A coherent life

Emil Wolf died in June 2018 at the age of 95. The father of optical coherence theory was at the University of Rochester for nearly 60 years. A memorial in August at the university attracted more than 150 attendees from around the world.

P. Scott Carney and Joseph Eberly

Emil Wolf, who joined the University of Rochester in 1959 and was the Wilson professor of optical physics and professor of optics, made an enormous, sustained and lasting impact in optics (Fig. 1). He published over 400 papers across eight decades and edited 60 volumes of the book series *Progress in Optics*. This is impressive certainly, but doesn't explain why he is seen as a genuinely transformative figure. A glance through textbooks of optics written in the three decades of the 1930s through the 1950s gives the impression of a field characterized by rules of thumb, descriptions of instruments, ancient accomplishments, and no significant future, either theoretical or technological, beyond photography. Today, one easily says that in 1960 the laser remade optics, opening an entirely fresh landscape to explore. But Wolf got there first. He was already making optics into a discipline of fundamental science in the 1950s. The book *Principles of Optics*^{1,2}, which Wolf co-authored with Max Born (Nobel Prize winner perhaps best known for contributions to the foundation of quantum mechanics), has long been standard reading for students of physics and researchers in optics alike.

Wolf's breakthrough conception was a balance between two partly contradictory observations — the certainty that optics was not radiometry, meaning that light was primarily, fundamentally, about optical fields, not optical beams, and the realization that the optical field was not itself observable, presenting oscillations much too rapid to be followed by any known detector. All of optics then represented a challenge to find how light could be field-based but observable.

Wolf showed the challenge could be met with field correlation functions. His understanding of the powerful role correlations play and the way they underlie all of observable optics led to a series of seminal publications, one titled 'Optics in terms of observable quantities' published in 1954³. This paper provided the principle that unified a disorganized zoo of correlation effects and parameters of optics. In one

Fig. 1 | Emil Wolf (1922–2018), who co-authored the famous book *Principles in Optics* with Max Born and made major advances in the field of optics including diffraction, coherence, spectroscopy and scattering, is pictured here on a street in April 1950 with Ann Ward (whom he married in 1951). Credit: Image courtesy of Bruno Wolf

stroke, classical coherence theory emerged, crystal clear.

Born to Jewish parents Josef and Pavla Wolf in Prague in 1922, Wolf became a refugee at the age of 16 following the 1939 Nazi invasion of Czechoslovakia. He made his way illegally from Prague to Paris where he found work with the Czech government in exile. When Paris fell, he was evacuated along with the Czech government officials to London. The evacuation was made in extremis and decades later Wolf would take care to credit Julius Firt, a Czech journalist also with the government in exile, for

saving his life with a 3 am phone call to come get on the truck leaving Paris. With the exception of his brother Karel and one cousin, none of his extended family survived the Holocaust.

As a refugee in Britain, Wolf finished high school and attended Bristol University on scholarship where he earned a BSc in mathematics and physics and a PhD in mathematics (Fig. 2). His advisor, E. H. Linfoot, was soon named director of the Cambridge Observatory and Wolf followed him as a post-doc to Cambridge.

In Cambridge, Wolf would travel to London for meetings of the Optical Society where he met both Leonard Mandel and Dennis Gabor, then at Imperial College London. Gabor and Wolf were fast friends. Holography would eventually make an appearance in *Principles of Optics*. Wolf would maintain an interest in the information carried by scattered fields for the rest of his career, perhaps most famously leading to his paper 'Three-dimensional structure determination of semi-transparent objects from holographic data' in 1969⁴, a field that would come to be called diffraction tomography.

When Max Born approached Gabor for suggestions for a co-author for his book on optics, Gabor introduced Wolf. This led to a move to Edinburgh and a collaboration between Born and Wolf that would produce *Principles of Optics*^{1,2}. Born initially had some reservations. He had previously had an assistant, Klaus Fuchs, who turned out to be an atomic spy. Wolf would say that Born probably had to question whether he should hire a Wolf after a fox. Nonetheless, Gabor's recommendation won through and a collaboration began that would indelibly mark the world of optics, and would be treasured by Wolf for the rest of his life.

When Born retired and moved back to Germany, Wolf moved to the University of Manchester, held a series of teaching positions and had some support under an Imperial Chemical Industries (ICI) Fellowship. During this period, Wolf would do some of his most impactful work. He made a new formulation of the focusing

Fig. 2 | A graduation portrait of youthful Emil Wolf, probably taken on 29 June 1945 when he received his BSc in mathematics and physics from Bristol University. Credit: Image courtesy of Bruno Wolf

problem that would take into account energy conservation, polarization and the real shape of lenses. The results were published in the *Proceedings of the Royal Society of London*^{5,6} and the second paper, with a student, Bernard Richards, is still referred to by practitioners simply as ‘Richards and Wolf’. It remains his most cited journal paper. Also in Manchester, in 1954, he published in *Il Nuovo Cimento* his famous paper on coherence theory and optical observables³.

Wolf’s accomplishment in coherence theory was noted by many, including Henry Lipson and his assistant Brian Thompson. Thompson had designed an instrument to determine crystal structure from diffraction patterns, but the results were slightly off. They suspected the discrepancies were related to coherence and, indeed, Wolf was able to account for the observations and even predict — correctly — that the pinhole in their system was not quite the size the supplier claimed. Thus began a collaboration and long friendship that would eventually see Thompson at the University of Rochester and the Institute of Optics, as director, then dean of the School of Engineering, and then provost.

Throughout the Manchester period, Wolf was working on *Principles of Optics*. What was originally supposed to be a collaborative effort among a large cast of authors had dwindled to a few contributed chapters and the remainder largely fell to the younger author to fill in. At one point in 1958, anxious to see the book come out

after years of work, Born asked Wolf what was taking so long. Wolf explained he was working on an exposition of coherence theory. According to Wolf, Born responded “Wolf, who in the world apart from you is interested in coherence theory?”

Wolf prevailed on him to wait for the chapter to be done and shortly after the publication of the book, the arrival of the laser ensured that many people were indeed very interested in coherence theory. Six more editions and nearly 60 years later, they still are. The transition of the book’s publisher from Pergamon¹ to Cambridge² was a minor triumph Wolf liked to recall. He had discovered that Pergamon, under Robert Maxwell, had been cheating them by a miscounting of sales. Cooperating with Born’s son in London, Wolf brought suit in Britain, fought Maxwell in court, and won.

Robert Hopkins, director of the Institute of Optics at the University of Rochester also noticed Wolf’s work in coherence. Hopkins wanted to build strength in the area and was on his way to England for a conference. Wolf’s ICI Fellowship was running out and he was anxious to find a position. Hopkins wrote asking for a meeting, but the meeting nearly didn’t happen. The letter from Hopkins got misfiled by a secretary and was only discovered by Wolf as he was searching for a missing chapter of *Principles of Optics* also misplaced by the same secretary. Recalling the events⁷, he said, “It was all a matter of luck, particularly that phone call in Paris at three in the morning saying to get on the lorry, the truck. It just shows you how much luck there is in life. First to get out of Paris and then to get to America.” Of course, the meeting did happen and he came to the Institute the next year.

Shortly after arriving in Rochester, he took a joint appointment with the physics department and recruited his friend Mandel. In 1965, in *Reviews of Modern Physics*, they published ‘Coherence properties of optical fields’, bridging classical, semiclassical and quantum optical theories of coherence and statistical optics⁸. The two of them would go on to many fruitful collaborations culminating in their brilliant book⁹. They could never quite agree to settle on Gaussian or SI units and, emblematic of a friendship that was ascendant over such petty differences, they simply used both.

That collaboration also brought about the Rochester Conference on Coherence and Quantum Optics (CQO). Since 1960, CQO has been a venue where fundamental issues of coherence and quantum mechanics get to be announced, discussed and sometimes settled. The 10th CQO, held in 2013, opened with a retrospective account by Wolf, and its first scientific session

celebrated the 50th anniversary of the famous Jaynes–Cummings paper published in 1963¹⁰. The 11th CQO is being prepared for summer 2019.

In the 1970s, Wolf brought the machinery he had developed for coherence theory to bear on radiometry. He provided the foundations of radiometry and a means to generalize it to arbitrary sources and states of coherence. With Girish Saran Agarwal, he made significant inroads in quantum optics and the mathematical underpinnings of a statistical optical field theory. In the 1980s, he identified a mechanism for shifts of spectral lines other than the Doppler shift, culminating in his 1987 paper ‘Non-cosmological redshifts of spectral lines’¹¹. This so-called Wolf shift was observed and posed as a possible mechanism for anomalous spectral shifts in certain astronomical observations.

Wolf continued to produce notable work throughout the 1990s and 2000s. One of the authors of this Comment, P.S.C., was a graduate student in his group in the mid-1990s. Wolf was remarkable as an advisor for many reasons, the most remarkable of which was his accessibility. His students saw and interacted with him at length every day. We would usually have coffee or lunch with him and this would sometimes stretch well into the afternoon, talking together about the science we were working on and where we were going with it.

Long-time colleague and collaborator Taco Visser recalled at the memorial a classic reaction to a negative referee report. Wolf began going through all the things that were wrong with the report, becoming more and more vehement, his tone rising, going to the blackboard and flourishing chalk on slate. Finally, Visser said, “Emil, we’ll respond, there’s no need to be so upset,” to which Wolf replied in total calm, as though revealing something he thought was understood, “But Taco, I ‘want’ to be upset.” His passion for science was intentional and joyous, even in disagreement.

Over his long and illustrious career, some 30 students completed their PhDs under Wolf. Many have gone on to successful research careers in academia while others have succeeded in industry. All were impressed with the importance of clearly communicating ideas and the joys of collegial argument. Well beyond his own group, he deeply affected many students’ lives and careers simply by being available, interested and generous. Right to the end, his was a well-known face at student events of the Optical Society of America, a society for which he served as 1978 president. His impact in the community will be felt for generations. □

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Published online: 26 October 2018

<https://doi.org/10.1038/s41566-018-0287-0>

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