The tradition of lens design at The Institute of Optics began in about 1930 when Rudolf Kingslake took up the activity. Lens design at the Institute was of course a manual activity from this beginning up to the mid-1950s. The approaches to ray tracing and third-order-aberration calculation evolved from the base developed by designers in the early part of the twentieth century. By the 1940s, mechanical calculators had been developed that would permit accurate calculation of arithmetic operations, and were rapid enough to supersede the use of hand calculations using logarithmic tables.

Lens design at that time was based upon experience more than anything else. The successful lens designer was a somewhat lonely soul, who would be immersed in a single problem for months on end. The basis for the work was an understanding of thin lens theory, paraxial optics, and third-order aberrations based upon the computation of Seidel coefficients. Adjustments were made until the third-order aberrations were within a reasonable level to balance the expected higher-order aberrations. The design was then evaluated using ray tracing. The designer then manually adjusted the lens parameters and redid the calculations until he could declare the design completed. The principal reference book on the subject was published by A. E. Comrady in 1929. This book provided a useful manual for self-learning as well as a text for academic instruction.
Classical forms of lenses that had previously been found successful were the basis for understanding how to develop a lens design that would meet a certain need. Ray tracing by hand was exhausting, with meridional rays constituting the core of the work. An understanding of the effect of close skew rays and occasionally the tracing of a few general skew rays was used to determine whether a lens had any chance of meeting the specifications for a particular application.

Image evaluation was a subjective and comparative process. Ray intercept curves were hand-calculated and hand-plotted and used to estimate the energy concentration. This estimate was used in empirical models to suggest the resolution that could be attained with a lens.

The understanding of diffraction images had progressed to some level of practicality, with diffraction integral evaluation for simple apertures and some basic aberrations, such as defocus, available by the 1940s. The Optical Transfer Function, now a common image evaluation criterion, had been defined in the 1940s, but it was not until late in that decade that the basic theory of the computation for the diffraction-based transfer function was developed.

Lens design at the Institute was a major activity during the World War II period. The need was for practical photographic and visual systems, in which the aberrations were generally necessarily larger than the diffraction-limited range. This required significant practical experience to evaluate the imagery that could be expected from a specific design. A variety of problems were worked on at the Institute during that time, with rapidity of solution and construction being of prime importance. Approaches to understanding this range of problems underlay most of the Institute’s design activities at the time. This experience formed the basis for the practical approach to lens design that was exhibited at the Institute following the war.

At The Institute of Optics the basic knowledge for understanding lens design was provided by the course taught by Rudolf Kingslake, who had left the Institute in 1940 to join the design department at Eastman Kodak. The continuity behind the development of design approaches and programs within the Institute was due to Bob Hopkins. He had developed an approach to design in the early 1940s and had been responsible for several designs during that time.
In the late 1940s and early 1950s, the U.S. optical industry was moving into a peacetime basis and toward the production of volumes of camera lenses. The Institute provided a natural focus of the efforts in developing new approaches to design. During the 1940s Hopkins and Jack Evans, along with Don Feder, devised a projector unit that was integrated with an approach to ray tracing using a Marchant calculator. This allowed a human calculator to read a number from the register of a Marchant calculator, turn a dial on the display to slide the trigonometric tables projected conveniently just above the calculator, and locate and interpolate the appropriate required sine or cosine without having to turn the pages in a table of trigonometric functions. This innovation increased the speed of manual ray tracing and probably represented a step in the state of the art. The ray trace speed even with that innovation remained the order of a minute or more per surface for a meridional ray.

There were some significant lenses developed by Hopkins and others at The Institute of Optics in the 1950s. One of the most outstanding was the optics for the Todd-AO cinema system. This was developed as a result of Michael Todd approaching Brian O’Brien of The Institute of Optics about devising a wide-screen projection system like the multi-projector Cinerama, but in which it “all comes out of one hole.” O’Brien and Walt Siegmund of The Institute of Optics looked at Cinerama and devised a system which used wide film to provide sufficient image quality and illumination for the purpose. One of the key parts of the system devised by Siegmund was the use of a very wide-angle lens which, when used for taking the picture, would provide a very strong sense of viewer participation by providing a useful peripheral image to the audience. This lens was a new state-of-the-art type of system which was designed at the Institute by Bob Hopkins. This “bugeye” lens was an important part of the overall Todd-AO system. The design was carried out largely by hand but with assistance in ray tracing on computers at American Optical, with construction and testing of some of the lenses by the Institute. This bugeye lens was used in the initial production of Oklahoma but never became popular for successive productions, probably because it was a concept not well understood by directors and cameramen.

Appearance of Computers

Electronic digital computers began to appear in the late 1940s. The primary use for these machines was to support the financial operations of companies, and most were rather unsuited for such activities as ray tracing. There had been some developments in scientific computing that had resulted in computers such as ENIAC, a large-scale vacuum tube machine located at Harvard. Such machines were marvels of the period but were very limited in terms of computational capability and speed.

At that time there was a large amount of activity for technical computation purposes in analog computers which allowed the very rapid, almost real-time solution of differential and other equations. The output speed of an analog computer was far greater than that of the day’s digital computers for the types of problems to which it was applicable. The accuracy required in ray tracing indicated that digital computers were required for any useful computing on lenses.

There was one analog computer for lens design that briefly resided at the Institute in the 1950s. This was engineered at American Optical—it was an electrical analog computer.
that could be used to obtain the power distribution for a thin lens triplet to obtain the desired chromatic residual and Petzval sum, and included the glass data and separations of the elements. The information on each piece of data was dialed in and the output was the required powers of the three elements. (At least, that is how I remember it. There does not seem to be any existing description of the device. Chuck Rimmer remembers being given the task of “calibrating” the computer, a concept alien to today’s digital computers.)

It was obvious that digital computers were the only type of machine suited for the accuracy required in ray tracing and aberration calculation; thus interest moved onto using computers first for simple ray tracing and later into applications for “Automated Optical Design.” As for the application of digital computers to “automatic” design at mid-century, there were two different philosophies expressed in the 1950s. In a 1963 paper Gordon Spencer took note of these two points of view. In summary:

**Philosophy A:** Lens design can be completely stated in explicit mathematical terms and hence a computer can be expected to carry out the total activity.

**Philosophy B:** Lens design inevitably requires qualitative judgments and compromises to be made and hence the computer should be regarded as a tool capable of presenting the designer with possible solutions.

This was a hot topic for debate back then. Today, even with digital computers more than a million times faster than those of the 1960s, the role of the lens designer seems secure. The answer seems obvious now, but in the 1960s the promise of even better and faster computers left the option of replacing the designer with a complete piece of software a possible option. The course of software development by each group of designers through the 1950s and 1960s would follow the choice of philosophy chosen by that group.

**Teaching Lens Design at the Institute**

A sample of the lens design teaching at the Institute at mid-century can be obtained by examining one year. The example chosen is 1953–54. The lens design course was generally taken in the senior undergraduate or second year graduate period. Design was taught both by Rudolf Kingslake and Bob Hopkins. Kingslake taught his course on Wednesday nights for about two hours with a short break during the lectures. Hopkins offered a lens design computation laboratory on Saturday Mornings.

The Kingslake course content was contained in an extensive set of course notes which covered topics that eventually appeared in an expanded form in his book *Lens Design Fundamentals*. The Kingslake course consisted of a very intensive series of lectures with some question-and-answer sessions and provided the classical basis for understanding lens design. The course provided a very thorough grounding in the fundamental concepts of design, with a moderate amount of guidance on practical aspects of carrying out the designs.

Hopkins’s laboratory session complemented this with the practical design of some specific lenses. At that time all of the computation was done on Marchant calculators, with the students each carrying out their own ray traces. There was heavy use of third-order aberration calculation with manual variation of the design parameters. The designer would identify key parameters and develop change tables for the variation of the third-order aberrations with these parameters. Verification of the design was accomplished using meridional
ray tracing done by hand. Examination of ray fans and reference to the change tables on third-order aberrations was used to adjust the lens to a final design. It is notable that only a few of these designer-driven iterations were usually required to approach a reasonable design.

The types of lenses designed in the course were some doublets, a landscape-type lens, and a triplet. The approach toward these designs was more or less described in the well known Mil-Handbook 141 sections on lens design.

Beginning about 1954, Bob Hopkins was convinced of the importance of applying computers to lens design in some way. There had been some application of computers of the time to ray tracing, and some early work on correction of lenses. There was a bit of a problem in that he did not have access to a computer. In fact, the University of Rochester was devoid of any scientific computing capability. The first program in computer programming was taught in the absence of a computer by a professor in the Mathematics Department. In order to touch any reality, the professor invented a generic computer and computer language called, as I remember, HYPAC for “hypothetical computer.” The course was basically on how machine language and assembly coding operated, using some examples of simple solving and search algorithms. FORTRAN was still a few years away.

In the absence of other resources, Hopkins arranged for the students to have access to an IBM 604 calculating punch at Bausch & Lomb that did permit very awkward ray tracing at several seconds per ray surface, but was a very welcome innovation. By 1955 he had arranged for access to an IBM CPC, or Card Programmed Calculator, located at the Cornell University Computer Center. Input was through punched cards, and the program to calculate third-order aberrations or to trace rays was stacked on cards between the surface data cards. Output was through an IBM vertical bar printer, a remarkable mechanical monster of which very few people have any recollection. There was a difficulty in that the cards had to be delivered ninety miles to Ithaca, and one of the vivid memories students of that time carried with them was of high-speed drives with Hopkins in a wood-sided station wagon to and from the computer center at Cornell University.

The first stored program computer that became available at the University of Rochester was the Burroughs E101. This machine seemed to have been obtained by the urging of the Institute, because I do not recall significant use by any other department. Nevertheless, this constituted the beginning of one of the first university-associated digital computer centers in the country, and Tom Keenan was hired to head and develop the center.

The stored program on the Burroughs machine was about 144 steps that were programmed by inserting metal pegs into a set of pegboards that were then set into the machine. Data in and out was through a Burroughs Accounting Machine set on top of the computer. This computer was used for third-order calculation and ray tracing, and some limited attempts at aberration mapping versus lens parameters. This was a computer of limited application and interest, but did indicate the possibilities inherent in stored program machines. There was, of course, very great relief at not having to carry out hand calculations for ray tracing on a desk calculator.

The Burroughs was soon replaced by an IBM 650 which permitted a thousand stored program steps on a magnetic drum that could be programmed using symbolic assembly language (which occupied the other thousand words of memory on the drum). This machine was the first that permitted any attempt at automatic correction, and a third-order aberration correction program was written by Charles McCarthy. The machine also
carried out ray tracing and did geometrical image analysis using radial energy distribution and geometrical modulation transfer function.

Once real stored program computers were available, a sequence of programs began to be developed at The Institute of Optics for optical design. These started with ray tracing, included third-order calculation and automatic correction to defined targets of these aberrations, and eventually led to programs capable of using ray aberration targets for automated design. Subsidiary programs to permit calculation of image evaluation functions were eventually incorporated into these programs, and the way was paved toward the general automatic lens design programs. The practicality of this at the University of Rochester was enhanced with the replacement of the IBM 650 with an IBM 7070 computer in 1961. This was a sort of advanced version of the drum-based 650 that permitted scientific computing such as lens design, along with character-based data manipulation required by other departments at the University. It, in turn, was eventually replaced by a faster transistorized 7074 in 1963.

The practical approach of linking the designer to the design program was a fundamental part of the Institute’s developments under Bob Hopkins. He was a strong believer in integrating the designer into the process, rather than treating design as a mathematical exercise. The programs developed in the late 1950s and early 1960s eventually included high-order Buchdahl Aberration coefficients which permitted better control of the aberration targets. Ray trace targets were eventually added, but the speed of computation of these, especially on the IBM 650 computer, tended to be used as finishing rather than in-process design aberrations.

The ALEC (Automatic Lens Correction) program was written by Gordon Spencer in support of his Ph.D. dissertation. This program used aberration coefficients plus a small set of rays and differential rays to construct the merit function.

Once the IBM 7070 had been acquired, a true large-scale stored-program computer was available for optical design programming. This enabled the development and use of the ORDEALS program—the acronym stood for Optical Routines for Design and Analysis of Optical Systems. ORDEALS was initially based on the set of IBM 650 programs converted to machine language to operate at higher speed. This program eventually was ported to the 7070/7074. The ORDEALS program incorporated third- and fifth-order aberration correction as well as a full set of ray trace analysis capabilities. The fifth-order aberration coefficients were based upon Buchdahl’s coefficients, as translated into Rochester language by Chuck Rimmer. ORDEALS was the core of The Institute of Optics teaching and design activities during the 1960s.

Gordon Spencer, Chuck Rimmer, and Pat Hennesey formed Scientific Calculations Inc. in 1963. At the beginning, they worked on variants of ALEC. Spencer took on a task to develop a program for Bob Potter at IBM Research on the 7094 computer which contained extensions beyond ALEC. This became the FLAIR program, which was distributed by IBM and eventually became a staple of the Institute’s program package. (It is not known what FLAIR is an acronym for.) The FLAIR program was further developed at the Institute in the 1970s by Peter Sands, who wrote an extensive manual for the program. The major independent optical design program development to arise from Scientific Calculations was the ACCOS program (Automatic Correction of Centered Optical Systems) developed by Spencer and Hennesey, which became a standard in the optical industry in the 1970s. This program was expanded to include many features as several versions were developed. The core of the program retained the practical approach to lens design which was characteristic of The Institute of Optics during the 1960s.
Development of the Field

The developments at the Institute were limited by the available computing gear, which did not always keep up with the state of the art of the time. Others did, however, move forward with larger and possibly better machines. Donald Feder at Eastman Kodak had access to an IBM 704 machine that ran Kodak’s financial software, and while slower than the leading 7090 class machine, did permit reasonably large and fast programs to be written. Feder had developed a program called LEAD (acronym unknown, but likely Lens Evaluation And Design). This program was directed toward the philosophy of leaving all the design work to the computer program with minimal human designer guidance.

This development stimulated Hopkins to hold an informal symposium in 1962 at The Institute of Optics at which a dozen or so lens designers were invited to discuss the state of the art. At that symposium, Feder issued a challenge for the assembled designers to set specifications of a lens which he would design totally automatically. The specifications called for an F1.2, six-degree lens using four elements, and remaining within some minimal set of boundary conditions. Feder went off and overnight came up with a design that was reasonable, but in subsequent discussion did not totally impress the assembled designers. This symposium lens became a sort of de facto standard for studying the capabilities of various computer programs being developed at the time. Several papers in the 1960s resulted from attempts to improve the original design obtained from the Feder program. The importance of careful selection of appropriate boundary conditions in carrying out automatic design was an important feature of these discussions.

The activity at the Institute in lens design was supported by a number of visitors in the 1960s. Charles Wynne visited and discussed his work on the high-speed Atlas computer in developing the SLAMS program for lens optimization. This program was one of the first that incorporated all of the major features into a ray-trace-based optimization program. His description of the course of design roaming through solution space intrigued those at the Institute.

Hans Buchdahl also spent a period at the Institute. This led to the aforementioned development of computer algorithms based upon the Buchdahl Coefficients by Chuck Rimmer. These coefficients are a part of all the major lens design programs today.

The status of automatic lens design programs was summarized in a landmark meeting at the Institute in 1966, the first Conference on Lens Design with Large Computers. This conference, organized by Lem Hyde and sponsored by the Institute, brought together most of those involved in lens design software at the time. The timing was right, and this conference was perhaps the single most important landmark in the history of the field of automatic optical design.

The conference began with Charles Wynne summarizing his work using the Damped Least Squares approach to design. The importance of appropriate selection of the damping factor as a driver in finding solutions had been recognized and served in part as the subject for some other papers at the conference. Dave Grey, then of Aerospace Corp., introduced his concept of linearizing the design problem by orthonormalization of variables in design space. Other programs described other approaches, including adaptive setting of aberration targets as devised by Glatzel at Zeiss.

Gordon Spencer described in some detail the status of the ORDEALS program on the Rochester 7074 computer. It is interesting to note that this program took up some 27,000
36-bit words when compiled onto an IBM 7090 computer. In today’s language this equates to about 135 kilobytes or so, a fraction of what is carried on one floppy disc today. The efficiency of programming of that time versus today’s profligate use of storage space is remarkable. This discussion was supplemented by a discussion by John Buzawa on the design of a specific lens using this program. He noted that the total computer time for this design was about one-half hour on the 7074 at a cost of about $150.

Several papers discussed experience with other programs of the day, and provoked much discussion. There was consideration as to whether the computer would really become the total designer, or whether the ultimate use is as an adjunct to a human designer. One notable recorded remark from an unnamed participant in the audience: “This lens designer is almost ready to believe that the computer, even though it is less intelligent than the human being, is more intelligent than a lens designer.”

By this time the approach to automatic design had progressed to the point where much of the discussion was directed to the establishment of a useful and functional merit function to set the direction of the program when iterating through the design.

The late 1960s and early 1970s saw a change in the momentum regarding the activity in lens design programming at the Institute. Part of this can be attributed to Bob Hopkins leaving the Institute to concentrate on developing Tropel in 1968. By this time much of the program development was being done in industry, where there was better access to the latest high-speed computing equipment. In addition, several groups, such as Scientific Calculations and Optical Research Associates, had been formed and began to develop the major commercial optical design programs that form the core of the industry today.

Automatic lens design programs had developed by 1970 to the point where they were commercially viable, and several organization developed programs that became universal standards. The momentum passed to these organizations, and the Institute concentrated on other aspects of the lens design and manufacturing problem.

Lens design software development at the Institute did not entirely stop. The FLAIR program was maintained and documented by Peter Sands, but not significantly expanded. Doug Sinclair became interested in the use of small computers to provide a personal link between the computation and the designer. He started first with the HP65 programmable calculator in about 1970 and moved on to various other expanded desktop calculators such as the HP 9845 and other machines in the early 1970s. These saw considerable use in teaching at the Institute. Sinclair also saw an opportunity to pioneer the rapidly emerging technology of applications of small computers, and left the Institute in 1975 to form Sinclair Optics and market the expanded set of OSLO optical design programs for the then-new personal computer.

The final major expansion of Automatic Optical Design into a universal tool occurred with the introduction of the personal computer in the early 1980s. Today the designer has on the desk his or her own machine with orders of magnitude more capability than even the 650 and 7044 computers. The personal computer also is optimized to communicate graphically with the designer, leading to the observation that the ultimate development of the lens design program is to integrate and extend the capabilities of the individual designer. Now, instead of a few optimizations against estimated image quality targets, the lens designer, including the lens design student, can carry out hundreds of iterations on a single design and obtain a thorough evaluation of the lens performance. Certainly the lens designers and design students at the Institute at mid century would have been understandably elated by the ability to have such tools at that time.
The 1950s and 1960s were an exciting time in the field of optical design. The traditional intuitive understanding of how complex lenses operated was being melded into the new age of computers. The work done at The Institute of Optics during that time formed a basis for most of the computer program developments that followed.

Chuck Rimmer, Gordon Spencer, and Doug Sinclair provided valuable information regarding their recollections of the period and activities discussed in this essay.