adheres to a particular crystal facet can be used to slow the growth of that side relative to others, leading to the formation of rod- or disk-shaped nanocrystals. **c**, More intricate shapes result from sequential elimination of a high-energy facet. The persistent growth of an intermediate-energy facet eventually eliminates the initial high-energy facet, forming complex

structures such as an arrow- or zigzag-shaped nanocrystals. **d**, Controlled branching of nanocrystals. The existence of two or more crystal structures in different domains of the same crystal, coupled with the manipulation of surface energy at the nanoscale, can be exploited to produce branched inorganic nanostructures such as tetrapods. Inorganic dendrimers can be further prepared by creating subsequent branch points at the defined locations on the existing nanostructures. The red and green dots in **a** and **b** represent metal coordinating groups with different affinities to nanocrystal facets.

General synthesis scheme

A typical synthesis system for colloidal nanocrystals consists of three components: precursors, organic surfactants and solvents. In some cases, surfactants also serve as solvents. Upon heating a reaction medium to a sufficiently high temperature, the precursors chemically transform into active atomic or molecular species (monomers); these then form nanocrystals whose subsequent growth is greatly affected by the presence of surfactant molecules. The formation of the nanocrystals involves two steps: nucleation of an initial 'seed' and growth. In the nucleation step, precursors decompose or react at a relatively high temperature to form a supersaturation of monomers followed by a burst of nucleation of nanocrystals. These nuclei then grow by incorporating additional monomers still present in the reaction medium.

This thermolysis approach generates nanoparticles that will be crystalline solids only if the constituent atoms can rearrange and anneal during growth. This rearrangement is associated with significant thermal barriers. The cohesive energy per atom, which correlates with the melting temperature of the solid, is therefore a decisive factor in determining optimal conditions for nanocrystal growth. The first step in colloidal nanocrystal synthesis is to choose a temperature for growth that is hot enough to allow rearrangement of atoms and annealing within a growing nanocrystal over the course of the synthesis. A great benefit in this regard is that small crystals require a lower melting temperature. This effect is the subject of one of the most famous and well-documented scaling laws for the properties of solids in the nanometre regime¹². It is driven by the fact that in the nanoscale regime, the liquid phase has lower surface energy than a solid with facets, edges and corners. The effect can be quite significant, leading to a halving of the melting temperature for a solid particle of 2–3 nm diameter relative to that of the corresponding bulk solid.

The large reduction in melting temperature greatly increases the range of inorganic colloidal nanocrystals that can be grown at temperatures where common organic molecules are stable, which is in the range of 200–400 °C. In fact, the desire to extend colloidal nanocrystal synthesis to the widest possible range of materials has focused much interest on growth at these temperatures. Organic surfactant molecules in the growth medium are chosen for their propensity to

adhere to a growing crystal. Because up to half the atoms making up a nanocrystal may be on its surface, this completely alters the growth strategy to the point where the organic–inorganic interface becomes pivotal. Therefore, colloidal nanocrystal growth is strongly related to the field of biomineralization, where complex patterns of biologically organized organic functionalities control the size, shape and spatial arrangement of some inorganic solids^{13,14}. However, the common biominerals produced in this way are strongly ionic solids, with cohesive energies that allow growth at room temperature and in water.

As recognized by Steigerwald^{15,16}, an important step in the generation of colloidal inorganic nanocrystals is the identification of suitable precursor molecules, such as organometallic compounds. The precursors need to rapidly decompose or react at the required growth temperature to yield reactive atomic or molecular species (the monomers), which then cause nanocrystal nucleation and growth. The most famous example of this process is the use of dimethyl cadmium and trialkyl phosphine selenide to yield cadmium selenide (CdSe), where injection of the precursors into a hot solution can yield supersaturation, nucleation and subsequent growth. The most successfully employed precursors have been relatively simple molecules with 'leaving groups' that readily depart leaving behind the desired reactive species. This is somewhat distinct from the precursors employed in chemical vapour deposition (CVD) processes in high vacuum, where volatile precursors react and/or decompose on the substrate surface to produce desired deposit at much higher growth temperatures. Still, the two approaches share many features such as similar basic chemical reactions involved. A literature review of CVD precursors is often a good starting place for finding a new pathway to making a colloidal nanocrystal.

In colloidal solution, the true microscopic mechanism of monomer addition is often still not well understood, owing to the complexity of the growth medium.

Organic–inorganic interface and dynamic solvation

Surfactant-coated nanocrystals, in which an inorganic core is surrounded by a 'monolayer' of organic molecules, hold the potential for the creation of new materials^{17,18}. The possibility of combining the

physical properties of inorganic solids with the low-cost high-volume processing of plastics provides a major impetus for this research¹⁹. Because the organic–inorganic interface present in these systems is the key to the synthesis of far more advanced materials, it is attracting growing interest.

The energy with which surfactant molecules present in the growth medium adhere to the surfaces of growing nanocrystals is one of the most important parameters influencing crystal growth. The adhesion energy needs to be such that it allows dynamic solvation at the growth temperature: the surfactant needs to be able to exchange on and off the growing crystals, so that regions of the nanocrystal surface are transiently accessible for growth, yet entire crystals are, on average, monolayer-protected to block aggregation. The classic paper of Murray, Norris and Bawendi²⁰ introduced this concept for the growth of CdSe nanocrystals in trioctylphosphine oxide (TOPO).

Examples of organic surfactants that dynamically solvate nanocrystals include alkyl phosphine oxides, alkyl phosphonic acids, alkyl phosphines, fatty acids and amines, and some nitrogen-containing aromatics. These molecules all contain metal coordinating groups as well as solvophilic groups. The metal coordinating groups are typically electron-donating to allow coordination to electron-poor metal atoms at the nanocrystal surface. This prevents further growth and aggregation. The other end of the surfactant molecule extends to the solvent and therefore determines the solubility of the nanocrystals; in most cases, it provides the particles with a hydrophobic surface. At the time of writing, there is no generally accepted experimental or theoretical method for determining the adhesion energy of an organic surfactant on a nanocrystal surface, so the choice of surfactant remains empirical. This makes screening techniques borrowed from biochemistry promising tools for discovery of appropriate surfactant systems²¹. In all cases, great care must be taken to examine the purity of the organic surfactants and their thermal stability: in numerous instances small amounts of organic impurities were found to play an important part in the growth kinetics. For example, phosphonic acids were only recognized as essential ingredients for shape control of CdSe and other II–VI nanocrystals²² after their presence in TOPO was finally controlled.

As the temperature decreases, surfactant molecules are less likely to leave the nanocrystal surface. But dynamic solvation can also be achieved at room temperature. For instance, if CdSe nanocrystals coated with TOPO are refluxed in pyridine, the more weakly adherent but more abundant pyridine displaces the TOPO by mass action. Owing to its inherently weaker adhesion energy, pyridine dynamically solvates CdSe, even at room temperature, so that nanocrystals deposited from pyridine and placed in vacuum display ultra-high vacuum (UHV) clean surfaces²³. The introduction of other competing ligands through surfactant exchange makes it possible to further derivatize the nanocrystal surface, allowing the introduction of a wide range of possible chemical functionalities. This strategy provides an additional method for chemical manipulation of the physical nanocrystal properties, which tend to be sensitive to the nature of the surface coating²³. It also provides various means to link the nanocrystals to other surfaces and biomolecules^{24–26}.

The surfactant molecules not only bind to the growing nanocrystal surface, but also form a complex with the reactive monomer species produced upon heating. The stability and diffusion rate of these complexes, as well as the binding strength of the surfactant molecules to the growing nanocrystal surface, are all strongly temperature dependent. Increasing the temperature greatly decreases the stability of the intermediate complexes formed in solution and the binding of the surfactants to the nanocrystal surface, while increasing the diffusion rates of the complexes. This favours the nucleation and growth of the nanocrystals. However, too high a temperature may lead to uncontrolled growth so that it is impossible to exploit subtle kinetic or energetic effects to achieve precise control over the size and size distribution of the nanocrystals. Choosing an appropriate temperature range is one of the key steps in obtaining control over nanocrystal growth.

Kinetic size control

The ability to produce nanocrystals with a relatively narrow size distribution is also a key feature of many modern preparation methods²⁷. To understand the concepts at work here, consider the dependence of growth rate on nanocrystal radius illustrated in Fig. 2. The dependence of the surface energy on size explains the left-hand side of the curve: very small crystals are unstable owing to their large fraction of active surface atoms, as indicated by the negative growth rate. The right-hand side of the curve illustrates that larger crystals with smaller surface-to-volume ratio are stable and grow. The zero-crossing point occurs at the critical size, where nanocrystals neither grow nor shrink. The critical size depends on the monomer concentration, with low monomer concentration favouring a larger critical size. The peak in growth rate versus radius on the right-hand side arises because of a geometric factor: increasing the radius of large crystals requires the incorporation of many more atoms than does increasing the radius of smaller crystals.

These considerations explain why a slow growth rate, which produces equilibrated and nearly round crystals, also yields very broad size distributions. That is, slow growth is associated with low monomer concentrations and a high likelihood that the critical size falls within the distribution of nanocrystal sizes present (Fig. 2). The resultant Ostwald ripening — the shrinking of small crystals while large ones grow — then leads to a broad, skewed size distribution. It is still possible to recover a monodisperse sample by separating out fractions of particles with a narrow distribution from the original broadly distributed sample, using one of several separation techniques. Of these, ‘size-selective precipitation’ is the most generally applicable method^{20,28}. It involves stepwise addition of a poor solvent to a stable solution of nanocrystals to gradually reduce the solvating power and allow for aggregation. Larger nanocrystals, with greater attractive van der Waals or dipolar forces between them, will then precipitate out first. This approach produces nanocrystal fractions with narrow size distributions, but it can be time-consuming, tedious and yields small quantities of the desired material. Further, it only works well with round crystals because the attractive forces between anisotropic nanocrystals depend on multiple parameters²⁹.

A more robust approach to obtaining narrow distributions uses the concept of ‘size-distribution focusing’ (Fig. 2), which is based on the prediction, more than 50 years ago, of Howard Reiss that small crys-

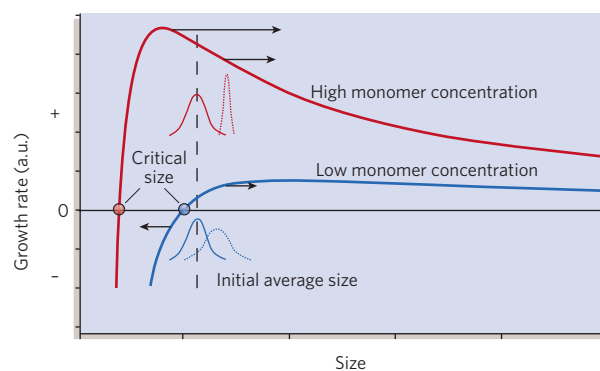


Figure 2 | Size-distribution focusing. The growth process of nanocrystals can occur in two different modes, ‘focusing’ and ‘defocusing’, depending upon the concentration of the monomer present. A critical size exists at any given monomer concentration. At a high monomer concentration, the critical size is small so that all the particles grow. In this situation, smaller particles grow faster than the larger ones, and as a result, the size distribution can be focused down to one that is nearly monodisperse. If the monomer concentration is below a critical threshold, small nanocrystals are depleted as larger ones grow and the size distribution broadens, or defocuses. The preparation of nearly monodisperse spherical particles can be achieved by arresting the reaction while it is still in the focusing regime, with a large concentration of monomer still present. a.u., arbitrary units.

tals will grow more rapidly than larger ones if monomer concentrations are sufficiently high³⁰. Consider the slow growth conditions described above and imagine that the monomer concentration is abruptly increased by a secondary injection of precursor. Immediately after injection, the distribution of nanocrystal sizes present does not change, but the critical size, which depends on monomer concentration, shifts to a smaller value. If this shift is large enough, the entire distribution of sizes will now lie on the falling side of the growth versus radius curve (that is, all nanocrystals are larger than the size for which the growth rate peaks). Therefore, the distribution will spontaneously narrow or 'focus'. The concept of size-distribution focusing has now been clearly demonstrated experimentally³¹. Size focusing is optimal if the monomer concentration is kept such that the average nanocrystal size present is always slightly larger than the critical size. When the monomer concentration is depleted owing to growth, the critical size becomes larger than the average size present, and the distribution broadens as a result of Ostwald ripening. Judicious replenishment of the monomer can thus be an important feature of the synthesis strategy. Focusing has the advantage that it can produce large quantities of crystal with a narrow size distribution, provided that the reaction can be arrested in the appropriate regime (Fig. 3). It is a key first step in kinetic control over nanocrystal synthesis, and we have found that when focusing can be achieved, it opens the door to achieving kinetic shape control.

In general, it is desirable for nucleation to be separated in time from the growth step to obtain relatively monodisperse samples. This means that nucleation must occur on a short time scale. This may be achieved by rapidly injecting suitable precursors into the solvent at high temperature to generate transient supersaturation in monomers and induce a nucleation burst. A rapid and intense nucleation burst will lower the monomer concentration below the nucleation threshold, so monomers remaining in solution will only add to the existing nuclei. In many cases, there is some overlap between the nucleation and growth time scales, so the resultant dispersion in nanocrystal sizes needs to be compensated for with focusing. But in optimal cases, it is possible to remain in the fast growth-focusing regime while remaining below the nucleation limit.

Interestingly, rapid injection of precursor does not always lead to quick nucleation. For example, during the synthesis of iron oxide nanocrystals, the injection of the precursor of iron pentacarbonyl is followed by a long incubation time before a sudden burst of nucleation takes place (M. F. Casula *et al.*, unpublished data). This 'delayed nucleation' is caused by the gradual transformation of iron pentacarbonyl into intermediate species (such as higher nuclearity clusters of carbonyls or metal-surfactant complexes), which then serve as the active 'monomer' species during crystal growth. Because nucleation depends exponentially on the monomer concentration, when the nucleation threshold is surpassed, a brief spurt of nucleation occurs. The nucleation event depletes the monomer, and growth follows with no further nucleation. Delayed nucleation is extremely useful because it removes the need for a rapid (and in many cases irreproducible) initial injection of precursor.

Kinetic shape control

Compared with equilibrium nanocrystals with nearly 'round' shapes, nanocrystals with highly anisotropic shapes have larger surface areas, which renders them metastable, high-energy forms. Formation of the metastable nanocrystals thus requires a kinetic growth regime, whereas equilibrium nanocrystals with low aspect ratios are obtained in the slow growth limit under thermodynamic control. At low growth rate, nearly round nanocrystals are formed, with broad size distribution. At higher growth rate, focusing is observed. When the growth rate is increased just beyond the focusing regime, an astonishing variety of highly anisotropic shapes are obtained, starting with simple rods and disks, but ultimately including shapes like arrows and tetrapods.

The equilibrium shape of inorganic nanocrystals, although faceted, has a low aspect ratio both because this minimizes surface area and

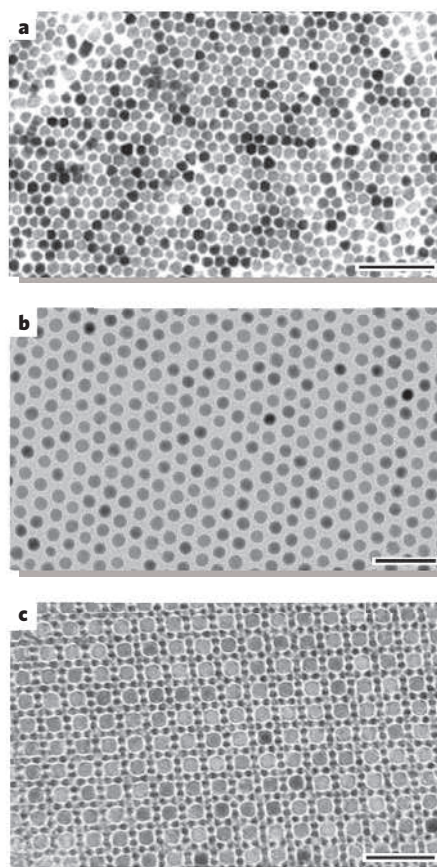


Figure 3 | Monodisperse colloidal nanocrystals synthesized under kinetic size control. **a**, Transmission electron microscopy (TEM) image of CdSe nanocrystals. **b**, TEM image of cobalt nanocrystals. **c**, TEM micrograph of an AB₁₃ superlattice of γ -Fe₂O₃ and PbSe nanocrystals. The precise control on the size distributions of both nanocrystals allows their self-assembly into ordered three-dimensional superlattices. Scale bars, 50 nm. Reprinted from ref. 27.

because the low-energy facets of the crystal are relatively close to each other in energy. However, the growth rate of a crystal facet depends exponentially on the surface energy, so that at high growth rates, in a kinetically controlled growth regime, high-energy facets grow more quickly than low-energy facets (Fig. 1a). The progression from Ostwald ripening to focusing to kinetic shape control was first seen in colloidal CdSe nanocrystals³² and has been subsequently observed in a variety of other systems, such as cobalt^{33,34} and titanium dioxide (TiO₂)³⁵.

The onset of kinetic shape control can be widely adjusted using selective adhesion (Fig. 1b). According to the concept of dynamic solvation, organic surfactants exchange on the nanocrystal's surface during growth. In a faceted crystal, however, the exchange rate on the different facets need not be the same. The introduction of an organic molecule that selectively adheres to a particular crystal facet can be used to effectively lower the energy and slow the growth rate of that facet relative to others (Fig. 4). It is more practical to adjust the relative growth rates than it is to increase the absolute rates to the point where the variations are significant. Selective adhesion effects have not been observed directly during nanocrystal growth, but theoretical studies lend credence to the concept^{36,37}. A possible alternative mechanism, however, involves complexation of the reactive monomer species in solution by organic molecules. This leads to an environment with high chemical potential, and it can be used to adjust relative growth rates³⁸.

In the kinetic growth regime, it is possible to create sequences of events that produce more intricate shapes. A first example is the remarkable phenomenon of sequential elimination of a high-energy facet²² (Fig. 1c). Fast-growing facets will eventually disappear during growth, resulting in a crystal terminated by slower-growing facets. Consider the possibility that the relative growth rates of two different low-index facets differ greatly. In that case, the higher-energy facet will grow so quickly that a second or even third layer of atoms can start to form before a first layer is complete. The possibility exists that there is another facet, intermediate in energy between the low- and high-

energy ones present initially. Such a facet may form transiently during the growth of the high-energy facet. Once such a facet forms, it will persist, replacing the initial high-energy facet. This new intermediate-energy facet will still grow more quickly than the initial slow-growing one, so that the shape will evolve in a complex pattern during growth. This has been used to form arrow-shaped nanocrystals of CdSe²² and zigzag-shaped crystals of TiO₂ (ref. 35; Fig. 5).

A different but related approach to the creation of nanocrystals with complex shapes and connectivity is 'oriented attachment'³⁹. This remarkable process, first described for TiO₂ by Penn and Banfield^{40–42}, involves the coalescence of faceted nanocrystals in such a way as to eliminate two high-energy facets. The detailed mechanism of oriented attachment remains unclear, but the process seems to occur for many materials systems. The most frequent products of oriented attachment are rods and wires. The signature of this mechanism is the observation of final one-dimensional products with the same diameter as the pri-

mary particles, whereas rod lengths are always multiples of the length of the primary nanocrystal. The degree and nature of the attachment process can be manipulated by surfactant control. In fact, specific chemical transformation of the surfactant on high-energy facets may play a crucial role in some of the synthesis strategies reported^{43,44}. Banfield has shown that many defects in natural minerals may have arisen through the oriented attachment process⁴⁵.

Another sequence of events results in controlled branching of colloidal nanocrystals⁴⁶ (Fig. 1d). Branched crystals of zinc oxide were originally discovered in smoke from zinc-smelting plants and have been prepared and studied in CVD systems for several decades⁴⁷. In colloidal systems, ensembles of centrally branched tetrapod nanocrystals can be prepared with a high degree of control over the branch length and diameter^{48,49}. Polytypism⁵⁰, or the existence of two or more crystal structures in different regions of the same crystal, coupled with the manipulation of surface energy at the nanoscale, is exploited to controllably produce the branched inorganic nanostructures. In the case of the II–VI semiconductors such as CdSe, the cubic zincblende ABC stacking of planes is slightly higher in energy but kinetically favoured over the hexagonal wurtzite ABAB stacking. Upon injection of precursors, the high concentration of monomer favours nucleation of a pyramidal seed with a zincblende structure. This seed shares a common crystal facet — the (111) facet — with rod-shaped CdSe with a hexagonal, wurtzite structure. As the monomer concentration drops, the (111) facets of the zincblende core switch to ABAB growth in the [1000] direction of the hexagonal phase. This yields a crystalline inorganic structure of four rods at the tetrahedral angle, a so-called tetrapod (Fig. 6a, b). The presence of a selective adhesion agent that stabilizes the sidewalls of the hexagonal rods relative to the (111) facet of the zincblende phase is a probable reason for the ability to produce these structures with uniformity and control. Most recently, a wide variety of such inorganic dendrimers with branch points at defined locations on rods and tetrapods have been prepared as well⁵¹ (Fig. 6c, d). The subsequent branch points can be created by kinetically driving the reaction again or by nucleation of a second material, such as CdSe on CdTe. These dendritic heterostructures are the most complex structures produced so far in colloidal nanocrystal synthesis.

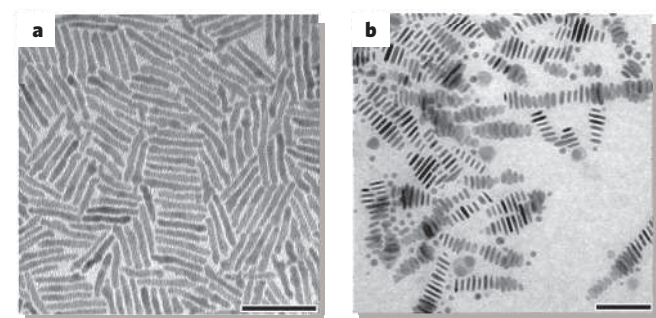


Figure 4 | Anisotropic growth of nanocrystals by kinetic shape control and selective adhesion. **a**, CdSe nanorods (scale bar, 50 nm). Reprinted with permission from ref. 52. **b**, Cobalt nanodisks (scale bar, 100 nm). The organic surfactant molecules selectively adhere to one facet of the nanocrystal, allowing the crystal to grow anisotropically to form a rod or disk.

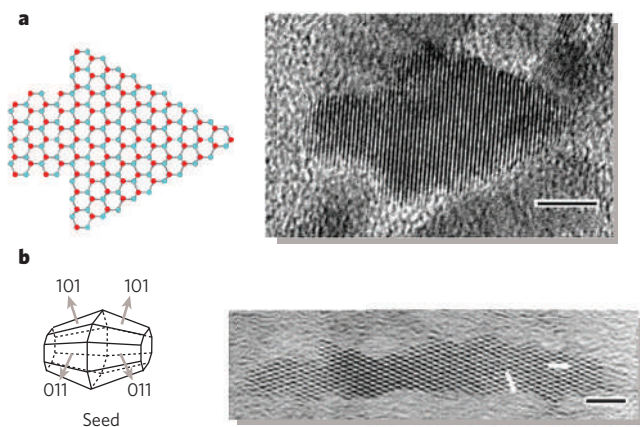


Figure 5 | Nanocrystals with complex shapes prepared by sequential elimination of a high-energy facet. **a**, Two-dimensional representation and a high-resolution TEM image of an arrow-shaped nanocrystal of CdSe. High-resolution TEM characterization shows that each shape of nanocrystal is predominantly wurtzite and that the angled facets of the arrows are the (101) faces. Scale bar, 5 nm. Red and blue dots represent selenium and cadmium atoms, respectively. Reprinted with permission from ref. 22. **b**, Simulated three-dimensional shape and high-resolution TEM analysis of a TiO₂ rod. The long axes of the nanocrystals are parallel to the *c*-axis of the anatase structure, while the nanocrystals are faceted with (101) faces along the short axes. Hexagon shapes (the [010] projection of a truncated octagonal bipyramid) truncated with two (001) and four (101) faces are observed either at the one end or at the centre of the nanocrystals. Scale bar, 3 nm. Reprinted with permission from ref. 35. Copyright (2003) American Chemical Society.

The outlook

The close topological similarity between inorganic and organic dendrimers helps to emphasize the similarity between organic polymers and inorganic nanocrystals from the point of view of chemistry. Will it ever be possible to create inorganic nanocrystals with the varied and rich compositional and spatial complexity of organic systems? Inorganic nanocrystals can already be created with far more complex shapes and with far greater control over size and shape than had long been thought possible. Colloidal nanocrystals are about the same size as an organic macromolecule, and with organic surfactants on the inorganic nanocrystal surface, they can be manipulated in much the same way as organic polymers⁵². The fact that solid-state materials can be manipulated chemically in such similar ways to polymers has led to a near explosion of work in organic–inorganic colloidal nanocrystals.

But at the time of writing, we are still far from a quantitative description of how organic molecules bind and pack on nanocrystal surfaces. To move beyond the qualitative phenomenology and general framework for kinetic shape control outlined here, detailed knowledge of selective surface-adhesion energies on nanocrystals, including the dependence of adhesion energy on coverage and co-adhesion, is essential. Obtaining such knowledge will, at a minimum, require combined input from experiments on suitable surface science models, appropriate quantum theoretical calculations and detailed structural characterization of colloidal nanocrystal surfaces using new synchrotron-based analysis methods. Improved experimental studies of nanocrystal growth kinetics, including spectroscopic identification of 'monomers' and real-time monitoring of average size and shape, could deliver much-needed further information. In this regard, microfluidics promises exciting opportunities, in that these systems enable

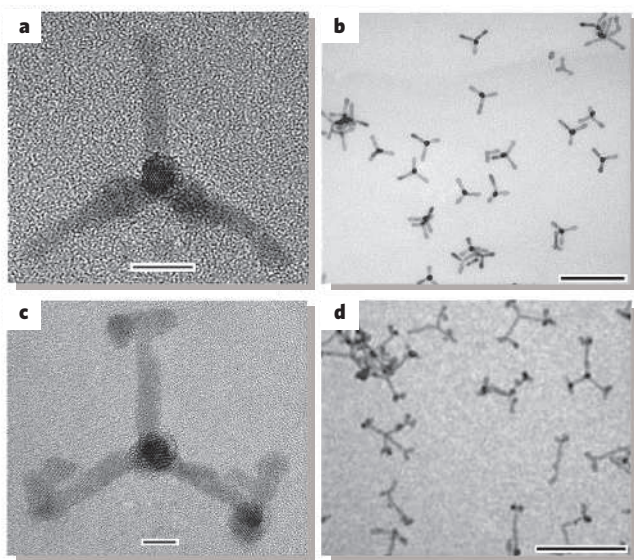


Figure 6 | Controlled branching of colloidal nanocrystals. **a**, High-resolution TEM image of a typical tetrapod-shaped CdSe nanocrystal, looking down the [001] direction of one arm. The nucleus is the zincblende structure, with wurtzite arms growing out of each of the four {111} equivalent faces. Reprinted with permission from ref. 22. **b**, Low-magnification TEM image of CdTe tetrapods. Scale bar, 100 nm. Reprinted from ref. 48. **c**, High-resolution TEM image of a tetrapod that has branches growing out of each arm. There are zincblende layers near the ends of the original arms, and the branches are wurtzite with some stacking faults. Reprinted with permission from ref. 22. **d**, TEM image of branched tetrapods result from nucleation of CdTe zincblende branch points on the end of each arm. Scale bar, 100 nm. Reprinted from ref. 51.

rapid temperature jumps, precise control over concentration as a function of time, and on-chip monitoring and analysis capabilities⁵³.

In the condensed-matter physics community, nanocrystals are commonly referred to as ‘artificial atoms’, with controlled density of states and designed properties⁵⁴. Staying with this analogy, the ultimate goal of colloidal nanocrystal synthesis is the creation of ‘artificial molecules’: inorganic nanocrystals with ever more complex yet precisely controlled shapes and compositions, and assemblies of such nanocrystals with carefully positioned interconnections^{27,55–62}. The complexity of such systems would rival that of organic molecules, and they may therefore exhibit a remarkable range of new functionalities. Clearly, exciting opportunities remain in this field, and better understanding and control of the organic–inorganic interface will hold the key to exploring these opportunities and the full potential of colloidal inorganic nanocrystals. ■

1. Alivisatos, A. P. Nanocrystals: building blocks for modern materials design. *Endeavour* **21**, 56–60 (1997).
2. El-Sayed, M. A. Small is different: shape-, size-, and composition-dependent properties of some colloidal semiconductor nanocrystals. *Acc. Chem. Res.* **37**, 326–333 (2004).
3. Alivisatos, A. P. Perspectives on the physical chemistry of semiconductor nanocrystals. *J. Phys. Chem.* **100**, 13226–13239 (1996).
4. Bruchez, M., Moronne, M., Gin, P., Weiss, S. & Alivisatos, A. P. Semiconductor nanocrystals as fluorescent biological labels. *Science* **281**, 2013–2016 (1998).
5. Michalet, X. *et al.* Quantum dots for live cells, *in vivo* imaging, and diagnostics. *Science* **307**, 538–544 (2005).
6. Alivisatos, A. P., Gu, W. & Larabell, C. Quantum dots as cellular probes. *Annu. Rev. Biomed. Eng.* **7**, 55–76 (2005).
7. Tessler, N., Medvedev, V., Kazes, M., Kan, S. & Banin, U. Efficient near-infrared polymer nanocrystal light-emitting diodes. *Science* **295**, 1506–1508 (2002).
8. Kazes, M., Lewis, D. Y., Ebenstein, Y., Mokari, T. & Banin, U. Lasing from semiconductor quantum rods in a cylindrical microcavity. *Adv. Mater.* **14**, 317–321 (2002).
9. Huynh, W. U., Dittmer, J. J. & Alivisatos, A. P. Hybrid nanorod-polymer solar cells. *Science* **299**, 2425–2427 (2002).
10. Cushing, B. L., Kolesnichenko, V. L. & O’Connor, C. J. Recent advances in the liquid-phase syntheses of inorganic nanoparticles. *Chem. Rev.* **104**, 3893–3946 (2004).
11. Pileni, M. P. The role of soft colloidal templates in controlling the size and shape of inorganic nanocrystals. *Nature Mater.* **2**, 145–150 (2003).
12. Buffat, Ph. & Borel, J.-P. Size effect on the melting temperature of gold particles. *Phys. Rev. A* **13**, 2287–2298 (1976).

13. Mann, S. Molecular recognition in biomineralization. *Nature* **332**, 119–124 (1988).
14. Bianconi, P. A., Lin, J. & Strzelecki, A. R. Crystallization of an inorganic phase controlled by a polymer matrix. *Nature* **349**, 315–317 (1991).
15. Stuczynski, S. M., Brennan, J. G. & Steigerwald, M. L. Formation of metal–chalcogen bonds by the reaction of metal–alkyls with silyl chalcogenides. *Inorg. Chem.* **28**, 4431–4432 (1989).
16. Steigerwald, M. L. Clusters as small solids. *Polyhedron* **13**, 1245–1252 (1994).
17. Nirmal, M. & Brus, L. Luminescence photophysics in semiconductor nanocrystals. *Acc. Chem. Res.* **32**, 407–414 (1999).
18. Alivisatos, A. P. Semiconductor clusters, nanocrystals, and quantum dots. *Science* **271**, 933–937 (1996).
19. Steckel, J. S., Coe-sullivan, S., Bulovic, V. & Bawendi, M. G. 1.3 μm to 1.55 μm tunable electroluminescence from PbSe quantum dots embedded within an organic device. *Adv. Mater.* **15**, 1862–1866 (2003).
20. Murray, C. B., Norris, D. J. & Bawendi, M. G. Synthesis and characterization of nearly monodisperse CdE (E = sulfur, selenium, tellurium) semiconductor nanocrystallites. *J. Am. Chem. Soc.* **115**, 8706–8715 (1993).
21. Whaley, S. R., English, D. S., Hu, E. L., Barbara, P. F. & Belcher, A. M. Selection of peptides with semiconductor binding specificity for directed nanocrystal assembly. *Nature* **405**, 665–668 (2000).
22. Manna, L., Scher, E. C. & Alivisatos, A. P. Synthesis of soluble and processable rod-, arrow-, teardrop-, and tetrapod-shaped CdSe nanocrystals. *J. Am. Chem. Soc.* **122**, 12700–12706 (2000).
23. Katari, J. E. B., Colvin, V. L. & Alivisatos, A. P. X-ray photoelectron spectroscopy of CdSe nanocrystals with applications to studies of the nanocrystal surface. *J. Phys. Chem.* **98**, 4109–4117 (1994).
24. Kuno, M., Lee, J. K., Dabbousi, B. O., Mikulec, F. V. & Bawendi, M. G. The band edge luminescence of surface modified CdSe nanocrystallites: probing the luminescing state. *J. Chem. Phys.* **106**, 9869–9882 (1997).
25. Klein, D. L., Roth, R., Lim, A. K. L., Alivisatos, A. P. & McEuen, P. L. A single-electron transistor made from a cadmium selenide nanocrystal. *Nature* **389**, 699–701 (1997).
26. Chan, W. C. & Nie, S. Quantum dot bioconjugates for ultrasensitive nonisotopic detection. *Science* **281**, 2016–2018 (1998).
27. Redl, F. X., Cho, K.-S., Murray, C. B. & O’Brien, S. Three-dimensional binary superlattices of magnetic nanocrystals and semiconductor quantum dots. *Nature* **423**, 968–971 (2003).
28. Vossmeier, T. *et al.* CdS nanoclusters: synthesis, characterization, size dependent oscillator strength, temperature shift of the excitonic transition energy, and reversible absorbance shift. *J. Phys. Chem.* **98**, 7665–7673 (1994).
29. Murray, C. B., Sun, S., Doyle, H. & Betley, T. Monodisperse 3d transition-metal (Co, Ni, Fe) nanoparticles and their assembly into nanoparticle superlattices. *Mater. Res. Soc. Bull.* **26**, 985–991 (2001).
30. Reiss, H. The growth of uniform colloidal dispersions. *J. Chem. Phys.* **19**, 482–487 (1951).
31. Peng, X., Wickham, J. & Alivisatos, A. P. Kinetics of II-VI and III-V colloidal semiconductor nanocrystal growth: focusing of size distributions. *J. Am. Chem. Soc.* **120**, 5343–5344 (1998).
32. Peng, X. *et al.* Shape control of CdSe nanocrystals. *Nature* **404**, 59–61 (2000).
33. Puentes, V. F., Krishnan, K. M. & Alivisatos, A. P. Colloidal nanocrystal shape and size control: the case of cobalt. *Science* **291**, 2115–2117 (2001).
34. Puentes, V. F., Zanchet, D., Erdonmez, C. K. & Alivisatos, A. P. Synthesis of hcp-Co nanodisks. *J. Am. Chem. Soc.* **124**, 12874–12880 (2002).
35. Jun, Y.-W. *et al.* Surfactant-assisted elimination of a high energy facet as a means of controlling the shapes of TiO₂ nanocrystals. *J. Am. Chem. Soc.* **125**, 15981–15985 (2003).
36. Puzder, A. *et al.* The effect of organic ligand binding on the growth of CdSe nanoparticles probed by ab initio calculations. *Nano Lett.* **4**, 2361–2365 (2004).
37. Manna, L., Wang, L. W., Cingolani, R. & Alivisatos, A. P. First-principles modeling of unpassivated and surfactant-passivated bulk facets of wurtzite cdse: a model system for studying the anisotropic growth of CdSe nanocrystals. *J. Phys. Chem. B* **109**, 6183–6192 (2005).
38. Yu, W. W., Wang, Y. A. & Peng, X. Formation and stability of size-, shape-, and structure-controlled CdTe nanocrystals: ligand effects on monomers and nanocrystals. *Chem. Mater.* **15**, 4300–4308 (2003).
39. Alivisatos, A. P. Naturally aligned nanocrystals. *Science* **289**, 736–737 (2000).
40. Penn, R. L. & Banfield, J. F. Morphology development and crystal growth in nanocrystalline aggregates under hydrothermal conditions: insights from titania. *Geochim. Cosmochim. Acta* **63**, 1549–1557 (1999).
41. Penn, R. L. & Banfield, J. F. Oriented attachment and growth, twinning, polytypism, and formation of metastable phases: insights from nanocrystalline TiO₂. *Am. Mineral.* **83**, 1077–1082 (1998).
42. Pacholski, C., Kornowski, A. & Weller, H. Self-assembly of ZnO: from nanodots to nanorods. *Angew. Chem. Int. Ed.* **41**, 1188–1191 (2002).
43. Yu, J. H. *et al.* Synthesis of quantum-sized cubic ZnS nanorods by the oriented attachment mechanism. *J. Am. Chem. Soc.* **127**, 5662–5670 (2005).
44. Adachi, M. *et al.* Highly efficient dye-sensitized solar cells with a titania thin-film electrode composed of a network structure of single-crystal-like TiO₂ nanowires made by the ‘‘oriented attachment’’ mechanism. *J. Am. Chem. Soc.* **126**, 14943–14949 (2004).
45. Banfield, J. F. & Penn, R. L. Imperfect oriented attachment: dislocation generation in defect-free nanocrystals. *Science* **281**, 969–971 (1998).
46. Wang, D. & Lieber, C. M. Nanocrystals branch out. *Nature Mater.* **2**, 355–356 (2003).
47. Yan, H., He, R., Pham, J. & Yang, P. Morphogenesis of one-dimensional ZnO nano- and microcrystals. *Adv. Mater.* **15**, 402–405 (2003).
48. Manna, L., Milliron, D. J., Meisel, A., Scher, E. C. & Alivisatos, A. P. Controlled growth of tetrapod branched inorganic nanocrystals. *Nature Mater.* **2**, 382–385 (2003).
49. Peng, X. Mechanisms for the shape-control and shape-evolution of colloidal semiconductor nanocrystals. *Adv. Mater.* **15**, 459–463 (2003).
50. Yeh, C. Y., Lu, Z. W., Froyen, S. & Zunger, A. Zinc-blende-wurtzite polytypism in semiconductors. *Phys. Rev. B* **46**, 10086–10097 (1992).
51. Milliron, D. J. *et al.* Colloidal nanocrystal heterostructures with linear and branched topology. *Nature* **430**, 190–195 (2004).
52. Li, L.-S., Walda, J., Manna, L. & Alivisatos, A. P. Semiconductor nanorod liquid crystals. *Nano Lett.* **2**, 558–560 (2002).

53. Chan, E. M., Mathies, R. A. & Alivisatos, A. P. Size-controlled growth of CdSe nanocrystals in microfluidic reactors. *Nano Lett.* **3**, 199–201 (2003).
54. Collier, C. P., Vossmeier, T. & Heath, J. R. Nanocrystal superlattices. *Annu. Rev. Phys. Chem.* **49**, 371–404 (1998).
55. Sun, S., Murray, C. B., Weller, D., Folks, L. & Moser, A. Monodisperse FePt nanoparticles and ferromagnetic FePt nanocrystal superlattices. *Science* **287**, 1989–1992 (2000).
56. Mirkin, C. A., Letsinger, R. L., Mucic, R. C. & Storhoff, J. J. A DNA-based method for rationally assembling nanoparticles into macroscopic materials. *Nature* **382**, 607–609 (1996).
57. Alivisatos, A. P. *et al.* Organization of 'nanocrystal molecules' using DNA. *Nature* **382**, 609–611 (1996).
58. Fu, A. *et al.* Discrete nanostructures of quantum dots/Au with DNA. *J. Am. Chem. Soc.* **126**, 10832–10833 (2004).
59. Yu, H. *et al.* Dumbbell-like bifunctional Au-Fe₃O₄ nanoparticles. *Nano Lett.* **5**, 379–382 (2005).
60. Gu, H., Zheng, R., Zhang, X. & Xu, B. Facile one-pot synthesis of bifunctional heterodimers of nanoparticles: a conjugate of quantum dot and magnetic nanoparticles. *J. Am. Chem. Soc.* **126**, 5664–5665 (2004).
61. Mokari, T., Rothenberg, E., Popov, I., Costi, R. & Banin, U. Selective growth of metal tips onto semiconductor quantum rods and tetrapods. *Science* **304**, 1787–1790 (2004).
62. Kudara, S. *et al.* Selective growth of PbSe on one or both tips of colloidal semiconductor nanorods. *Nano Lett.* **5**, 445–449 (2005).

Acknowledgements The authors acknowledge support from the US Department of Energy through the Molecular Foundry at the Lawrence Berkeley National Laboratory.

Author Information Reprints and permissions information is available at npg.nature.com/reprintsandpermissions. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to P.A. (alivis@berkeley.edu).