Every six years the University of Rochester is host to a conference that draws hundreds of registrants, including Nobel laureates and other distinguished members of the international quantum optics community. The Rochester Conference on Coherence and Quantum Optics that was held at the University in 2001 was the eighth in a series that began in 1960, barely in advance of the announcement of successful operation of the first laser. The first conference was intended as a showcase for work on the theme of optical coherence, which was then emerging as a frontier in optics. The conference was the public signal that the University had already installed research teams to probe the frontier, which gradually became identified with the name quantum optics, a subfield of the general domain known as AMO (atomic, molecular and optical) physics. The first University researchers established a strong identification of the University with the field, and built on their strengths with additional appointments. The success of their strategy has been striking. At the present time the University stands sixth in the national AMO ranking, ahead of traditional and usually much larger science schools including Caltech, Illinois, UC Berkeley, Yale and Chicago.

What is quantum optics? As briefly as possible, it is the study of light and matter at the single-photon and single-electron level. This oversimplification accurately suggests that the field’s attraction, and its expected future influence, both arise from its focus on the smallest units of opto-electronics, the photon and electron units that will dictate the development of advanced optical technology. Quantum theory itself arose a century ago in order to explain the way that electrons in atoms absorb and emit light, bringing with it the notion of wave-particle duality. This is the idea that a single photon or a single electron can be interchangeably considered either a particle or a wave, but not both at once. A tension persists to the present day in quantum optics between coherence (the wave aspect, permitting interference) and incoherence (the particle aspect, preventing interference), and this provided part of the intellectual motivation for the 1960 conference.

Robert Hopkins, director of the Institute in 1960, had previously noted that coherence and statistical optics were topics missing among the areas of faculty research, and in 1958 he approached one of Max Born’s former research assistants with the offer of a professorial appointment in the Institute.
This was Emil Wolf, who soon helped to recruit another physicist from England, Leonard Mandel, then studying the statistical behavior of single photons. Mandel joined the University as professor of physics. These were the founders who would become friends and long-time collaborators and participants in the activities of the Institute and the Physics Department, and are recognized world-wide as the originators of the University’s quantum optics research groups. The results of their collaboration are summarized in a book that they co-authored, *Coherence and Quantum Optics* (Cambridge University Press, 1995).

By the end of the 1960s, quantum optics was expanding internationally, and additions were made to the local team. Joseph Eberly was appointed to the faculty in Physics, and Carlos Stroud was appointed in The Institute of Optics. Not quite coincidentally, Eberly at Stanford and Stroud at Washington University had worked with the same faculty supervisor, E. T. Jaynes, an early pioneer of quantum optical coherence theory and one of the inventors of the field of cavity quantum electrodynamics. During the 1970s the University’s presence in quantum optics expanded greatly. Topics with such descriptions as multiphoton absorption, photon statistics, self-induced transparency, superradiance, Rabi splitting, resonance fluorescence, atomic dark states, non-classical light, cross-spectral purity, time-dependent spectra, and coherence trapping were introduced and discussed and expanded by workers here and around the world. Researchers in pure science were strongly supported by efforts in other areas of optical science and technology that are described in other articles in this volume.

Visitors and other collaborators were frequent participants in quantum optics research activities, with a number of notable results. The well-defined phase of laser light prompted re-examination of the phase-intensity relation in quantum theory as well as a careful treatment by Mandel, Wolf, and field-theorist colleague George Sudarshan of the photoelectric detection of light fluctuations. The first detailed textbook with quantum optics in the title was almost certainly *Fundamentals of Quantum Optics*, published in 1968 by Sudarshan with John Klauder at Bell Labs. It was designed to disseminate consequences of this new line of research. There were also undesigned consequences of the rapid progress being made in Rochester that led to publication. When the existence of two different but similar sets of unfinished lecture notes was discovered during an
impromptu dinner during the 1972 IQEC conference in Montreal, Eberly and a former visitor in Mandel’s group, Leslie Allen of Sussex University, found that they had practically already written a textbook together. In 1975 their small book appeared with the title *Optical Resonance and Two-Level Atoms*. It was distinguished immediately by the odd fact of having its Japanese translation available in print before the original English edition, and distinguished subsequently by remaining in print to the present day, more than thirty years after the dinner in Montreal. The book has since been translated into two more languages (legally) and is still in use as a classroom resource by Eberly and Stroud. Their introductory graduate course on quantum optics has defined entry into the field for scores of Rochester students and postdoctoral associates in optics and physics over the past three decades. Many of them have since become leaders in academic and industrial institutions in the various rapidly expanding fields of laser science, both in the United States and elsewhere, including England, Poland, Mexico, Russia, Spain, Switzerland, Norway, Netherlands, India, Pakistan, China, Japan, Australia and New Zealand. A related Eberly-Stroud project, almost completed more than once, is an introductory text of about twenty chapters. Another frequent collaborator in the quantum optics group was H. M. Nussenzweig, who authored another early book in the field, *Introduction to Quantum Optics*, in 1973.

In the 1980s Michael Raymer joined the group as a faculty member in optics, and then at the end of the 1980s and at the beginning of the 1990s two more faculty members joined the group: Ian Walmsley in optics and Nicholas Bigelow in physics. More recently John Howell arrived to take a position in physics. Several other current faculty members
of optics have strong overlapping interests in the field, including Robert Boyd, Govind Agrawal, and Lukas Novotny. Collectively the members of this extended group in optics and physics have published well over one thousand research papers, several widely used textbooks, and they have edited literally dozens of books and conference proceedings. They have served and are serving as editors and associate editors of journals and officers of professional societies. Over many years they have received honorary degrees, medals, and awards, and have held distinguished lectureships and memberships in national and foreign academies of science.

Key contributions to quantum optics in its first quarter century have come from the University of Rochester, and several prominent breakthroughs and widely known “firsts” are among them. These contributions have come in the form of both theoretical and experimental innovations, and from many individuals. Prominent themes engaging more than one person or research group over extended periods have included several that deserve particular mention: Optical coherence and statistical optics, the quantum-classical boundary, light generation and laser development, and resonant absorption and atomic coherence.
Optical coherence and statistical optics formed the core themes of the first Rochester Conference in 1960, and their importance and relevance were continuously and vigorously expanded by Emil Wolf and Len Mandel together with their research teams. A wide variety of collaborators included George Sudarshan, whose interest in phase space functions that rigorously connect classical variables with quantum operators led to his co-invention of the so-called Glauber-Sudarshan P distribution, a building block in quantum optical calculations. It prompted the rapid exploitation of the phase-space approach by C. L. Mehta and other students working with Wolf. Particularly notable was the series of papers with Girish Agarwal beginning in 1970 on phase space methods in statistical optics. The first major overview of light coherence and fluctuations following the 1960 conference appeared in an article by Mandel and Wolf, in Reviews of Modern Physics in 1965. This was probably the University’s first “citation classic,” reaching the five-hundred-citation level very quickly in the world literature. Along with two other more recent citation classics, it is listed in bold face in the table.

In a very different project, Eberly and Krzysztof Wodkiewicz established a consistent theory for time-dependent spectra of statistical light fields. This is not the oxymoron it may appear to be, since time-dependent spectra form the background for instrumental developments that came later, including frequency-resolved optical gating (FROG) and Ian Walmsley’s invention of spectral phase interferometry for direct electric-field reconstruction (SPIDER).

For almost two decades, announcements of exotic instances of quantum coherence were practically continuously arriving from the Mandel labs. These included the invention of a totally new concept in interferometer design based on two-photon entanglement,
the discovery of what is now referred to as the Mandel dip in two-photon interference, and other quantum statistical marvels, such as photon beams that are anti-bunched and/or have sub-Poisson noise. It was in this work that the widely used Mandel Q parameter was introduced.

*The quantum-classical boundary* is an ill-defined region noted for its strange inhabitants such as the Schrödinger Cat, which is neither alive nor dead but rather is both at once. One of these beasts was actually tracked and captured in Wilmot, a highly publicized result of Rydberg wave packet experiments by Carlos Stroud and his group in the 1980s. Ian Walmsley and Mike Raymer more recently described a similar animal, a molecule with obviously classical vibrational motion but which behaves purely quantum mechanically when subtly observed.

Arguments concerning whether light itself belongs on one side or the other of the quantum-classical boundary have a long and honorable history. Are photons necessary to use as the fundamental light unit or not? Direct demonstration that the answer is definitely *yes* became much easier in 1980 when Joe Eberly’s group used the context of cavity QED to predict a new phenomenon called quantum revivals, experimental signals that are not compatible with non-quantized light. Revivals have been observed in several ways now, settling the original question, and Stroud’s group has found that fractional revivals also exist. They explain a large multiplicity of little quantum cats, Schrödinger Kittens, that can coexist in a single Rydberg atom. Behavior just as unnerving can be exhibited by light pulses. For example, Len Mandel’s group showed in a landmark experiment that a photon in an interferometer can be smart enough to tell when an experimenter *could* be watching a second photon, *whether he is watching or not*. John Howell’s experiments crowd the quantum-classical boundary from a different direction, by asking how closely can photons be cloned, since Mandel and Peter Milonni and others have shown that nothing can be cloned perfectly, with implications for very practical tasks such as cryptography. The impossibility of perfect cloning, however, doesn’t rule out perfect teleportation, but that’s another matter.

Light generation and laser development had top priority in many optics labs in the 1960s. Ways were found at that time to make lasers wavelength-tunable by adopting a variety of dyes as laser media, partly through Mike Hercher’s work and the concurrent efforts of Ben Snavely’s group at Kodak. Later advances in light generation and manipulation came in a number of forms, via stimulated Raman and Brillouin scattering, parametric amplification, free electron lasing, and others. One of the most general and useful remains multi-wave mixing. For example, the visibility of a hologram relies on wave mixing, and Emil Wolf explained how holographic data can provide structure information on semi-transparent objects. Later, the unexpected appearance of Rabi resonances in four-wave mixing was explained by Bob Boyd, Mike Raymer, Paul Narum, and Don Harter. What was certainly the least expected new light form came in the late 1980s from the optics-physics team of Jim Durnin, Joe Miceli, and Joe Eberly, when they announced diffraction-free beams. In the face of world-wide skepticism, their papers provided experimental evidence that so-called
Bessel beams with beam spots as small as 100 microns in diameter have the exotic ability to propagate without observable spreading an order of magnitude farther than the Rayleigh range of a more usual Gaussian beam focused at the same aperture. Despite their counterintuitive character, such Bessel beams are currently being used in a number of optical applications.

Advances in laser operation also led quickly to higher output intensities. Within barely more than a decade of the first laser in 1960, the successive adoption of Q-switching and then mode-locking techniques gave laser powers in the multi-megawatt range, but further increases came very slowly for more than a decade. Then a stunning advance came with the Rochester demonstration of a table-top terawatt laser (called simply the T-cubed laser by everyone). Conceived by Gerard Mourou, and based on chirped pulse amplification, this was the thesis goal of optics student Donna Strickland, and was realized, with other members of Mourou’s LLE team, in 1985. To the present day, all subsequent high power solid state lasers, some now operating above the petawatt level, have employed the T-cubed chirped-pulse laser principle.

Such increases in laser power fit perfectly with both theoretical and experimental programs around the world. A hierarchy of predicted high-intensity effects awaited experimental study, and the first efforts were directed to the detection of multiphoton ionization, for which a workable high intensity theory had already been provided by optics professor Al Gold and his student Barry Bebb in 1966. Work with very strong laser fields has been continuous at the University since then, and results have included the first observation of the suppression of the photo-electric effect under high-intensity irradiation, the dramatic direct conversion of light into matter by the Melissinos-Meyerhoefer collaboration on positron-electron pair creation, and new faculty member Chunlei Guo’s design of high-intensity experiments to track molecular electrons on attosecond time scales. The two largest international conferences that are focused on strong-field effects in atoms and molecules were founded by Eberly and first held on campus. Both conferences are held regularly and are now being scheduled for off-campus venues such as Budapest, Crete, Monterey, Garmisch-Partenkirchen, Quebec, and even a Volga River cruise boat.

Resonance absorption and atomic coherence became more and more closely connected as tunable lasing allowed formerly impossible experiments to be executed worldwide. These included studies of nonlinear oscillation in laser systems as well as laser threshold studies employing photon-counting techniques pioneered by Len Mandel using the Poisson transform widely known as the Mandel formula, which connects the probability densities of the quantum photocount with the classical intensity of light. Strong resonance effects were most vigorously explored in the sodium D-line manifold with dye lasers based on Rhodamine 6G (a wonderfully intense orange dye, particularly when spraying at high pressure all over a lab from a ruptured hose). The ease of seeing coherent resonance effects focused attention on fictitious (but very popular) two-level atoms. These imaginary atoms were and are real enough to give backbone to quantum optics intuition, and served as the platform for calculations in the 1970s of radiative frequency shifts such as the Lamb shift by Jay Ackerhalt, Peter Knight, and Peter Milonni in Joe Eberly’s group to determine the quantum counterparts to neoclassical predictions (see “The Jaynes-Franken Bet,” chapter 30), using radiation reaction rather than vacuum fluctuations as their foundation. Two-level theory not only made clear the governing role of Rabi oscillations in coherent stimulated transitions, but also permitted detailed but simplified calculations that revealed a wide variety of effects never seen before. Among the most noted of these were the Rabi splitting of the
spectrum of resonance fluorescence into three peaks rather than one, first observed by Felix Schuda, Carlos Stroud, and Mike Hercher, and the prediction and subsequent first observation of anti-bunched photon generation by Len Mandel working with Jeff Kimble and Mario Dagenais.

Highly coherent and strong laser interactions allowed terminology from wave optics to be sensibly applied to atomic dynamics, where conventional rate equations for absorption and emission had to give way to equations for phase-coherent probability amplitudes. New effects such as confluence of coherences, adiabaton pulses, and coherence transfer were announced in theoretical papers of Kazik Rzazewski, Rainer Grobe and Fock Hioe, working with Joe Eberly, and confirmed in experiments later. Tests of quantum theory offered a fundamental application of statistical coherence, and the truly odd features of the quantum side of the classical-quantum boundary began to be appreciated in the 1980s. Len Mandel explained how to design unbreakable cryptographic devices, a forerunner of John Howell’s latest work with biphotons from parametric down conversion. Wodkiewicz and Eberly exported the notion of squeezing from photons to atoms, and Nick Bigelow’s recent work has led to observations in atoms of macroscopic spin squeezing, the reduction of an uncertainty below the standard quantum limit of the Heisenberg Uncertainty Principle. The final stage of this work probably lies in conditional Heisenberg violation in high quantum entanglement of the type associated with Einstein’s famous objections to quantum mechanics published in 1935 with Podolsky and Rosen. One route to reach this goal has recently been elucidated by Eberly with C. K. Law, and collaborative experiments by Bob Boyd and John Howell are moving quickly in the same direction.
A resonance breakthrough occurred as soon as two strong optical fields at different but tunable wavelengths could be exploited in the same experiment. The first double-optical strong resonance studies became possible, and these led to the discovery of the atomic “dark states” that were studied by the Stroud team, explained in Rich Whitley’s thesis and confirmed in experiments with Bob Gray. Similar states in cavity QED described by the physics student H. I. Yoo extend the concept of revivals. The discovery by Oreg, Hioe, and Eberly of the unexpected advantage of anti-intuitive pulse ordering in double excitation is now exploited globally in a variety of double resonance applications. Mike Raymer and Ian Walmsley took double resonance right to the classical-quantum border when they showed how classically stimulated Raman scattering gives rise to giant spontaneous quantum fluctuations.

Large-scale collaborations among groups have been founded at the University to exploit the existence of vigorous research teams covering different sectors of quantum optics. The Rochester Theory Center for Optical Science and Engineering was established by the National Science Foundation in 1995. Its mandate has been to provide opportunities for young theorists in a wide range of fields of optical science and technology to interact for one-to-three years with leading optical theorists in the University. Faculty from five different departments and LLE have cooperated within RTC in mentoring more than two dozen post-docs. The recent widespread interest in developing quantum computers has directed new attention to old questions within quantum mechanics and quantum information theory, many of which have optical aspects. In a coast-to-coast collaboration with scientists in four other universities, four faculty members in optics and physics have formed the core of the Center for Quantum Information, supported through the Army Research Office since 1999. The purpose is to coordinate different approaches to research on fundamental aspects of quantum information.

Every discussion of this type could be continued almost indefinitely and still not credit all the important contributions and contributors. The intent has been to focus mostly on the earliest days of quantum optics at the University, and the developments that came from them. The table below is an attempt to finish with a cross-section of University papers from those days that played key roles in the evolution of quantum optics here, and that were also “selected” by the entire world-wide optics community. That is, the articles are those from the quarter century 1965–1990 that have been cited by authors of at least three hundred other published papers. Three of the articles have achieved what is usually called “Citation Classic” status, that is, they have received more than five hundred citations. These are highlighted in bold face.

L. Mandel and E. Wolf, Reviews of Modern Physics 37, 231 (’65), Coherence Properties of Optical Fields

E. Wolf, Optics Communications 1, 153 (’69), Three-dimensional structure determination of semi-transparent objects from holographic data

G. S. Agarwal and E. Wolf, Physical Review D 2, 2161–2186 (’70), Calculus for Functions of Noncommuting Operators and General Phase-Space Methods in Quantum Mechanics. I. Mapping Theorems and Ordering of Functions of Noncommuting Operators
F. Schuda, C. R. Stroud, Jr., and M. Hercher,
Journal of Physics B 7, L198 (’74),
Observation of the resonant Stark effect at optical frequencies

H. J. Kimble and L. Mandel,
Physical Review A 13, 2123 (’76),
Theory of resonance fluorescence

R. M. Whitley and C. R. Stroud, Jr.,
Physical Review A 14, 1498 (’76),
Double optical resonance

J. H. Eberly and K. Wodkiewicz,
Journal of the Optical Society of America, 67, 1252 (’77),
The time-dependent physical spectrum of light

**H. J. Kimble, M. Dagenais and L. Mandel,**
**Physical Review Letters 39, 691 (’77),**
**Photon Antibunching in Resonance Fluorescence**

H. R. Gray, R. M. Whitley and C. R. Stroud, Jr.,
Optics Letters 3, 218 (’78),
Coherent trapping of atomic populations

L. Mandel,
Optics Letters 4, 205 (’79),
Sub-Poissonian photon statistics in resonance fluorescence

**J. H. Eberly, N. B. Narozhny and J. J. Sanchez-Mondragon,**
**Physical Review Letters 44, 1323 (’80),**
**Periodic Spontaneous Collapse and Revival in a Simple Quantum Model**

N. B. Narozhny, J. J. Sanchez-Mondragon and J. H. Eberly,
Physical Review A 23, 236 (’81),
Coherence versus incoherence: Collapse and revival in a simple quantum model

H.-I. Yoo and J. H. Eberly,
Physics Reports 118, 239 (’85),
Dynamical theory of an atom with two or three levels interacting with quantized cavity fields

J. Durnin, J. J. Miceli, Jr., and J. H. Eberly,
Physical Review Letters 58, 1499 (’87),
Diffraction-free beams

C. K. Hong, Z. Y. Ou and L. Mandel,
Physical Review Letters 59, 2044 (’87),
Measurement of subpicosecond time intervals between two photons by interference

P. Maine, D. Strickland, P. Bado, M. Pessot and G. Mourou,
IEEE Journal of Quantum Electronics 24, 398 (’88),
Generation of ultrahigh peak power pulses by chirped pulse amplification