CHAPTER 1

GUIDE, PHILOSOPHER, AND FRIEND

Brian J. Thompson

Emil Wolf, "Thou wert [and art] my guide, philosopher, and friend."*

1.1 Introduction

Having good mentors during the graduate student years and in the early-career professional experience provides a major stimulus to a productive life as a scholar and teacher. Our international university doctoral and postdoctoral programs are at their best when they fully integrate research, educational, and teaching opportunities so that intellectual development and scholarship go hand-in-hand with clear insight, exposition, and formal teaching.

In my own case I was blessed with three major mentors. The first was Prof. Henry Lipson, Chairman of the Physics Department in the Faculty of Technology of the University of Manchester [UMIST—University of Manchester Institute of Science and Technology, as it is now called]. I had been an undergraduate in Lipson's department, graduating in 1955. Before I entered this program I had served for two years in the British Army in the Royal Electrical and Mechanical Engineers, where I had the opportunity to learn as a technician about radar systems and predictors (i.e., early single-function electronic computers).

Immediately upon graduation with my bachelor's degree, I entered the doctoral program at UMIST and continued to have Henry Lipson as a mentor and acquired my second mentor—Dr. Charles Taylor, who was my thesis advisor. My third mentor was Dr. Emil Wolf, who came into my life in late 1955.

* Alexander Pope, "An Essay on Man," Epistle iv 1.389

1.2 Manchester 1955–1959

Both Lipson and Taylor were x-ray crystallographers with a deep interest in developing optical analog to x-ray diffraction and the analog computing opportunity that this optical approach provided. This matched my own interest in optical science and its applications. Thus, I had access to the optical diffractometer, the relatively new device that had been developed starting in 1949 [5,6,17,19].

The optical system of the diffractometer is shown in Fig. 1. The source was a high-pressure mercury arc operated with one of the hot-spots in the arc imaged onto a pinhole at S_1. The light emitted by this effective secondary incoherent

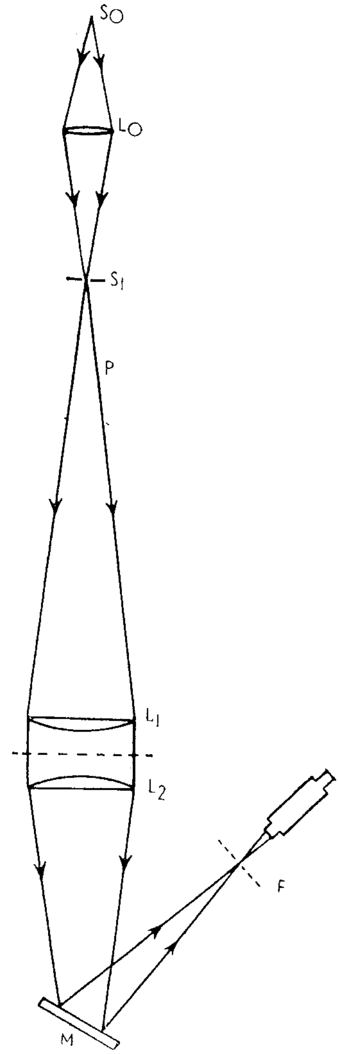

Figure 1 Schematic diagram of the optical diffractometer.

source was collimated by lens L_1, a 5-foot focal length telescope lens. The diffracting object was placed between lens L_1 and L_2 (a matching 5-foot focal length telescope objective lens) and the diffraction pattern was formed in the focal plane of L_2, where it was observed, recorded, and measured. Figure 2 shows an old photograph of the lower half of the diffractometer that was mounted on a vertical I-beam—I-beams and H-beams became quite popular later on for long optical benches.

My initial tasks were to fully characterize this instrument and its performance and solve a number of specific problems of optical and mechanical alignment, focusing, resolution, and coherence control. Clearly it was very important to think about this basically simple system in terms of its expected performance as a generator of diffraction patterns of planar two-dimensional binary objects (i.e., a diffracting mask containing circular holes laid out in various specific geometries). For example, Fig. 3 shows in (a) a representation of a projection of a molecule of hexamethylbenzene in which each atom in the molecule is represented by a circular hole; (b) shows the diffraction pattern of (a). It is relatively easy to recognize the symmetry relationships and see the reciprocal diffraction structure of the original benzene ring. Quantitative positional information is readily available. Figure 4 shows a much more complicated arrangement of holes representing part of the projected structure of deoxyribose nucleic acid and its corresponding diffraction pattern.

Making a quantitative analysis of the performance of the optical diffractometer and interpreting the relatively complicated and detailed diffraction patterns required a significant knowledge of the coherence properties of the illumination of the diffracting mask. Thus, I studied the papers of Zernike, van Cittert, H.H. Hopkins, and most particularly the writings of Emil Wolf, I also reread the work of Michelson on the stellar interferometer. I could not believe my good fortune in finding that Dr. Wolf was a resident in Manchester as a Research Fellow in the Theoretical Physics Department at Owens College of the University of Manchester, having arrived there the previous year (1954). Thus, my third major mentor, Emil Wolf, became a significant influence in my life and my work starting in 1955. Our relationship and friendship have continued over the intervening years and I am pleased to say exists today (I should also note that my professional and social relationship with Henry Lipson and Charles Taylor continued throughout their lives).

Emil Wolf was born in Prague, Czechoslovakia, almost exactly 10 years before I was born in Glossop, England. I believe he came to England as a teenager and then entered Bristol University in 1941, receiving his B.Sc. degree in 1945 and his Ph.D. in 1948; these degrees were in mathematics and physics. He then went to Cambridge University as a postdoctoral fellow (1948–1951), next moved to Edinburgh University and spent a period of several years as a University lecturer and

CHAPTER 2

RECOLLECTIONS OF MAX BORN

Emil Wolf

At the request of the organizers of the SPIE International Symposium on Optical Science and Technology, which was held in San Diego, CA on 3–8 August 2003, I gave an after-dinner speech at the Symposium Banquet. I spoke about my collaboration with Max Born, a halfcentury earlier. The talk followed closely an article that was originally published in *Optics News* **9**, 10–16 (1983) and is reprinted below.

The editor of this volume, Dr. Tomasz Jannson, asked me to add some remarks about the early days of holography and coherence that might be of special interest to the reader. The brief remarks that follow were written in response to this request.

Max Born knew well the inventor of holography, Dennis Gabor, and because of it, we learned about Gabor's invention long before the great discovery became generally known and appreciated. In fact, *Principles of Optics* was, I believe, the first book in which the principles of holography were explained. Gabor was very pleased that our book presented an account of his invention, as will become evident on reading the article that follows.

The subject of coherence was, at the time of my collaboration with Max Born, in its infancy. I became aware of it when I was working on the chapter concerning interference for our book. The theory of interference, as described in optics textbooks of that time, dealt mainly with monochromatic waves, not with wavefields that randomly fluctuate. These more complicated waves, which, in general, are partially coherent, can be adequately described only in statistical terms. While attempting to develop in our book a more satisfactory treatment of interference by using elementary statistical concepts, I was able to introduce a more realistic treatment of interference. It was a very fortunate coincidence that only a year after our book was published, the first lasers were developed, which triggered great interest in questions concerning coherence of light.

More about these two topics is briefly mentioned in the pages that follow.

2.1 Introduction

The invitation to address this meeting has given me the rare opportunity to set aside my customary activities and try to recall a period of my life several decades ago when I had the great fortune of being able to collaborate with Max Born. As the title of my talk suggests, this will be a rather personal account, but I will do my best to present a true image of a scientist who has contributed in a decisive way to modern physics in general and to optics in particular; it will also present glimpses of a man who, under a somewhat brusque exterior, was a very humane and kind person and who in the words of Bertrand Russell was brilliant, humble, and completely without fear in public utterances.

The early part of my story is closely interwoven with another great scientist, Dennis Gabor, through whose friendship I became acquainted with Born.

I completed my graduate studies in 1948 at Bristol University. My Ph.D. thesis supervisor was E. H. Linfoot, who at just about that time was appointed Assistant Director of the Cambridge University Observatory. He offered me, and I accepted, a position as his assistant in Cambridge. During the next two years while I worked in Cambridge I frequently traveled to London to attend the meetings of the Optical Group of the British Physical Society. They were usually held at Imperial College and were often attended by Gabor, whose office was in the same

Figure 1 Max Born at his desk, ca 1950. (Credit: AIP Niels Bohr Library.)

complex of buildings. From time to time I presented short papers at these meetings. At the end of some of the meetings Gabor would invite me to his office for a chat. He would comment on the talks, make suggestions regarding my work, and speak about his own researches. Gabor liked young people, and he always offered encouragement to them. He knew Born from Germany, and he had great admiration for him.

Through Gabor I learned in 1950 that Born was thinking of preparing a new book on optics, somewhat along the lines of his earlier German book Optik, published in 1933, but modernized to include accounts of the more important developments that had taken place in the nearly 20 years that had gone by since then. At that time Born was the Tait Professor of Natural Philosophy at the University of Edinburgh, a post he had held since 1936, and in 1950 he was 67 years old, close to his retirement. He wanted to find some scientists who specialized in modern optics and who would be willing to collaborate with him in this project. Born approached Gabor for advice, and at first it was planned that the book would be written jointly by him, Gabor, and H. H. Hopkins. The book was to include a few contributed sections on some specialized topics, and Gabor invited me to write a section on diffraction theory of aberrations, a topic I was particularly interested in at that time. Later it turned out that Hopkins felt he could not devote adequate time to the project, and in October of 1950, Gabor, with Born's agreement, wrote

Figure 2 Dennis Gabor.

CHAPTER 3

WHAT POLARIZATION OF LIGHT IS: THE CONTRIBUTION OF EMIL WOLF

Christian Brosseau

3.1 Introduction and Scope

Whenever I teach my polarization optics course, one of the central messages I try to get across early is that polarization of light abounds with dichotomies. This has been known for more than three centuries, and there is no question that it has generated a considerable amount of excitement among researchers in the last decades. It is an aspect of the visual world detected by insects and many vertebrates other than mammals but is hidden from us, its origins rooted deep in statistical physics and electromagnetism. Its applications involve areas as diverse as photonics, information technology, and biology, yet its understanding is still incomplete. Before starting to consider the details of the theory of polarized light, I would like to draw the reader's attention to a brief consideration of the historical background to illustrate that Emil Wolf is a most influential and contemporary theoretical physicist in the development of polarization optics.

3.1.1 Pulling the strands of Emil Wolf's contributions to polarization optics

Emil Wolf is a living legend in the field of physical optics. Born in Prague, Czechoslovakia, Emil Wolf began research on the behavior and physics of light under the auspices of Prof. Linfoot at the University of Bristol, U.K. After holding several research positions (at Cambridge and Edinburgh), Prof. Wolf moved to the United States (University of Rochester) in 1959, where he was soon making classic contributions to the theories of coherence and polarization of light. Not only has

Wolf's productivity continued unabated, his work has been a turning point in the history of modern optics.

Wolf's ideas on partial coherence and partial polarization were first published in his 1954 paper "Optics in terms of observable quantities," [1] and later discussed in his 1959 magnum opus *Principles of Optics* [2] coauthored with Nobel laureate Max Born, which is among, perhaps, five of the most famous books ever written on optics. A generation of students (including my own when I was an undergraduate) has learned the basics of optics thanks in no small part to courses based on *Principles of Optics*. Through seven editions it has established an enviable record for high-quality presentation, with the author showing a remarkable ability to make both basic concepts and cutting-edge research topics accessible to readers [3]. I can remember that this book was my first exposure to the amazing facts of optics, and it also taught me some remarkable mathematics that I could actually see for myself made sense. Wolf has also written standard works on a large variety of topics ranging from medical imaging to astronomy, and a pioneering textbook [4] on the coherence of light coauthored with the late Leonard Mandel, which is today the undisputed bible of the subject. His prolific publications have influenced all aspects of the discipline and are actively discussed in academic literature (e.g., correlation-induced shift is now identified with the adjective "Wolf"), as well as in engineering fields (e.g., diffraction tomography).

It is a daunting task to integrate the many facets of the extraordinary career of Emil Wolf into a unified whole. Rather than trying to do that, I focus here on his work on coherence and polarization, which were early influences on my interests in optics. Wolf's growing influence on the statistical description of polarized light was recognized as long ago as 1954 [2], when he introduced a precise measure of the correlations between the fluctuating field variables at two space-time points. The idea of correlations represents a landmark in the history of polarization optics and has been highly successful. Still, it was Wolf who gave us the alphabet from which the field of coherence and polarization optics was written. We celebrate his work and hope to live up to it in some small way.

3.1.2 Structure of the review

The remainder of this introduction presents an overview of the salient historical and experimental facts and qualitatively describes the ideas and issues that have been shown to be important for understanding the phenomenon of polarization. In Sect. 3.2.1, it will be shown how the polarization and coherence concepts call for a statistical method that can handle the second-order description of the fluctuations of the electric field vector of light. A number of questions related to scalar invariants are considered. Section 3.2.1 describes the statistical method in just the right amount of detail for the reader to appreciate its use in polarization theory. The application of the general concepts to the problem of light scattering is then given in

Chapter 4

Electromagnetic Theory of Optical Coherence

Ari T. Friberg

4.1 Introduction

Almost half a century has passed since the polarization of light beams and the theory of optical coherence, in classical and quantized forms, were formulated in a systematic manner. In a classic paper [1] published in 1955, Emil Wolf introduced the two-point space-time correlation function, now known as the mutual coherence function, and showed that in free space this function obeys two wave equations (see Fig. 1). This demonstrated the fundamental phenomenon that not only the field but also the spatial coherence propagates in the form of waves. In another pioneering work [2], Wolf analyzed the state of polarization of a light beam in terms of its "coherency matrix" and the now well-familiar Stokes parameters. Using the properties of the 2×2 coherence matrix, the degree of polarization could be introduced in an unambiguous manner. The formal theory of space-time coherence of arbitrary stationary electromagnetic fields was put forward in twin papers in 1960 by Roman and Wolf [3,4]. In these works the four general 3×3 correlation tensors (electric, magnetic, and mixed coherence matrices) were introduced and their properties were analyzed. This research, which took place before or around the time the first lasers were produced, has become the cornerstone of most of the subsequent studies on polarization and electromagnetic coherence. The quantum theory of coherence was formulated soon afterwards [5].

Entirely new physical insights were subsequently gained through the formulation of optical coherence phenomena in the space-frequency domain, in terms of the cross-spectral density tensors (matrices) [6]. This is natural in many circumstances since, for example, the material response (e.g., refractive index) in optics is frequency dependent. A novel but rather subtle quantity, the spectral degree of coherence, which is a measure of the spatial coherence of a statistically stationary

$$\nabla_1^2 \Gamma - \frac{1}{c^2} \frac{\partial^2 \Gamma}{\partial \tau^2} = 0$$

$$\nabla_2^2 \Gamma - \frac{1}{c^2} \frac{\partial^2 \Gamma}{\partial \tau^2} = 0$$

Figure 1 Two wave equations for mutual coherence function Γ, in Wolf's own hand-writing. (From the cover of special issue on physical optics and coherence theory in honor of Prof. Emil Wolf's 75th birthday, *J. Eur. Opt. Soc. A: Pure Appl. Opt.* **7**, September 1998.)

field at a given frequency, was introduced [7]. The space-frequency theory of optical coherence was extensively employed by Wolf already in the 1970s in studies of radiative energy transfer [8] and generalized radiometry [9]. Many of these subjects are reviewed in the comprehensive textbook by Mandel and Wolf [10].

The electromagnetic description of light, with its inherent polarization and vectorial coherence properties, has quite recently attracted increased attention in many areas of modern optical science and engineering such as diffractive and microoptics, near-field physics and spectroscopy, and nanophotonics. The electromagnetic correlations of light are altered on propagation and scattering, resulting in corresponding changes in the spectrum [11], the (spatial and temporal) coherence, and the polarization state. In general, all these effects are described by a unified theory of coherence and polarization of random electromagnetic fields, which lately has become a topic of intensive research.

4.2 Fundamental Scalar Results

To begin, briefly recall from the scalar theory of optical coherence, some key concepts and results that have a direct bearing on the subsequent electromagnetic analysis. In coherence theory the fluctuating field is represented by a complex analytic signal $U(\mathbf{r}, t)$, where $\mathbf{r}$ denotes position and t time. The real and imaginary parts of $U(\mathbf{r}, t)$ form a Hilbert transform pair [10]. Assuming the field is stationary in time and ergodic, the mutual coherence function is defined as

$$\Gamma(\mathbf{r}_1, \mathbf{r}_2, \tau) = \langle U^*(\mathbf{r}_1, t) U(\mathbf{r}_2, t + \tau) \rangle, \tag{1}$$

where the asterisk denotes a complex conjugate and the angular brackets indicate time or ensemble averaging. In the space-frequency representation, the central quantity is the cross-spectral density function, which is obtained from Eq. (1) via the (generalized) Wiener-Khintchine theorem [10]

$$W(\mathbf{r}_1, \mathbf{r}_2, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \Gamma(\mathbf{r}_1, \mathbf{r}_2, \tau) \exp(i\omega\tau)\, d\tau. \tag{2}$$

~Chapter 5~

Physical Optics at Physical Optics Corporation

Tomasz P. Jannson

5.1 Introduction

My venture with physical optics started during my graduate studies at Warsaw Tech in Poland when my supervisor, the late Prof. Bohdan Karczewski, proposed to me as a subject of my M.S. thesis, "electromagnetic analysis of polarization states of waves diffracted on a perfectly conducting half-plane [1]," based on Emil Wolf's coherency matrix formalism [2,3]. (This so-called Sommerfeld problem [4], as well as the coherency matrix formulation of polarization states, are discussed elsewhere in the present work [5,6].) From his Rochester discussion with Emil Wolf, Prof. Karczewski also suggested to me as a subject of my Ph.D. dissertation "inverse diffraction coherence theory [7]," a subject closely connected with inverse properties and the information content of evanescent waves [8], later seen as one of the earlier attempts at nano-optics, also discussed in this book [9]. At that time in Poland considerable study was stimulated by Prof. Rubinowicz and his school into diffraction of electromagnetic and acoustic waves, including the equivalence problem of integrating the Young and Huygens approaches, first solved for spherical incidence wave by Rubinowicz [10,11], and then generalized by Miyamoto and Wolf [12].

Working as an Adjunct Professor at Warsaw Tech, I had directed my interest to the engineering aspects of physical optics, mostly in holography, holographic interferometry, and Fourier optics. Here again, critical to my studies were Emil Wolf's inverse diffraction problem developments [13] based on the first Born approximation [14], which was instrumental in volume (Bragg) holography and diffraction tomography, the latter developed by A.J. Devaney, also described in this book [15]. My further efforts in Poland concentrated on structural information in volume holography [16,17], planar holograms [18], and integrated optics [19].

Those efforts materialized later in the U.S. in such applications as chip-to-chip waveguide interconnects [20,21].

My real venture with physical optics, however, started when I met Joanna. We soon married, and have worked together ever since. It was a fantastic cooperation from the beginning, and I would wish for anybody to work in such a "coherent" way, when *"1+1>2."* While working together in Poland at Warsaw Tech, we had developed a new approach to Fourier optics [22,23], based on the temporal Fourier transform [22,23]. She then started her Ph.D. dissertation under Prof. Jan Petykiewicz, in which she developed the basic theoretical framework for prism coupling into an anisotropic waveguide [24], based on complex-variable Rieman spaces, as an extension of those in the Sommerfeld problem [25]. She completed her Ph.D. a year later at the University of New Mexico, in Albuquerque.

Just before leaving Poland, I spent three months in Olomunc, Czech Republic (then Czechoslovakia), where Prof. Jan Perina [26] advised me to study Carter's and Wolf's paper on physical radiometry [27]. This paper turned out to be critical for engineering applications of physical optics, because, by introducing the concept of quasi-homogeneous sources, it opens up the theoretical framework of physical optics into a broad range of partially coherent light sources such as thermal, fluorescent LEDs and LDs. This paper stimulated my own studies in this new area of physical optics [28,29], later critical in our development of diffuser products at Physical Optics Corporation (POC). Today at POC and the company's subsidiaries [30] only about half of our efforts are directly related to physical optics. Other areas include electronic imaging [31] and soft computing [32,33]; small RF communication platforms [34,35] such as unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs); fiber sensors [30], fiber communication [30], microwave phased array antennas based on physical optics [30], remote lighting, and others [36,37]. Nonetheless, physical optics still plays a crucial role in our product efforts, and these physical optics-based commercial efforts at POC will be the main subject of this paper.

5.2 Non-Lambertian Diffusers Theory

While many semitransparent scattering media, either natural or artificial (such as milky glass), can be considered diffusers most of them are Lambertian scatterers. The main issue then is how to control and/or modify their angular spectrum in a useful way for specific practical lighting applications such as backlighting, cellular phones displays, diffuser screens for rear projection and front projection TV; optical sensors and illuminators producing wide angle uniform white light; flat panel displays; and other lighting systems. For projection screens in particular, it would be useful to develop diffusers with broader horizontal angular divergence usually characterized by a so-called half-width and half-maximum angle (HWHM) and