Measuring Photons:

Optical Approaches to Fundamental Issues in Quantum Mechanics

University of Ottawa | 14, 15, and 16 March 2014

Contact: Mary Ann Meyers, Ph.D., *Senior Fellow*

"The photons which constitute a ray of light behave like intelligent human beings: out of all possible curves they always select the one which will take them most quickly to their goal."

Max Planck
Scientific Autobiography and Other Papers (1968)

Purpose

The "weirdness" and "mysteries" of quantum mechanics have been recognized for nearly a century. Advances in our understanding of this branch of physics occurring over the past two years suggest that there are fundamental features of quantum mechanics, specifically those related to the measurement of photons, that have been, somewhat surprisingly, under investigated until now. Anticipating the International Year of Light in 2015, the purpose of this symposium is to explore these and other foundational issues concerning the nature and effects of light as quantized photons, placing special attention on questions that are suitable for laboratory investigation using an optical approach, which is the preferred methodology for such studies. A specific goal will be to establish a comprehensive strategy, including specific experimental protocols, for addressing these basic measurement questions about quantum phenomena in light with the intention of formulating a major research initiative.

A very general working hypothesis of the proposed work is that it will lead to a more comprehensive understanding of quantum mechanics. While modern physics has learned to deal with numerous, highly counterintuitive features of quantum mechanics, including the concepts of entanglement, wavefunction collapse, the role of which-way information in quantum interference, quantum uncertainty, quantum indeterminism, local realism, interaction-free measurements, the Einstein-Podolsky-Rosen effect, Hardy's paradox, and Popper's thought experiment, two developments occurred over the past two years that presented the possibility of shedding new light on aspects of these enigmas even as they raised new questions.

The first was an experiment conducted by Ralf Menzel that proved an intriguing new addition to the literature on wave-particle duality. Dr. Menzel and his colleagues observed that they could seemingly violate a well-established tenet of quantum mechanics stating that quantum interference, of the sort that might be measured in a variant of Thomas Young's classic double-slit experiment, will disappear if an experiment can be performed to determine *which* opening the particle passed through. By making use of the strong correlations of entangled photon pairs, the Berlin-based physicists showed that if the two photons are entangled in position then the measurement of the position of one photon reveals the position of the other photon, and in this way one can determine through which opening in a barrier with two slits the photon has passed. But despite the fact that the experimentalist "knew" through which slit the photon passed, strong interference effects were observed in contradistinction to the prevailing view. Work currently in progress suggests that Dr. Menzel's results are in fact consistent with standard quantum mechanics. Nonetheless, this experiment provides yet another example of the strongly counterintuitive effects that can occur in quantum mechanics.

These experimental results lead immediately to questions to be addressed in the symposium: Do the interference effects persist because the position of the photon was not truly "measured" but rather deduced by means of the properties of entanglement? Can similar results be observed for other independent physical parameters, known as degrees of freedom, and other forms of entanglement? Could the nature of the measurement (weak versus strong, for instance, as in Lev Vaidman's interaction-free measurement experiment) influence the outcome of the experiment?

The second recent development involves work in quantum optics that challenges the generally accepted view that one cannot directly measure the wavefunction of a quantum particle, which could describe how a quantum system evolves over time, because a measurement of the function at one point will cause the entire wavefunction to "collapse." Or to put it differently, determining the quantum state of a photon requires knowledge of both its position and its momentum, but in the process of measuring the position of the photon, one would lose all knowledge of its momentum. Traditionally, scientists measure a quantum state by means of quantum-state tomography, which is an extremely time consuming procedure. Recently, however, an alternative procedure for the direct measurement of the photon wavefunction was proposed and, for the first time, implemented by J.S. Lundeen and his associates at the National Research Council of Canada. They performed a "weak measurement" on one degree of freedom (the position) followed by a "strong measurement" of the complementary degree of freedom (the momentum). Because the first measurement was performed in a gentle way using a method in which the measured system was very weakly coupled to the measuring device, it did not collapse the wavefunction, and thus the *momentum* could be measured with high accuracy. This procedure was then repeated many times to determine the *position* with high accuracy as well. Detailed analysis showed that this measurement procedure is much more time-efficient than tomography. In a series of experiments, Robert Boyd's research team at the University of Ottawa and the University of Rochester has recently extended the Lundeen method to allow the measurement of the state of a qubit, the fundamental unit of information in quantum information science, thereby providing a second example of a situation in which direct measurement can be used to determine a quantum wavefunction.

Follow-up questions flowing from this work include: Can these methods be applied to still other degrees of freedom and especially to complex systems described by a very large Hilbert space? And, more broadly: Can the direct measurement of the wavefunction, which has often been taken to be an abstract mathematical concept, lead to new conceptual understandings of the nature of quantum mechanics and its philosophical implications?

The probe for answers brings together twelve physicists and philosophers from eight countries, located on four continents, in Ottawa, Canada's capital city.

Approach

The symposium is part of the Templeton Foundation's *Humble Approach Initiative*. The goal of the initiative is to bring about the discovery of new spiritual information by furthering high-quality scientific research. The "humble approach" is inherently interdisciplinary, sensitive to nuance, and biased in favor of building linkages and connections. It assumes an openness to new ideas and a willingness to experiment. Placing high value upon patience and perseverance, it retains a sense of wondering expectation because it recognizes, in Loren Eiseley's haunting phrase, "a constant emergent novelty in nature that does not lie totally behind us, or we would not be where we are." A fundamental principle of the Foundation, in the words of its founder, is that "humility is a gateway to greater understanding and open[s] the doors to progress" in all endeavors. Sir John Templeton believed that in their quest to comprehend foundational realities, scientists, philosophers, and theologians have much to learn about and from one another. The humble approach is intended as a corrective to parochialism. It encourages discovery and seeks to accelerate its pace.

Chair

Robert W. Boyd, a leading scientist in the field of photonics, holds a Canada Excellence Research Chair in Quantum Nonlinear Optics at the University of Ottawa, where he directs a major research center. He is also a professor of physics and a professor of optics at the University of Rochester and holds a visiting professorship in the School of Physics and Astronomy at the University of Glasgow. Dr. Boyd's award-winning research focuses on nonlinear optical interactions and nonlinear optical properties of materials, as well as the application of nonlinear optics, including quantum and nonlinear optical imaging. A graduate of the Massachusetts Institute of Technology, he went on to study with Nobel laureate Charles H. Townes at the University of California, Berkeley, where he earned a Ph.D. in physics in 1977. He then joined the faculty of The Institute of Optics at Rochester. Promoted to a full professor in 1987, he was named the M. Parker Givens Professor of Optics in 2001 and appointed to the faculty of physics the following year. Dr. Boyd accepted his present position at the University of Ottawa in 2010. A fellow of the Optical Society of America (OSA) and of the American Physical Society (APS), he was the recipient in 2009 of the Willis E. Lamb Award for Laser Science and Quantum Optics. The prize recognizes his breakthroughs in manipulating light, notably, shooting a pulse of light into an optical fiber that departs before it enters and, within the fiber, travels backward and faster than the speed of light, thus demonstrating an effect predicted by equations describing the progression of waves. In 2010, Dr. Boyd was awarded the Humboldt Prize for Physics, an international award made in honor of a cumulative body of work. His research was selected by *Discover* as one of the top one hundred research stories in 2006—and one of only six from physics chosen by the science and technology magazine. He is a past chair of the Division of Laser Science of the APS and a former member of the board of directors of the OSA and the John Templeton Foundation. In addition to more than 350 papers published in scientific journals, Dr. Boyd is the editor (with M.G. Raymer and L.M. Narducci) of *Optical Instablities* (1986), (with Govind P. Agrawal) of *Contemporary Nonlinear Optics* (1992), and, most recently, (with Svetlana G. Lukishova and Y.R. Shen) of *Self-Focusing: Past and Present* (2009), a critical review of theoretical and experimental investigations of a non-linear optical process induced by change in the speed of light within materials exposed to intense electromagnetic radiation. He is also the author of *Radiometry and the Detection of Optical Radiation* (1986) and *Nonlinear Optics*, a highly-praised volume first published by Academic Press in 1992 and updated in 2008 in a new third edition. Dr. Boyd has been awarded nine U.S. patents.

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Anton Zeilinger

A philosopher of physics, **Harvey R. Brown**, **FBA**, is professor of philosophy at Oxford University and a fellow of Oxford's Wolfson College. His research interests include the foundations of quantum mechanics, relativity theory and thermal physics, the philosophy of space and time, and the role of symmetry principles in physics. He was educated at St. Bede's College in Christchurch, New Zealand, earned a bachelor of science degree with first-class honors in physics at the University of Canterbury (New Zealand), and took his Ph.D. in the history and philosophy of science at what is now King's College London in 1978. For the next six years he served as an assistant professor of philosophy at São Paulo State University at Campinas in Brazil. Dr. Brown was appointed a lecturer in the philosophy of physics at Oxford in 1984 and named a full professor in 2006. A fellow of the British Academy, he is co-winner of the 2006 Lakos Award in Philosophy of Science. He has been a Visiting Erskine Fellow and a Visiting Oxford Fellow at the University of Canterbury, as well as a long-term visitor to the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada. His research on the foundations of quantum physics has been supported by a Leverhulme Trust Institute Award, and he has been the recipient of a Radcliffe Research Fellowship in Philosophy. Dr. Brown is a past president of the British Society for the Philosophy of Science. The former secretary of the journal *Cadernos de História e Filosofia da Ciência* (Brazil), he is a member of the editorial advisory boards of *Studies in History and Philosophy of Modern Physics*, *International Studies in the Philosophy of Science*, *Principia* (Brazil), and *Physics in Perspective*. He has published more than fifty papers in academic journals, is the editor of two books, (with H. R. Harré) *Philosophical Foundations of Quantum Field Theory* (1988) and (with Simon Saunders) *The Philosophy of Vacuum* (1991), and the author of two others: *Albert Einstein: A Simple Man of Vision* (1984) and *Physical Relativity: Space-time Structure from a Dynamical Perspective*, a book published in 2005 by Oxford University Press that considers the explanatory role of the geometry of spacetime from a critical perspective.

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Avshalom C. Elitzur, a physicist and a philosopher, is the co-founder of *Iyar*, the Israel Institute for Advanced Research in Natural Sciences. Born in Iran and raised from early childhood in Israel, he had no formal training before earning a Ph.D. in physics and philosophy of science from Tel-Aviv University in 1999, under the guidance of Yakir Aharonov. Since then, he has taught at universities in Israel, France, and India. Dr. Elitzur is best known for a thought experiment that he proposed with Lev Vaidman in 1993, which was later realized in several laboratories. Referred to as IFM (Interaction-Free Measurement) or the bomb-testing problem, it illustrates the observability of quantum counterfactuals, which obliges even an event that *might* have happened but *did not* (e.g., the detonation of bombs as a result of photons triggering sensors) must have measureable consequences. Later he formulated with Shahar Dolev and Anton Zeilinger the so-called "quantum liar paradox" (an EPR experiment where one particle's state indicates non-entanglement with the other one while this very outcome is due to entanglement). Together with Yakir Aharonov and Eliahu Cohen, he has proposed the "future-anticipating EPR" (an EPR experiment where weak measurements preceding the strong ones "anticipate" the experimenter's future choice of measurement) and, with Eliahu Cohen, the "quantum oblivion effect"— a feasible experiment where two particles undergo subtle interaction such that one of them carries its effects while the other remains totally unaffected, in apparent contradiction with Newton's third law. This effect is believed to underlie several quantum peculiarities. His current areas of research range from quantum nonlocality, to special and general relativity, and the applications of thermodynamics and information theory to the study of living systems. In addition to research in quantum physics, Dr. Elitzur has written on several foundational issues in philosophy of mind and psychology. He has published more than sixty papers in scientific journals. A paper (with Haim Omer) on suicide prevention ("What would you say to the person on the roof?") has been warmly greeted by mental health professionals and several translations of it are available on the web. Co-editor of six books, including, most recently, (with Alexander Batthyána) *Mind and Its Place in the World* (2006) and (with Alexander Batthyána) *Irreducibly Conscious: Selected Papers on Consciousness* (2009), he is also the author of two books in Hebrew, a 1987 volume offering psychological insights into the Bible and Judaism and another, published in 1994, on time and consciousness.

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A physicist who also serves as a leader of big research initiatives, **Elisabeth Giacobino** is CNRS Research Director of the Laboratoire Kastler Brossel, a joint research institute of the École Normale Supérieure de Paris, the Université Pierre-et-Marie-Curie, and the Centre National de la Recherche Scientifique (CNRS). She became widely known for her expertise in quantum optics, nonlinear optics, and quantum information after early work concerned with laser spectroscopy. In 1987, Dr. Giacobino demonstrated for the first time that an optical parametric oscillator could be used to “squeeze” a pair of photons or so-called “twin beams” of light. Using a cloud of laser-cooled atoms, she proposed a new method for generating squeezed light in 1995, and, in 2003, of generating entangled beams of light. Recently, after demonstrating the capability of vapors to store quantum states of light, she began work on the development of a quantum memory register based on a cold atom cloud. Another line of her research concerns semiconductor systems of critical importance in information-processing technology. Recently with her team, she demonstrated quantum fluid properties, such as superfluidity, in semiconductor microcavities. A graduate of the École Normale Supérieure, she received a Ph.D. in physics and optics from the University of Paris IV in 1976. She had joined CNRS as a researcher in 1969, became a senior research fellow in 1982, and was named head of the Laboratoire Kastler Brossel in 1999. She served as director of the CNRS Department of Physics and Mathematics from 2001 to 2002. She was then appointed as the general director for research at the French Ministry of Higher Education and Research, where she served from 2003 to 2006. She currently chairs the Institut d’Optique in Palaiseau and serves as president of the Scientific Council of the City of Paris. She was formerly a member of the European Commission’s Information Society Technology Group and served as chair of the European Research Council’s Panel for Physics. Dr. Giacobino is a member of Leopoldina, which is the German National Academy of Sciences, and has been awarded the Fabry-de-Gramont Prize (1990), the Félix-Robin Prize (2010), and the Gay Lussac-Humboldt Prize in Physics (2012). The author of some 180 scientific papers, she is the editor (with Serge Reynaud and J. Zinn Justin) of *Quantum Fluctuations* (1997).

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Andrew N. Jordan is an associate professor of physics at the University of Rochester whose research interests include theoretical quantum physics, condensed matter physics, and quantum optics. He has worked on the theory of quantum measurement, quantum information, and random processes in nature as well as nanophysics. His most recent investigations tracked the continuous random path of a superconducting system's quantum state as the state changed during measurement, a feat that opens up the possibility of steering quantum systems into desired states. He also has described how it is probabilistically possible to restore an unknown state that has been disturbed by a generalized measurement to its initial configuration, thus theoretically "uncollapsing" wavefunction by undoing quantum measurement. Dr. Jordan is a *magna cum laude* graduate of Texas A&M University with an honors degree. After earning a Ph.D. in theoretical physics at the University of California, Santa Barbara, in 2002, he did postdoctoral research at the University of Geneva, where he worked with the late Markus Büttiker, then returned to Texas A&M as a research scientist working with Marlan O. Scully. He joined the physics faculty at Rochester as an assistant professor in 2006 and was appointed to his present position two years ago. The recipient of a National Science Foundation (NSF) Career Young Investigator Award, he also won an award for excellence in undergraduate teaching from Rochester. Dr. Jordan served as guest editor of the *Journal of the Optical Society of America B* special issue on quantum optical information technologies in 2010. He is the author of some 60 papers published in scientific journals.

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A professor of physics at the University of Erlangen-Nuremberg, **Gerd Leuchs** is the founding director of the Max Planck Institute for the Science of Light (MPL). His wide-ranging research includes modern aspects of classical optics, quantum optics, and quantum information. A particular focus has been on soliton pulses in optical fibers, on quantum cryptography with intense coherent light beams, and on time reversal symmetry in optics. Dr. Leuchs studied mathematics and physics at the University of Cologne and was awarded a Ph.D. in physics from the University of Munich in 1978. After working as a research associate at Munich, he went to the United States, first as a visiting fellow and then as a German Research Council Heisenberg Fellow, for post-doctoral research at JILA (formerly the Joint Institute for Laboratory Astrophysics), a joint physics institute of the University of Colorado at Boulder and the (U.S.) National Institute of Standards and Technology. He became head of the German Gravitational Wave Detection Group at the Max Planck Institute in Garching, Germany, in 1985. Four years later, he was appointed technical director of Nanomach AG in Buchs, Switzerland, a post he held until 1994 when he was named to a professorship at Erlangen-Nuremberg. He served as director of the Max Planck Research Group for Optics, Information, and Photonics there from 2003 to 2008, and the next year was named head of the new MPL. Since last summer, he has been a visiting professor at the University of Ottawa. A member of Leopoldina, which is the German National Academy of Sciences, Dr. Leuchs is a fellow of the Optical Society of America, of the Institute of Physics, and of the European Optical Society. He is the 2005 recipient of the Quantum Electronics and Optics Prize of the European Physical Society. He has published more than 200 papers in scientific journals and edited two books, including (with Thomas Beth) *Quantum Information Processing* (2003; revised edition 2005) and (with Dagmar Bruss) *Lectures on Quantum Information*.

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Gerard J. Milburn, professor of physics at the University of Queensland in Brisbane, serves as the founding director of the new Australian Research Council Centre of Excellence in Engineered Quantum Physics (EQuS), a multi-institutional collaborative dedicated to using quantum theory to develop new scientific insights and fundamentally new technical capabilities across a range of disciplines. His current research is focused on quantum nanomechanics and superconducting circuit quantum electrodynamics, which provides a means of studying the fundamental interaction between light and matter. He also has worked in the fields of quantum optics, quantum measurement and stochastic processes, atom optics, quantum chaos, mesoscopic electronics, quantum information, and quantum computation. A graduate of Griffith University in Brisbane, where he took first class honors, he earned a D.Phil. in physics in 1983 at the University of Waikato in New Zealand. Dr. Milburn then spent two years as a research assistant at Imperial College, London, where he held an Elizabeth Challenor Royal Society Research Fellowship. He returned to Australia in 1985 to take up a lectureship in theoretical physics at The Australian National University and was appointed an associate professor of physics at Queensland in 1988. He was named a professor of physics in 1996, and four years later became the deputy director of Queensland's Centre for Quantum Computer Technology. He accepted his present position in 2011 with the founding of EQuS by five Australian universities. Dr. Milburn has been a visiting professor at the University of Melbourne and at the National Institute of Informatics in Tokyo, and he currently holds a visiting professorship at Oxford University. A fellow of the Australian Academy of Science (AAS) and of the American Physical Society, he is the recipient of the Moyal Medal for Mathematical Physics, the Boas Medal of the Australian Institute of Physics, and the 2010 International Quantum Communication Award. He has served as chair of the AAS's National Committee for Physics and its National Committee for Spectroscopy, chair of the International Advisory Board of the Pacific Institute of Theoretical Physics, and chair of the Scientific Advisory Board of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada. He is the editor-in-chief of the *Journal of Quantum Technology* and currently serves on the editorial boards of *The New Journal of Physics* and *Open Systems and Information Dynamics* and as an associate editor of the *Journal of Quantum Information and Computation.*
Dr. Milburn has published more than 220 papers in scientific journals and is the author of four books: (with D.F. Wells) *Quantum Optics* (1994; revised edition, 2008), *Quantum Technology* (1996), which was published in the United States in 1997 as *Schrodinger's Machines*, *The Feynman Processor* (1998), and, most recently, (with Howard M. Wiseman) *Quantum Measurement and*

Control, the first comprehensive treatment of subjects essential to realizing quantum technology, which was published in 2010 by Cambridge University Press.

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Professor of theoretical physics and director of the Institute of Quantum Physics at the University of Ulm, **Wolfgang P. Schleich** is engaged in research on the foundations of quantum physics, as well as on quantum mechanics in relation to general relativity and to number theory. His most recent work includes elaborations on the role of the Wigner function, a mathematical object called a quasi-probability distribution, in terms of quantum optics.

Dr. Schleich was educated at Ludwig-Maximilians-Universität (LMU) in Munich. He studied with Marlan O. Scully, first at the Max Planck Institute for Quantum Optics in Garching, Germany, and then at the Institute for Modern Optics at the University of New Mexico, and was awarded his Ph.D. in physics by LMU in 1984. After postdoctoral research with John A. Wheeler at the Center for Theoretical Physics at the University of Texas at Austin, he returned to the Max Planck Institute for Quantum Optics where he worked as a research scientist with Herbert Walther for five years and received his Habilitation from LMU in 1989. Dr. Schleich was named to his present position in 1991. A member of the Academia Europaea, Leopoldina, which is the German National Academy of Sciences, and the Heidelberg Academy of Sciences and Humanities, he is a corresponding member of the Austrian Academy of Sciences and of the Royal Danish Academy of Sciences and Letters, as well as a fellow of the European Optical Society, the American Physical Society, the Institute of Physics, and the Optical Society of America. He is the recipient of the 1991 German Physical Society Prize, the 1992 Ernst Abbe Medal of the International Commission for Optics, the 1995 Gottfried Wilhelm Leibniz Prize given by the German Research Foundation, the 2002 Max Planck Research Award, the 2007 First Class Medal of the Czech Technical University in Prague, and the 2008 Willis E. Lamb Award for Laser Science and Quantum Optics. Dr. Schleich has been a Distinguished Adjunct Professor at the University of North Texas and is currently a faculty fellow at Texas A&M University's Institute for Advanced Study. The organizer or co-organizer of some thirty-five international conferences, he has served as chair of the Quantum Optics Division of the German Physical Society and as vice president of the Heidelberg Academy of Sciences and Humanities. He currently serves on the advisory board of the Wilhelm and Else Heraeus Foundation. A member of the editorial board of *Progress in Optics* and the editor of eleven special issues of scientific journals, he is the author of more than 320 papers published in scientific journals or in volumes of collected works. He is the co-editor of seven books, including (with Wolfgang Arendt) *Mathematical Analysis of Evolution, Information, and Complexity* (2009), (with Ennio Arimondo, Wolfgang Ertmer, and Ernst Rasel) *Atom Optics and Space Physics* (2009), and (with Helmut Maier) *Prime Numbers 101: A Primer on Number Theory*, forthcoming in August 2014 from Wiley-Interscience. His textbook, *Quantum Optics in Phase Space*, published in 2001 by Wiley-VCH, has been translated into Russian and a Chinese edition was published in 2010.

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John E. Sipe is a professor of physics at the University of Toronto whose work focuses on quantum aspects of the interaction of light with matter. His research interests include classical and quantum nonlinear optical phenomena in artificially structured materials, linear and nonlinear optical properties of bulk semiconductors, quantum wells and superlattices, polarization effects in soliton propagation, solitons in periodic media, effects of quantum coherence and the emergence of classical behavior, and the foundations of macroscopic electrodynamics. A *summa cum laude* graduate of Brown University where he earned an honors baccalaureate degree, he took a master's degree in physics at the University of Waterloo and received a Ph.D. in physics from Toronto in 1975. After spending a year as a science don at Trinity College, Toronto, he became a research associate at Erindale College, Toronto, in 1979 and joined the physics faculty of Old Dominion University two years later. Dr. Sipe returned to Toronto as an assistant professor of physics in 1981, serving two years as the C.A. Ashley Fellow at Trinity College, Toronto, and was named to his present position in 1990. He is a fellow of the Optical Society of America, the American Physical Society, and the Royal Society of Canada. His research has been supported by grants from the National Science and Engineering Research Council of Canada. The author of more than 275 papers published in scientific journals or as chapters in volumes of collected works, Dr. Sipe is writing a book (with Robert Spekkens) on interpretations of quantum mechanics for Oxford University Press.

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Hooke Professor of Experimental Physics at Oxford University, **Ian A. Walmsley, FRS** serves as Oxford's pro-vice-chancellor for research, academic services, and university collections. His contributions to the fields of quantum optics and ultrafast optics include pioneering experimental work in areas as diverse as quantum state tomography and ultrashort pulse characterization. The impact of Dr. Walmsley's research ranges across domains from coherent control of complex quantum systems to quantum information processing. In particular, he has developed methods and concepts applying ultrashort light impulses to the study of non-classical phenomena in both atomic and optical physics. His widely used methods for the characterization of both quantum and classical wave fields have had broad implications for dynamical spectroscopy and quantum state measurement amongst many key areas of theoretical and practical research. A graduate of Imperial College, London, Dr. Walmsley earned a Ph.D. in optics from the University of Rochester. He did postdoctoral research at Cornell University before returning to Rochester, where he joined the faculty of the university's Institute of Optics in 1988 as an assistant professor. He was named a full professor ten years later and, in 2000, appointed director of The Institute of Optics. He moved on to Oxford the next year as professor of experimental physics. In 2002, he was appointed head of Atomic and Laser Physics at Oxford's Clarendon Laboratory. Dr. Walmsley was named to his present academic chair in 2005, became pro-vice-chancellor for research in 2009, and took on expanded university-wide administrative responsibilities for the Bodleian Library and Oxford's museums and Botanic Garden in 2011. He has been a visiting professor at the University of Ulm and a senior visiting fellow at Princeton University. Elected a Fellow of The Royal Society in 2012, he is also a fellow of the Optical Society of America, the American Physical Society (APS), and of the Institute of Physics (IP) as well as a fellow of St. Hugh's College, Oxford. He has been awarded honorary degrees from the Université Libre de Bruxelles and Université Paul Sabatier in Toulouse. Among other honors are a National Science Foundation Presidential Young Investigator Award, two teaching awards from the University of Rochester, the Wolfson-Royal Society Research Merit Award, the APS's J.F. Keithley Award, and the IP's Young Prize and Medal. A member of the board of reviewing editors of *Science* and the editorial boards of *Annalen der Physik*, the *Journal of Modern Optics*, and the *Journal of Physics B*, Dr. Walmsley is the author of more than 250 papers published in scientific journals or as chapters in volumes of collected works and the editor of five books and special issues of journals, including (with Ferenc Krausz, Georg Korn, and Paul Corkum) *Ultrafast Optics IV*, which was published in 2004 by Springer-Verlag. He holds five U.S. and three European patents, which are licensed to APE GmbH.

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William K. Wootters, Barclay Jermain Professor of Natural Philosophy at Williams College, is a leading contributor to the field of quantum information theory. With Wojciech Zurek, he proved the no cloning theorem of quantum mechanics, which holds that an arbitrary unknown quantum state cannot be copied, a prohibition with profound implications for quantum computing. He also has discovered quantum rules governing the entanglement of quantum objects and has worked on the quantification of entanglement. Among the other advances to which he has contributed is the recognition that quantum states can be teleported, a possibility that has now been confirmed in many experiments. A graduate of Stanford University, Dr. Wootters earned a Ph.D. in physics at the University of Texas at Austin (UTA) in 1980. He did post-doctoral research with John A. Wheeler at UTA's Center for Theoretical Physics then joined Williams's physics department as an assistant professor in 1982. He was promoted to full professor in 1994 and named to his present chair in 2002. Dr. Wootters has been a visiting research associate at UTA's Center for Theoretical Physics, a visiting associate professor at the Santa Fe Institute and collaborator at the Center for Nonlinear Studies at the Los Alamos National Laboratory, an invited researcher at the University of Montreal, a collaborator at the IBM Watson Research Center, a visitor at the Isaac Newton Institute at Cambridge University, a visitor at the Institute for Theoretical Physics at the University of California, Santa Barbara, and a visiting professor at the Perimeter Institute in Waterloo, Ontario, Canada. A fellow of the American Physical Society (APS), he is a recipient of APS Prize to a Faculty Member for Research in an Undergraduate Institution, as well as the winner of the 2006 International Quantum Communications Award. He is a former member of the editorial board of *Physical Review A* and a former associate editor of *Physical Review Letters*. He currently serves on the editorial advisory board of the *American Journal of Physics*. The author of some sixty-five papers published in scientific journals and in volumes of collected works, Dr. Wootters is the author (with Susan Loepp) of *Protecting Information: From Classical Error Correction to Quantum Cryptography*, which was published in 2006 by Cambridge University Press.

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William K. Wootters
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One of the world's leading researchers in the foundations of quantum mechanics, **Anton Zeilinger** is professor of physics at the University of Vienna and president of the Austrian Academy of Sciences (AAS). He served as scientific director of the AAS's Institute of Quantum Optics and Quantum Information from 2004 to 2013. His pioneering investigations of multi-particle entanglement received international attention in 1997 when he and his colleagues at the University of Innsbruck, where he was then directing the Institute of Experimental Physics, confirmed the possibility of quantum teleportation by demonstrating, through the use of pairs of entangled photons, that the information carried by one particle can be instantly transferred to another over an arbitrary distance. Dr. Zeilinger's quantum interference experiments with "buckyballs" (molecules whose shapes resemble the geodesic domes designed by R. Buckminster Fuller), at that time the largest objects to have demonstrated quantum behavior, have attracted the attention of the scientific community. By proving that clusters of more than one hundred atoms obey quantum-mechanical rules, he has extended the quantum domain further than ever before. More recently, he has focused his interest in tests of quantum nonlocality and entanglement to novel systems like photons carrying high angular momenta. He is also interested in establishing quantum communication on a global scale. In addition, he investigates fundamental phenomena in quantum entanglement of ultra-cold atoms amongst other scientific problems. Dr. Zeilinger studied at the University of Vienna and earned a Ph.D. in physics and in mathematics in 1971. After a lectureship at the Technical University of Vienna, a Fulbright fellowship at the Neutron Diffraction Laboratory of the Massachusetts Institute of Technology, and professorial positions at MIT, the Technical University of Vienna, and the University of Innsbruck, he accepted his present professorship in 1999. Dr. Zeilinger has been a visiting professor at the University of Melbourne, the Technical University of Munich, and the Collège de France, as well as an adjunct professor at Hampshire College in Amherst, Massachusetts, a visiting research fellow at Merton College, Oxford University, and a senior Humboldt fellow at Humboldt University in Berlin. His long list of honors include the Senior Humboldt Fellow Prize, Germany's Order pour le Mérite, the 2000 Science Prize of the City of Vienna, the 2005 King Faisal Prize, the Isaac Newton Medal of the British Institute of Physics, the 2010 Wolf Prize in Physics, and the 2013 Urania Medal. Dr. Zeilinger is a foreign associate of the National Academy of Sciences, a fellow of the American Association for the Advancement of Science and of the American Physical Society, a member of the Academia Europaea, an honorary member of the Slovak Academy of Sciences, a foreign member of the Serbian

Academy of Sciences, an honorary professor of the University of Science and Technology of China, and a former member of the board of advisors of the John Templeton Foundation. The author of more than 450 papers published in major scientific journals, he is the editor (with Dirk Bouwmeester and Artur Ekert) of *The Physics of Quantum Information* (2000), (with Reinhold Bertlmann) of *Quantum [Un]speakables: From Bell to Quantum Information* (2002), and (with Chiara Macchiavello and G. Massimo Palma) of *Quantum Computation and Quantum Information Theory* (2001). He is also the author of three books, *Einstein's Schleier* (2003), *Einstein's Spuk* (2005), and *Dance of the Photons*, which was published by Farrar, Straus and Giroux in 2010. Mindful of the practical applications of his research for the processing and transmission of information, including quantum teleportation, quantum cryptography, and quantum computing, Dr. Zeilinger is also intrigued by the epistemological implications of quantum physics. He has met with spiritual leaders, including the Dalai Lama and the late Cardinal Franz Koenig, to discuss epistemological and conceptual issues and has challenged his scientific colleagues to consider which notions appearing distinct and even opposed today will turn out to be so for future generations.