coherent laser created the polaritons directly in a coherent state, one cannot say that the polaritons underwent spontaneous coherence, but these experiments show that the coherent polariton wave will remain coherent over macroscopic distances because of stimulated scattering.

Concluding Remarks

The long-range transport of coherence in exciton or polariton states is one of the tantalizing possibilities of Bose effects in these systems. Although the theory of excitonic and polaritonic condensates is well established, most of the experiments done so far do not provide a direct measurement of spontaneous coherence. As the above survey shows, research on excitonic condensates has taken many directions, and many new results have stimulated the field.

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67. Supported by NSF under grant no. DMR-0102457 and by the U.S. Department of Energy under grant no. DE-FG02-99ER45780.

REVIEW

Cavity Quantum Electrodynamics: Coherence in Context

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Modern cavity quantum electrodynamics (cavity QED) illuminates the most fundamental aspects of coherence and decoherence in quantum mechanics. Experiments on atoms in cavities can be described by elementary models but reveal intriguing subtleties of the interplay of coherent dynamics with external couplings. Recent activity in this area has pioneered powerful new approaches to the study of quantum coherence and has fueled the growth of quantum information science. In years to come, the purview of cavity QED will continue to grow as researchers build on a rich infrastructure to attack some of the most pressing open questions in micro- and mesoscopic physics.

Every real physical system is an open system, and open systems are never more than partially coherent. At its conceptual core, quantum mechanics takes coherence for granted; fully accounting for real-world quantum phenomena thus requires a lot more than straight-ahead integration of the Schrödinger equation. Modern research on open quantum systems scrutinizes this gap between axiomatic theory and empirical realism, and it seeks to clarify murky issues in mesoscopic physics such as decoherence and the emergence of semiclassical dynamics. Cavity QED has long been a central paradigm for the study of open quantum systems and plays a leading

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role in defining research goals for the coming decade.

In the term "cavity QED," "cavity" refers to an optical or microwave resonator and "QED" implies the interaction of some material system (usually atomic) with the electromagnetic field (photons) inside the cavity. Enclosure in a high-quality cavity can largely insulate an atom–photon system from decohering interactions with its environment, allowing it to maintain quantum coherence over dynamically important time scales. Because the residual external couplings of such an intracavity system can be treated perturbatively, comprehensive theoretical models for cavity QED have been derived essentially from first principles. Cavity QED thus provides a unique model in which decoherence can be studied rigorously and quantitatively, and for which exacting standards of agreement between experiment and theory can reasonably be upheld. The high degree of coherence achievable in modern cavity QED experiments likewise makes them an ideal proving ground for basic principles of quantum control and quantum computation, which are fields of rising prominence in our modern technological outlook.

The aims here will be to survey the current state of experimental research in cavity QED, to describe some conspicuous technical obstacles, and to discuss future directions relative to historical motifs in the field. Readers interested in a more comprehensive review or theoretical details may wish to consult references (*1–4*).

entity comprising a system and its environment should evolve in an overall coherent fashion. As a result, coherences that originate within the system of interest will tend to be converted into entanglement of—that is, coherences between—the system and the environment. This process greatly diminishes the visibility of coherences in measurements performed on the system alone, thereby producing the effect known as decoherence. Figuratively one can think of coherence "leaking out" from the system into the environment, in loose justification of the name open quantum system. The cavity in cavity QED can correspondingly be understood as a means of suppressing such leakage from a localized system of interacting atoms and photons.

The predominant component of decoherence in cavity QED systems corresponds simply to the escape or emission of photons, either by absorption into the cavity walls or mirrors or by scattering or transmission into electromagnetic modes outside the cavity. In some cases, the escape of photons into one specific electromagnetic mode can dominate all other forms of external coupling (such as atomic spontaneous emission), thus constituting a well-defined "output channel" for the open quantum system. Technical setups that make such output channels accessible to high-efficiency photodetection are enabling a new genre of cavity QED experiments that examine how the quantum measurement process interrupts the build up of system-environment entanglement. As a result of wave

strongly correlated with the measurement signal. The resulting scenario may be characterized as "conditional quantum evolution" of the intracavity system. Detailed investigations of such phenomena will substantially mature our understanding of quantum measurement and of how both measurement and decoherence relate to the mesoscopic interface between quantum and classical physics.

Highly coherent evolution can only be achieved in cavity QED systems that meet certain hierarchy requirements on technical parameters. Recent discussions in the literature have emphasized a strong coupling regime for cavity QED (*5*), in which the basic rate characterizing the quantum mechanical atom–photon coupling (the vacuum Rabi frequency) is much larger than both the atomic dipole decay rate and the cavity field decay rate. The definitive attainment of strong coupling has been a hallmark of recent experimental work in microwave (*3*, *4*) and optical (*5*) cavity QED with alkali atoms (Fig. 1) and will be implicit in most of the discussion that follows. Strong coupling is what makes cavity QED relevant to schemes for quantum information processing. Some implementations of cavity QED have yet to achieve strong coupling but hold great promise to do so in the future, e.g., solid state systems incorporating quantum dots (*6*). Tremendously important physics has been done and continues to be done with cavity QED systems that do not satisfy the strong coupling criteria (*7*, *8*).

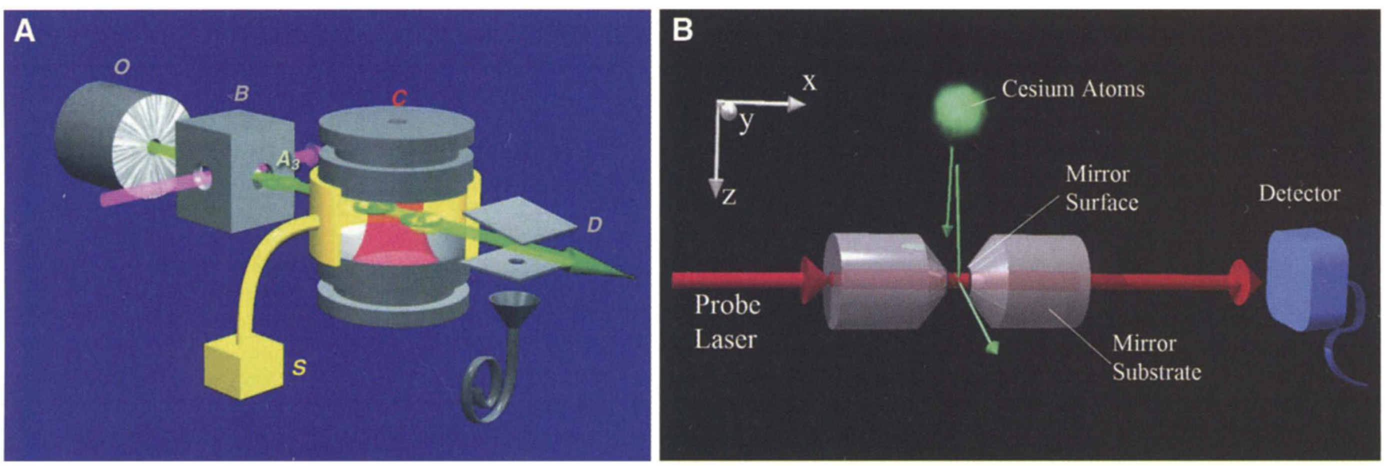

Fig. 1. Representative experimental setups for cavity quantum electrodynamics reproduced from Rauschenbeutel *et al.* (*31*) and from Hood *et al.* (*18*). (**A**) In microwave cavity QED experiments (*31*), atoms in a thermal beam (*O*) are prepared in Rydberg states (*B*) before passing through a superconducting cavity (*C*). Interrogation of intracavity dynamics is performed by state-selective detection of atoms via field ionization (*D*). The intracavity atoms can be driven by a microwave source (*S*) for direct state manipulation. (**B**) In optical cavity QED experiments (*18*), atoms are dropped from a magneto-optical trap into a Fabry-Perot cavity formed by dielectric mirrors. Interrogation of intracavity dynamics is performed by high-efficiency measurement, via homodyne or heterodyne detection or photon counting, of a probe laser that is transmitted through the cavity.

Coherence, Decoherence, and Strong Coupling

Why do environmental couplings induce decoherence of quantum systems? Simply put, quantum mechanics dictates that the joint function "collapse" associated with the monitoring of a given output channel, that channel's contribution to decoherence of the intracavity system should be replaced by a stochastic dynamical perturbation that is

Highlights of Recent Progress

The past decade has been witness to great advances in experimental cavity QED. Scientific interests in the community have been evolving rapidly of late, as researchers have been finding deep connections between longstanding goals in quantum optics and contemporary challenges from quantum information science. The advent of quantum trajectory theory and its extensions has likewise prompted renewed interest in exploiting cavity QED as an experimental venue for fundamental studies of conditional quantum evolution (*9*) and nonequilibrium quantum statistical mechanics (*10*).

Counting intracavity photons. Quantum nondemolition (QND) measurement of photon number has long been recognized as a central goal of quantum optics. Roughly speaking, the objective is to count the number of photons in a field mode without having to absorb (or otherwise remove) them. In addition to acquiring such information, an ideal QND measurement process should project the light field onto the corresponding photon number state. Nogues *et al.* recently demonstrated QND detection of single photons in a microwave cavity (*11*). Their successful experimental approach exploits the extreme sensitivity (in the strong coupling regime) of atomic internal-state dynamics to intracavity photon number. Atoms injected into the microwave cavity in a well-defined reference state are interrogated after they have passed completely through. Destructive measurement of the atom's final state allows one to infer whether the cavity contains zero or one photon in a manner that projects the intracavity field into the corresponding number state. In a clear demonstration of the relation between QND measurement and quantum information processing, similar procedures have been used by the same group to realize a universal quantum logic gate between the state of the atom and that of the cavity field (*12*).

Quantum nonlinear optics. Just as individual photons can substantially perturb atomic dynamics in the strong coupling regime, even a single atom can strongly influence the state of the intracavity field. These two effects in combination imply that the strong effect of an atom on one photon can be strongly modulated by the presence or absence of a second photon, thus providing entry to a quantum regime for nonlinear optics. Experiments in optical cavity QED have dramatically demonstrated such nonlinearities. In recent work by Turchette *et al.* (*13*), cesium atoms in a high-finesse optical cavity provided a nonlinear medium whose transmission could be varied over a factor of two by a change of only 0.024 photons in the intracavity field. This variation in the optical power transmitted through the cavity is naturally accompanied by changes in the phase of the transmitted beam, which was used (*14*) to demonstrate that optical cavity QED with strong coupling provides the physical interactions required for a universal quantum logical gate between photons. This was an important milestone for early research on quantum computation and has stimulated a great deal of theoretical activity to explore further connections between cavity QED and quantum information science.

Atom-cavity microscopy. The magnitude of the atom-induced phase shift or change in cavity transmission depends on the strength of the coherent coupling of the atom to the cavity mode. Because this coupling is typically a function of the exact atomic position within the cavity, the phase and intensity of the intracavity field can provide sensitive meters of an individual atom's motion. It has been shown theoretically that the resulting position sensitivity can approach the standard quantum limit even when decoherence effects are taken into account (*15*, *16*). In optical cavity QED experiments that combine strong coupling with laser cooling techniques (*17*), it has been possible to track the motion of single atoms with high (but not quantum limited) sensitivity and high bandwidth by monitoring the change in transmission as the atom moves into and out of the center of the mode (*18*–*20*). Further improvements are being pursued through a combination of technical refinements (*21*) and investigation of more powerful signal recovery techniques.

Quantum state synthesis. The high level of coherent control achievable in both microwave and optical cavity QED experiments has enabled synthesis of highly nonclassical states of the electromagnetic field. Attention has focused on Fock states of the electromagnetic field (with an exact number of photons inside the cavity) and on superpositions of the zero- and one-photon Fock states (*22*–*26*). One method for the production of single-photon Fock states in microwave systems involves the passage of a single excited atom through the cavity with a transit time just sufficient for complete exchange of energy from the atom to the cavity field (*22*, *24*). As shown by Varcoe *et al.* (*23*), a second atom can deposit a second photon in the cavity field leading to the creation of a two-photon Fock state. Recently, an alternative procedure has been demonstrated in which a single excited atom scatters one photon out of an auxiliary mode of the cavity into the (initially empty) target mode, simultaneously contributing its own excitation energy for production of the second photon (*27*). A distinct scheme for microwave Fock-state synthesis can be implemented using the micro-maser experimental configuration. By appropriately controlling the velocity of the injected atomic beam, it is possible to realize a scenario in which a Fock state can actually be made the steady-state attractor for the atom-cavity dynamics. Weidinger *et al.* (*28*) have recently observed such "trapping states" experimentally, and the preparation of single-photon Fock states has been demonstrated (*24*).

In optical cavity QED, rather different quantum state synthesis schemes must be used in order to avoid rapid decoherence associated with population of the atomic excited state. Hence, Rempe and co-workers (*25*, *26*) have implemented schemes that deposit a single photon into the cavity field via "adiabatic passage" through a dark state of the coupled atom-cavity system, such that the atom transitions directly between two electronic ground states distinguished by spin. The coupling between atomic ground states is a combined effect of the cavity field (which is initially empty) and an external laser field injected through the gap between the cavity mirrors. This process should transfer one photon from the external laser field into the cavity mode each time an external laser pulse is applied. The resulting photon rapidly leaks out through one of the cavity mirrors, thus in principle creating a single photon in some traveling wave mode with a well-defined direction of propagation (the cavity output channel).

Nonclassical correlations. Quantum synthesis procedures have also been used to prepare states that test theoretical models of entanglement and decoherence. The experimental signatures of entanglement generally take the form of nonclassical statistical correlations of measured signals.

In the strong coupling regime, the influence of an atom on the intracavity field depends strongly on the atom's internal state. This effect has been used in microwave experiments to transform an initial superposition of atomic internal states into an entanglement of the atomic internal state with the intracavity field (*29*). These experiments were able to verify basic predictions that the decoherence rate of such an entangled state should increase as the cavity-field components become more widely separated in the phase plane. These experiments demonstrated that atom-cavity entanglement enables the observation of cavity field decay via induced decoherence of the atomic internal state. They also verified basic predictions that the decoherence rate of atom-field entangled states increased as the field components become more widely separated in the phase plane. In experiments involving the passage of several atoms through a microwave cavity, it has been possible to produce entanglement among the atoms with the use of the cavity field as an intermediary. Initial entanglement between one atom and the cavity field may be converted into atom-atom entanglement by passage of a second atom through the cavity, producing an atomic Einstein-Podolsky-Rosen state (*30*). Similar procedures have been used to create tripartite entangled states of two atoms and the cavity field (*31*) and entangled states of two cavity modes (*32*).

In optical cavity QED, leakage of photons into an accessible output channel makes it possible to study entanglement between the intracavity system and its environment. Optical experiments can reveal conditioning of the intracavity system on external photodetection events as well as investigate quantum dynamics of the regression to equilibrium (*33*). Foster *et al.* recently demonstrated nonclassical correlation functions for the intracavity field using conditional homodyne detection (*34*). In related work, the same group has used real-time feedback to verify explicitly the relation between such correlation functions and the dynamical evolution of the intracavity quantum state (*35*). Over the years, research in this general area of cavity QED has emphasized the deep connections between decoherence and broader issues in quantum statistical mechanics.

Impending Technical Obstacles

While cavity QED research continues at an intense pace, the short-term focus of experimental research has shifted from scientific to technical goals. Two key objectives are stronger coupling and greater determinism. The desired technical improvements are largely motivated by a surge of intriguing but demanding theoretical proposals, some of which will be discussed here.

For optical implementations in particular, future experiments would benefit greatly from higher ratios of the atom-photon coupling rate to decoherence rates. Within the established technical paradigm of Fabry-Perot optical resonators, this would require improvements in the reflectivity of dielectric mirrors and the development of procedures for working with extremely short cavities. Some feasible limits have been discussed by Hood, Kimble, and Ye (*36*). One of the main difficulties in working with extremely short optical Fabry-Perot cavities is inaccessibility of the intracavity volume, because two mirrors of millimeter diameter spaced micrometers apart leave very little solid angle from which to inject atoms and optical trapping or probe beams. Several groups have begun to explore alternative types of cavities that would not suffer from this problem. One promising approach uses fused silica microsphere optical resonators (Fig. 2A), which are solid dielectric spheres of $\sim$100 μm diameter that support high-quality whispering gallery modes. Although light is confined by total internal reflection and circulates on the inside of the sphere, the whispering gallery modes exhibit an evanescent tail that can couple to atoms (or molecules, quantum dots, *etc.*) located just outside the equatorial surface (*37*). It may also be possible to realize strong coupling with dopant ions incorporated into the dielectric sphere itself (*38*), which can in principle be fabricated from any low-loss optical material. Semiconductor photonic bandgap structures (Fig. 2B) may also provide a viable new "integrated" implementation of cavity QED (*39*). Basic estimates show that excellent parameters should be achievable, but numerous technical challenges involved in the use of such cavities for strong coupling (with neutral atoms) have yet to be seriously addressed (*40*).

Optical experiments have also been limited by short dwell times of individual atoms within the cavity, as the basic mechanism for injecting them has simply been to direct a collimated thermal beam of atoms towards the gap between the mirrors. The lack of control over an atom's exact spatial location within the cavity also causes problems, because the atom-photon coupling strength varies sharply over length scales comparable to the electromagnetic wavelength. Recent success in integrating laser cooling techniques with cavity QED (*17*) has led to substantial increases in the ratio of the single-atom dwell time to dynamical time scales of the atom-photon interaction, but so far in such experiments cold atoms have simply been dropped or ballistically launched into the cavity. As a result, the arrival statistics of individual atoms remain random, which makes it extremely difficult to perform experiments that require coincident arrival of several atoms within a limited time window. The latter consideration is also a severe limitation in microwave experiments, leading to a common interest in nonthermal atomic sources.

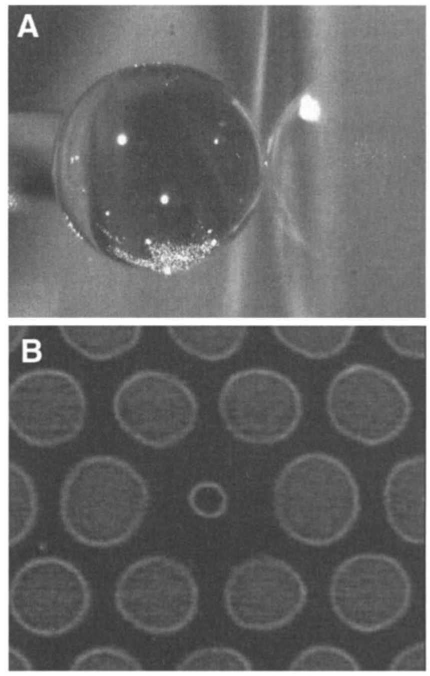

Fig. 2. (**A**) A quartz microsphere dielectric resonator shown next to a glass prism used for coupling via frustrated total internal reflection. (**B**) Electron micrograph of a photonic bandgap defect cavity formed in an InGaAsP membrane, as described in Painter *et al.* and in Vukovic *et al.*

Ongoing work in a number of groups seeks to ameliorate both the random arrival and uncontrolled motion issues with the use of several different technical approaches. An approach pioneered by Kimble and co-workers utilizes an optical dipole-force trap to catch and confine cold atoms that have been dropped into the cavity (*41*). Alternative methods that could be used deterministically to transfer atoms into a cavity from an external magneto-optic trap have recently been reported (*42–44*). Efforts to combine high-finesse optical cavities with ion traps have also made substantial progress in recent years (*45*, *46*). Although ion trapping is an essentially perfect means of confining and localizing atoms inside a cavity, there is some question as to whether charging effects will prevent the use of sufficiently short cavities to achieve strong coupling. Several groups have recently begun to consider the use of microfabricated magnetic traps (*47*) for cavity QED.

Research Themes and Outlook

The most compelling proposals for next-generation research in cavity QED fall roughly into two categories. One set of goals encompasses proof-of-principle experiments in coherent control and quantum information processing, and the other aims to demonstrate conditional quantum evolution and quantum feedback. Both of these themes represent forward projections of historical motifs in cavity QED, namely, micromaser research and investigations of optical bistability.

Coherent control and quantum information processing. Two basic aims of coherent control are the design of procedures for synthesizing arbitrary quantum states and for steering the dynamics of quantum systems. Quantum state synthesis has long been a topic of central interest in quantum optics and has recently gained importance for applications in quantum cryptography and in optical quantum computing. Coherent control of quantum dynamics has likewise been studied since the early days of nuclear magnetic resonance, and today it finds new motivating applications in both quantum computing and quantum chemistry. Within the context of cavity QED, various notions of coherent control have arisen in micro-maser research and its modern extensions.

The cavity QED criterion of strong coupling coincides with a crucial requirement for generation of entangled states for the atom-photon system. Because most of the quantum states that are theoretically possible for a bipartite system are entangled, it follows that the experimental achievement of strong coupling was a milestone for quantum state synthesis in cavity QED. In addition to making entangled states reachable as final target states (*29*, *31*), the ability to make an atom-photon system evolve through entangled states has been essential for recent demonstrations of synthesizing highly nonclassical states for the electromagnetic field only (*22*, *24*, *26*). Strong coupling has also enabled the engineering of specific evolution operators in cavity QED that correspond to fundamental quantum logic gates for quantum computing (*12*, *14*). Here, the control objective extends from the preparation of a desired final quantum state to the implementation of a specific mapping from some subspace of possible initial states to an image space of desired final states.

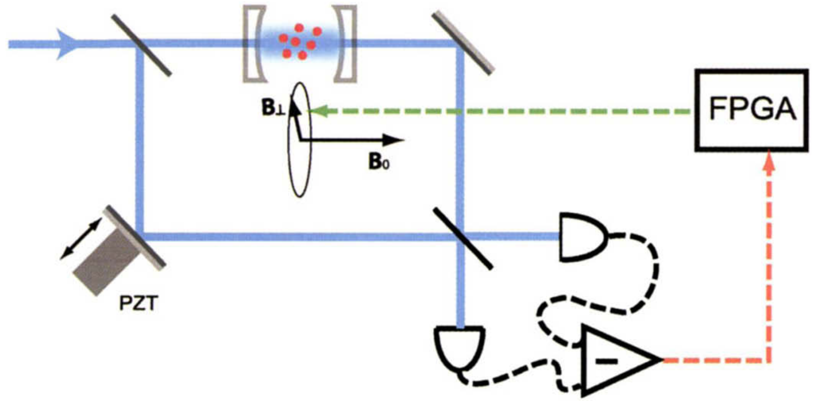

Fig. 3. Schematic of an experiment for quantum control of atomic states via strong coupling and real-time feedback, drawn after the scheme proposed in (*59*). Photocurrent generated by the detection of light transmitted through an optical cavity is processed by a field programmable gate array (FPGA), which sends a real-time feedback signal to influence the quantum state of intracavity atoms via an applied magnetic field *B*. PZT, piezoelectric transducer.

The combination of capabilities for state synthesis and implementation of quantum logic gates makes cavity QED a prime testing ground for new ideas in quantum information science. A new breed of synthesis schemes for reaching arbitrary states within a subspace of electromagnetic field states, which have been analyzed theoretically over the past decade, seems to be coming within experimental reach. These schemes rely on established techniques for quantum state synthesis on the space of atomic internal states (*48*) or atomic motional states (*49*) but propose methods for the use of strong coupling to implement coherent mapping of states from those spaces into the state space of the intracavity electromagnetic field. Quantum state mapping will in turn represent a crucial first step toward the realization of quantum communication protocols, which could be used for robust quantum state teleportation over long distances (*50*). Such methods will someday permit the creation of entanglement between trapped atomic or electromagnetic systems separated by very long (km scale) distances, enabling fundamental studies of quantum nonlocality and distributed quantum computing.

Conditional evolution and quantum feedback. Much of the early interest in optical implementations of cavity QED stemmed from investigations of the laser and optical bistability (a scenario closely related to that of the laser in which an atom-cavity system is probed by a resonant field rather than being pumped to produce gain) (*51*). In the semiclassical (many atom) limit, both lasers and optical bistability provide canonical paradigms for the study of nonlinear dynamics and nonequilibrium statistical mechanics in driven dissipative systems. The advent of high-finesse optical mirror technology has enabled experimental research to reach the quantum limit of such systems, leading to the demonstration of a micro-laser (*52*) and to quantitative studies of the breakdown of optical bistability in the few-atom limit (*33*).

Theoretical analysis of nonlinear dynamics in the quantum regime catalyzed some early connections between cavity QED research and generalized quantum measurement theory. In particular, analyses of photon antibunching in optical cavity QED with strong coupling (*53*) foreshadowed later developments in quantum trajectory theory and introduced ideas of conditional quantum evolution. Continuing research on the impact of continuous quantum measurement on strongly coupled cavity QED has produced a number of theoretical proposals for realistic experiments that would illustrate striking consequences of conditional evolution (*54*, *55*). Several groups are currently pursuing related goals, and an important set of milestones has already been achieved (*34*, *35*).

A primary motivator for research on conditional quantum evolution is the prospect of developing general methods for real-time feedback control of open quantum systems (*56*, *57*). Practically speaking, it would be nearly inconceivable to build any sophisticated classical technology without the benefit of feedback control methods, and one may expect that quantum feedback control should play a similar enabling role in the development of quantum technology. From the perspective of basic science, quantum feedback also provides a unique methodology for rigorous and quantitative testing for theoretical models of continuous measurement and conditional quantum evolution.

In optical cavity QED, monitoring of leaking photons provides a powerful method for continuous measurement of the intracavity atom-photon state. Proposals to use this output channel for real-time feedback have been discussed in relation to control of atomic motion (*58*) and internal atomic states (*59*). In these schemes, strong coupling provides a means of accessing truly quantum features of the intracavity dynamics, whereas having a single prominent output channel (as discussed above) makes it possible for real-time measurement and feedback to compensate certain effects of decoherence. Generally speaking, real-time feedback control should ultimately provide means of tailoring the dynamics of an open quantum system via implementation of carefully designed algorithms for processing the feedback signal (Fig. 3). In classical control theory, a great deal is known about the extents and limits of the modifications that can be achieved through use of feedback, but very little is yet known about the quantum case. Filling in the details will likely proceed by a lively interaction of experimental work in cavity QED, extensions of control theory, and a deepening of the theory of open quantum systems.

Concluding Remarks

Cavity QED provides a unique paradigm for matching theory with experiment in the study of quantum coherence. It will play a central role in basic research on quantum physics, especially in connection with decoherence, measurement, entanglement, and nonlocality. Cavity QED experiments with strong coupling will also demonstrate basic principles of quantum control and quantum information science, providing key support to the development of technologies such as quantum computation and communication.

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60. The authors wish to thank J. M. Geremia, J. Williams, J. Au, and M. A. Armen for providing Figs. 2 and 3.