Despite the protracted period of nucleation and the different growth modes, Zheng *et al.* report that nanocrystals on average reach approximately the same size.

The approach developed by Zheng *et al.* should open the way to single-particle studies of the mechanism of oriented attachment. In this process, discrete nanocrystal building blocks fuse or polymerize after crystal faces contact to yield extended, single-crystalline nanostructures (*11*), but a definitive mechanism underlying this process has remained elusive (*12*). Direct comparisons could be made with molecular dynamics simulations and ex situ characterization of materials from conventional syntheses (*13*).

These initial studies suggest many related in situ nanocrystal growth experiments, which could be as simple as studying the effect of introducing preformed monodisperse seed nanocrystals into the reservoirs. More complex studies may be able to separate nucleation steps from growth processes. If a series of stabilizers with different chain lengths or head-group chemistry could assessed effectiveness in preventing or promoting coalescence, the results would be immediately useful. Integrating temperature control or adapting the system for continuous flow would further expand the scope of these experiments.

This approach to nanoscale structural characterization is also perfectly aligned with advances in the development of microreactors for the microfluidic production of nanocrystals (*14*). Nanocrystal microreactors have been demonstrated with complex mixing, heating, and online optical monitoring, and have even allowed isolation of products in segmented plug flow (*15*). The mechanistic insights for these studies should quickly influence nanocrystal synthesis, whether researchers are pushing tailored nanoscale materials toward large-scale "bulk" production or exploring highly customizable point-of-use fabrication in lab-on-a-chip approaches.

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PHYSICS

Dealing with Decoherence

For quantum computers to be a reality, the effects of interactions of qubits with their environment must be minimized.

Jan Fischer and Daniel Loss

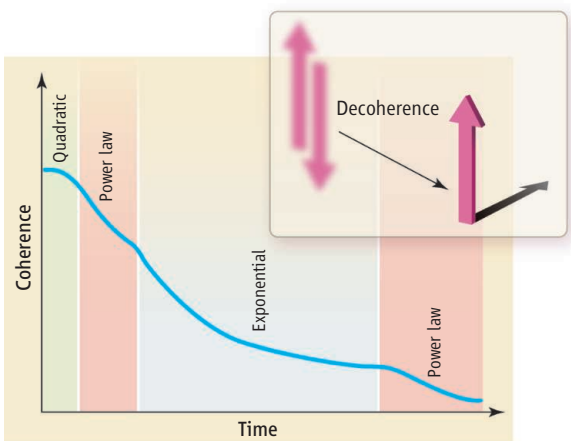
The dream of building computers that work according to the rules of quantum mechanics has strongly driven research over the past decade in many fields of basic and applied sciences, including physics, chemistry, and computer science. About 10 years ago, it was shown mathematically that the direct use of quantum phenomena such as interference and entanglement could crucially speed up data searching and prime factorization for encryption. To turn quantum computers into reality, however, many issues in engineering and in basic physics need to be addressed.

One issue of central importance is the physical implementation of the qubit—the quantum analog of the information bit processed by today's computers. Whereas conventional bits can be set to either of the distinct states 0 or 1, qubits can also be in a coherent superposition of these two states: both 0 and 1. In principle, any quantum mechanical system with two distinct states, which can be put into such a superposition, could be used to encode quantum information. Thus, a large variety of candidate qubit systems have been proposed. We discuss one of the leading candidates, the solid-state implementation of spin qubits in quantum dots; however, the same fundamental challenges are shared by all candidate systems.

The major problem in the realization of quantum computers is the short decoherence time. The qubit interacts with its environment, and the unavoidable coupling between the two causes a decay of qubit-state superpositions (see the figure, inset). The decoherence times are typically in the nano- to microsecond range for solid-state systems. However, they can easily vary over many orders of magnitude when the physical parameters (temperature, gate potentials, magnetic fields, material or isotope composition, confinement geometry, etc.) change.

Building a quantum computer is therefore not simply an engineering problem with predictable progress. Instead, it is a complex problem involving many unwanted interactions with the outside world, raising the principal question of whether these interactions will ever allow sufficiently long coherence on a larger scale.

Decoherence is not of a "generic type" but is system-specific. Thus, the devil is in the details, and only understanding those details can reveal strategies to deal with decoherence. For instance, quantum error-correction schemes, which are essential for scalable quantum computation, almost exclusively assume a decoherence model characterized by a single-exponential decay time. However, we under-



Losing it. A sketch of the decoherence of a spin qubit (electron in quantum dot) caused by a million nuclear spins that have been prepared in a noise-reduced state with a narrowed distribution. An initial quadratic decay is followed by a short-time power law, an intermediate-time exponential, and a long-time power-law decay. (**Inset**) Decoherence is the decay of quantum mechanical superpositions: The state evolves from "↑ and ↓" to either "↑" or "↓" as a result of interactions with the environment.

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stand now that there can be an entire "zoo of decoherence laws," even in the same system—with a time decay that can proceed through several different stages (see the figure).

The qubit in a quantum dot consists of a single electron whose spin states ↓ ("down") and ↑ ("up") represent the logical states 0 and 1 (*1*, *2*). These electrons can be initialized in either spin state, the state can be read out, and two neighboring spins can be coupled and decoupled. Thus, all the prerequisites for universal quantum computation are fulfilled. An attractive feature of this qubit system is that it can be operated in an all-electrical way, thus allowing the use of standard microelectronic technologies, which are flexible, fast, and scalable. The desired size would be a "quantum chip" containing about 10,000 qubits. Currently, however, only two-qubit quantum dots have been implemented.

The focus so far has been on GaAs-based (and also InAs-based) semiconductors, mainly because of the advanced nanofabrication techniques available (*2*). In these materials, decoherence at millikelvin temperatures arises from nuclear spins. There are typically a million of them inside a quantum dot, and they all couple to the single electron spin via the hyperfine interaction (*3*). This spin bath creates a random magnetic field, which leads to fluctuations in the electron spin precession and thus to decoherence. This happens fast, typically within tens of nanoseconds. In contrast, the flip of the electron spin due to lattice vibrations can be extremely slow, even exceeding seconds (*4*). For quantum computation to be viable, the coherence of a single qubit must be long enough to allow around 10,000 qubit operations. Although two-qubit operations to generate entanglement have already been demonstrated on a remarkably short time scale of about 0.2 ns (*5*), the decoherence time relative to this duration is still too fast.

Several strategies have been proposed and implemented to deal with this problem. One method to extend coherence, borrowed from nuclear magnetic resonance, is to apply magnetic field pulses (spin-echo sequences), which partly reverse the electron spin dynamics, thereby prolonging its coherence, even up to microseconds (*6*). Another idea is to prepare the nuclear spin bath in some less noisy state with a narrowed distribution width (*3*). Such state preparations have already been successfully implemented (*7*, *8*). Another strategy is to polarize the nuclear spins, either by electrical currents (*9*) or by cooling to ultralow temperatures, with the goal of freezing out the nuclear spins. It also may be possible to induce a magnetic phase transition in the nuclear spin system, resulting in a strong suppression of the harmful fluctuations of the spin bath (*10*).

An alternative approach is to use a hole—a missing electron in the valence band. The spin state of holes can be surprisingly long-lived (*11*). In contrast to electrons, their hyperfine interaction is weaker and, most important, highly anisotropic in GaAs dots, thus prolonging their decoherence time to tens of microseconds (*12*). Although the decoherence time has not yet been measured, initializing and reading out single-hole spins in quantum dots has been demonstrated (*13*).

Although the presence of nuclear spins is a nuisance, they can also be used to advantage. Manipulating the nuclear spins allows control over the electron spin, and the necessary coupling between two qubits can even be mediated by nuclear spins (*5*). Moreover, the nuclear-spin system itself is suitable for information storage, as it is more robust against perturbations from the environment because of its weaker magnetic coupling.

New materials may also be worth exploring. Quantum dots in carbon-based materials such as nanotubes, graphene, or diamond, or in other type IV semiconductors (especially silicon-germanium nanowires), have been investigated recently with a view toward spin qubits. These materials have the advantage of low abundances of spin-carrying nuclear isotopes, thus exhibiting weaker nuclear-spin interactions of the confined electron. For instance, natural carbon consists of 99% nuclei with zero spin. Coherent dynamics of single spins in diamond have already been reported (*14*), and coherence times on the order of microseconds have been measured (*15*). Finally, many proposals for hybrid systems have recently been made, suggesting the coupling of spins to photons in cavities. This opens up the possibility of storing the quantum information in one qubit type and processing the information in another one.

There is still a long way to go before a practical quantum computer will be reality. Nevertheless, the steady progress over the past decade is encouraging, and many workers in the field are cautiously optimistic that the goal can be reached.

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BIOCHEMISTRY

Force Signaling in Biology

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Single-molecule studies are revealing the biomolecular processes initiated when biological systems sense mechanical forces.

Many processes in our body, like muscle contraction, cell locomotion and division, or transport processes, need force-producing actuators such as molecular motors. In turn, biological systems can also sense mechanical forces. Examples are the sense of touch, hearing, and the strengthening of muscle tissues upon physical exercise. In these cases, force triggers a biochemical signal cascade, but the mechanisms by which forces affect biomolecular conformation and biochemical signaling have long remained elusive. The development of ultrasensitive instruments for nanomanipulation—such as atomic force microscopy and optical and magnetic tweezers—has allowed the effect of forces on protein conformation and function to be probed at the single-molecule level (*1*–*4*).

On page 1330 of this issue, Zhang *et al.* use optical tweezers to clarify the role that mechanical forces play in the regulation of primary hemostasis in blood clotting (*5*). A key player in this process is von Willebrand factor (VWF), a large protein complex in

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