Four Score Years of Saul I. Gass: Portrait of an OR Professional

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Summary. Saul Gass has practiced operations research for 55 years and continues to be a vigorous presence in the field. His multifaceted contributions as a scholar, practitioner, involved citizen, world ambassador, and chronicler of operations research are reviewed in this article.

Key Words: Linear programming; multiple criteria; modeling process; history of OR.

1 Introduction

Saul I. Gass turned eighty on February 28, 2006. As a member of Project SCOOP, he was certainly "in just after the beginning" of Operations Research (OR). Saul embraced OR as a profession in its early days. As a member of the Operations Research Society of America since 1954, Saul has been a model citizen who has bridged the academic-practitioner divide. Over a period of nearly 55 years, his involvement in OR as a scholarly and professional endeavor has never slackened and continues in full force to the present day.

Saul's career spans scholarship and what he calls the three P's of OR: practice, process, and professionalism. He has been a leader on all four scores. This article reviews his contributions to date. The first part of this paper is chronological. Sections 2-5 discuss Saul's early career and the road that led him to Project SCOOP, through his career as a practitioner of OR in industry, to his academic career at the University of Maryland. In Sections 6-9, we try to reflect the multiple facets of Saul's career as an OR professional, covering his roles as a scholar-teacher, expositor, practitioner, involved citizen, ambassador, and chronicler of OR. We hope that the rich tapestry that emerges shows why Saul commands the respect of his peers and his profession.

2 Portrait of a Young Mathematician

Saul Irving Gass was born on February 28, 1926 in Chelsea, Massachusetts, to Louis and Bertha Gass, who had emigrated from Russia around 1914. His father sold life insurance but was a writer as well: He wrote a column in Yiddish in a Boston newspaper and also ran a radio show. Saul was the second of two children: his brother Gerald A. Gass was born October 21, 1922.

Apart from a few months at the Pratt Elementary School in Chelsea, Saul's schooling was done in Boston. He attended the Quincy E. Dickerman Elementary School in Roxbury, the Phillips E. Brooks School for the sixth grade, and continued at the Patrick T. Campbell Junior High School for grades seven through nine. Saul went through high school at the Roxbury Memorial High School for Boys and graduated in 1943. During high school, his favorite subjects were mathematics and physics. He also took navigation and aeronautics in his senior year, and did well in military drill.

Saul started Northeastern University in 1943 and spent a full year in college before joining the army. His army training started on March 17, 1944 at Fort Devens, Massachusetts and continued at Camp Blandig, Florida and Camp Shelby, Mississippi, where he trained as a machine gunner. On January 10, 1945, Saul sailed from New York City to Le Havre, where he camped for a month. In the final weeks of World War II, Saul was part of the 65th division of the U.S. Army. This division continued to move east during April, took Linz on May 4, and stopped on the west bank of the Enns River in Austria on V-E Day, May 8, 1945; the Russian army was on the east bank. Saul was then stationed at Pfaffenhoffen in Germany for the remainder of his stay in Europe. His two years of German in high school came in handy. Saul sailed back home in April 1946 and was discharged on May 23, 1946 at Fort Devens.

After his military discharge, Saul planned to get married and hoped to resume his university studies. He had met his future spouse when he was 15, and had courted her just before going to Camp Shelby. He married Trudy Candler on June 30, 1946 in Los Angeles, and they moved back to Boston. Saul re-enrolled at Northeastern but soon transferred to Boston University (in January 1947) to major in education and mathematics, with the intention of becoming a high school teacher. He graduated with a bachelor's degree in education (with a mathematics major) in June 1949. Saul's interest in mathematics had led him to take extra courses in this subject. Therefore, it only took him an additional summer to earn his masters in mathematics in August 1949. Not having found his semester of student teaching inspiring, Saul decided against a career as a high school teacher and looked for another job.

In November 1949, Saul was offered a job as a mathematician with the U.S. Air Force (as a GS-7) and joined the Aberdeen Bombing Mission (ABM) in Los Angeles. This civilian Air Force group performed ballistics analysis for bombs. It was led by Grace Harris and had eleven members (nine women and two men). According to Saul [88], the main task was to analyze "*photographic plates and high-speed camera film of high-altitude aircraft and bomb drops that took place at Edwards Air Force Base, north of Los Angeles in the desert country.*" Saul continues:

> At ABM, we read the plates and film by eye on a Mann Comparator, recorded the results by hand, and processed the readouts on the Marchant and Monroe

desk calculators -- the old-fashioned way! I did become deeply involved in bomb ballistic work and was given the task of investigating new machine readers that could automatically record the positions of both the aircraft and bomb images and punch the results on IBM cards [88].

The Los Angeles group sent its results to the Aberdeen Proving Grounds in Aberdeen, Maryland, where bombing tables were developed. Saul visited this location and was offered a position. He declined the offer, but his work at ABM exposed Saul to the need for accuracy, constant checking, and data validation.

3 From Project SCOOP to Project Mercury

Saul was next offered a job as a GS-9 (at $5,060 a year) in the Directorate of Management Analysis of the Air Force in the Pentagon. Saul was a young father when he moved the family of three to Washington D.C. from Los Angeles in the first week of January 1952. Ronald S. Gass was born on June 3, 1951, to be followed by Joyce A. Gass (born June 22, 1955).

At the Pentagon, Saul joined Project Scoop (Scientific Computation of Optimal Programs). This Pentagon-based research program of the U.S. Air Force was formed in June 1947, and its official designation of Project SCOOP came in October 1948. This is where applied linear programming started. Saul has aptly dubbed it "*the first linear-programming shoppe*" and stressed its historical significance:

> All of us in OR are indebted to project SCOOP. The linear-programming model, the simplex method, the first computer-based solution of LP problems, much of the theory of linear and mathematical programming, the basic computational theory of linear programming, and the extension of LP to industry and business all stemmed, wholly or in part, from the research and developments of Project SCOOP. [81]

When Saul arrived at the Pentagon, the Directorate was headed by the economist Marshall Wood, and its scientist was George Dantzig. The main objective of Project SCOOP was to plan the requirements for air force programs. As Wood and Dantzig explained it in 1949:

> Programming, or program planning, may be defined as the construction of a schedule of actions by means of which an economy, organization or other complex of activities may move from one defined state to another, or from a defined state towards some specifically defined objective. Such a schedule implies, and should explicitly prescribe, the resources and the goods and services utilized, consumed, or produced in the accomplishment of the programmed actions. [150]

An example of an organization requiring such planning was the Air Force. A typical programming exercise was to construct a time-phased plan of requirements of materials for supporting a specific war scenario. Within Project SCOOP, the word "programming" was used in the specific military sense; computer programs were barely known and called codes at that time. As Dantzig has put it:

> The military refer to their various plans or proposed schedules of training, logistical supply, and deployment of combat units as a *program*. When I first analyzed the Air Force planning problem and saw that it could be formulated as a system of linear inequalities, I called my paper *Programming in a Linear Structure*. [12]

At the core of the Project was Dantzig and Wood's approach to modeling the economy or organization based on Dantzig's mathematical statement of the LP problem. The model used a triangular or rectangular technology matrix to specify the requirements and their interrelationships. This extended the Leontief input-output model from the triangular case (where no optimization was required) to the rectangular case where one could optimize an objective function using the LP structure. With the formulation of these planning models, the members of Project SCOOP came to realize the power of the LP model. While Dantzig, Alex Orden, and others were developing the key algorithmic procedures for the simplex method, the computational challenges of the task also came into clearer focus. With keen foresight, Wood and Dantzig identified the promise of the new technology:

> To compute programs rapidly with such a mathematical model, it is proposed that all necessary information and instructions be systematically classified and stored on magnetized tapes in the "memory" of a large scale digital electronic computer. It will then be possible, we believe, through the use of mathematical techniques now being developed to determine the program which will maximize the accomplishment of our objectives within those stated resource limitations. [150]

In the Mathematical Formulation Branch, Saul worked on the formulation and solution of Air Force problems and also developed and tested new procedures for solving LP structures. He recalls his entry into this dynamic and heady research environment.

> I was assigned to the Mathematical Formulation Branch. Walter Jacobs, a mathematician, was branch chief. He introduced me to linear programming by suggesting that I read reprints of Dantzig's three seminal papers .... Even though I was a fairly recent mathematics graduate, the concepts and ideas described in these papers were new to me and rather complex. What does the uninitiated make of such things as zero-sum games and the solving of hundreds of equations in hundreds of variables, especially in pre-computer days? Fortunately, I had a course in numerical calculus and knew something about Gaussian elimination and how to solve (3x3) systems of equations. [88]

The role of Project Scoop in advancing the use of computers is an important point made by Saul.

> Project SCOOP was responsible for much of the federal government's early involvement in computers, especially the efforts of the National Bureau of Standards (NBS). NBS received over $1 million from the Air Force, and used these funds to build the Standards Eastern Automatic Computer, the SEAC. [81]

The SEAC machine was located at the National Bureau of Standards (NBS) in Washington, D.C. Saul drove the problems from the Pentagon to the NBS campus on Van Ness Street. Early computational tests by Alex Orden on the NBS SEAC compared the simplex method with other approaches (relaxation and fictitious play), and typical results are reported in [81]. Project SCOOP also led to the installation of the second production unit of the UNIVAC machine in April 1952, formally turned over to the U.S. Air Force in June 1952. The simplex code for this machine was written by the Air Force's Mathematical Computation branch led by Emil Schell. The UNIVAC could handle LP problems of dimensions up to 250x500. Saul solved LP problems on this computer and describes it as follows:

> The UNIVAC had more than 5,000 vacuum tubes and could do about 2.000 additions or subtractions per second. It had an internal acoustical mercury-delay line memory of 1,000 12–character words... Its external memory consisted of 8 magnetic tapes that could read or write at the rate of 1,000 words a second. The UNIVAC, although a clunker by today's standards, was [a] great improvement over desk calculators. It was always exciting (and chilling) to walk into the special air-conditioned, room-sized cabinet that held the mercury delay-line memory tubes. [88]

George Dantzig left the Pentagon in June 1952 for the RAND Corporation. By 1955, Project SCOOP was starting to wind down, and research funds were being cut in the government. But Project SCOOP had assembled a remarkable network of researchers.

In addition to Marshall Wood and George Dantzig, its members included Saul Gass, Murray Geisler, Leon Goldstein, Walter Jacobs, Julian L. Holley, George O'Brien, Alex Orden, and Emil D. Schell. The summer students of the group included Phillip Wolfe from Princeton (Albert Tucker's student) and Tom Saaty, who was finishing his Ph.D. at Yale. This group also worked closely with the Washington-based national Applied Mathematics Laboratories that included Sam Alexander, John Curtiss, Alan Hoffman, Henry Antosiewicz, Peter Henrici, John Todd, and Olga Taussky-Todd. Also associated with the group were T. S. Motzkin and George Forsythe from the Institute for Numerical Analysis, the west-coast research arm of NBS, and Princeton's John von Neumann, Albert Tucker and his students Harold Kuhn and David Gale, Abraham Charnes and William Cooper from Carnegie-Mellon University, and Isidor Heller from Washington University. Listing this remarkable group, Saul remarks, "*What in the hell was I doing amongst* *that bunch of heavies?*" [65]. In fact, this group exposed Saul to the wave front of operations research just after the beginning. Project SCOOP also ran two symposia of great historical importance on linear programming in 1951 and 1955. Saul attended the second seminar and gave a paper on finding first feasible solutions in LP [24].

Saul left the Project in May 1955 to join IBM as an Applied Science Representative. The job advertisement for this position required a degree in mathematics or engineering and exposure to "automated computing equipment, or system design and methods." He was hired along with other new sales trainees who were new college graduates and went to the standard three-week sales training class in Endicott, New York, where he sang IBM songs from the IBM songbook! Saul was assigned to the Washington commercial sales office located at 1111 Connecticut Avenue. His job was to help the salesman selling and installing IBM computers. The IBM 701-704 series of machines were just out and, later, Saul was also trained to program the IBM 650.

Saul's next employer was CEIR, the Corporation for Economic and Industrial Research, a consulting services company at which Saul had helped install an IBM 650 machine. William Orchard-Hayes was an early hire of this firm. Saul was approached by Jack Moshman to build up the OR group at CEIR. He joined the firm in 1959 as Director of the Operations Research Branch. However, his tenure in this position was cut short by the expansion of the space program, which led to an offer for Saul to return to IBM.

Saul rejoined IBM in 1960 as Manager of the Simulation Group of the Project Mercury Man-in-Space Program. He was responsible for the development of a full range of real-time simulation procedures used to validate the computational and data flow equipment system that IBM developed for Project Mercury. The key task for IBM was to calculate the orbit of the space capsule based on radar telemetry data collected from various tracking stations across the globe. This data was processed at two IBM 7090 computers located at the Goddard Space Center. IBM had to conduct the necessary analysis and develop the computer programs, run a duplexed computing center, and operate an engineering and communications subsystem that enabled the flight controllers to monitor all phases of a Project Mercury mission. Saul's initial assignment at Goddard was to dry run the computer programs that computed the orbit with simulated data, which he describes as follows:

> We simulated radar data from the world-wide tracking stations and ran the programs in real-time by entering the timed data into teletype machines connected to the computers... By this time, IBM was also given the responsibility of analyzing lift-off radar data to predict whether the space capsule would go into a successful orbit.... We simulated that phase, plus predicting when to fire the retro-rockets to bring the capsule back to the earth and the splash point. Our computer-based system was the first real-time decision-making system with a man-in-the-loop. [97]

The first U.S. manned-capsule sub-orbital flight occurred on May 5, 1961 with Alan Shepard. Just a few days before (on May 1), Saul was appointed manager of IBM's Project Mercury. Saul's recollection of this event conveys the atmosphere:

> I recall the scene just before his [Shepard's] lift-off: the now spruced-up Goddard computer room with its duplexed (A and B) computers, the side-by-side plotboards, that would, hopefully, trace calculated launch track over the already inked-in nominal track, and the output console with its switch that enabled the computed output to come from either the A or B computer. Systems operations manager Al Pietrasanta and I manned the switching console. The crowds of NASA and IBM VIPs that gathered were kept back by a set of stanchions and ropes. We felt like gladiators who would be fed to the lions if something went wrong. All went well... [85]

Saul also went to Cape Canaveral to watch the launches for all the manned orbital flights. There, he supervised a team of engineers responsible for data transmission from the Cape to Goddard and the running of the control center charts as well as launch and orbital plot boards. From the VIP grandstand at Cape Canaveral, Saul watched John Glenn's liftoff on February 20, 1962 in the first U.S. manned orbital flight. He then rushed inside Mercury Control center to watch the tracking plotboards. The success of Glenn's historic flight brought top management attention to Project Mercury within IBM. The chief scientist for IBM paid Saul and his team a visit and questioned them on system reliability and testing. A week after the flight, Saul briefed the board of IBM directors in New York and received a standing ovation.

The computer-based activities of Project Mercury, which engaged a team of over 100 scientists, programmers, and engineers, paved the way for future manned-space projects. It also foreshadowed the critical role of real-time computing in making manned space flight a reality [28]. It was therefore not only one of the largest projects Saul had managed within industry, it was also a highly intense assignment in uncharted territories. Project Mercury was also a great practicum for project management.

> We all learned from Project Mercury. For me, it had to do with the integration of people, computers, programs, and real-world necessities. I learned the importance of bringing control to an ever-changing set of tasks and the need to impose a rigorous verification and validation process. I learned how pressure, contractual responsibilities, and finances can be honed to meet a project's goals given that those involved communicate, cooperate, and compromise in a manner that does not seriously distort their objectives.... I had to negotiate what it meant to turn over a real-time, man-rated system that had never been developed. How does one demonstrate to tough-minded NASA managers and engineers that one met system specifications when such specifications, although set down in the past, had to be constantly changed to meet the realities of the present? [85]

As Project Mercury came to a close, the NASA space program moved to Houston, Texas. Saul had a principal role in preparing IBM's proposal for developing the Houston Real-Time Computing Center, but did not want to move to Houston himself.

4 Back to School and Return to OR Practice

Ever since his days at SCOOP, Saul had shown a continuing interest in taking courses related to his areas of interest. In 1953-54, he took the two semester course that Albert Tucker and Harold Kuhn taught at the American University on Thursday nights. Kuhn and Tucker were involved with a research project at George Washington University. One or the other would come down to Washington, D.C. for this purpose and teach the night course. Later, Saul formally enrolled in the doctoral program in mathematics at American University and took the following classes: "Linear Programming and Game Theory" from Alex Orden; "Methods of Operations Research" from Joe McCloskey (known for his early work in the history of OR); "Linear Programming" from Alan J. Hoffman; and "Numerical Analysis" from Peter Henrici. Saul also took two computer courses from the NBS staff.

In September 1963, Saul decided to take advantage of IBM's resident graduate fellowship program that allowed IBM employees to go back to school on a two-year leave with full pay. The IBM fellowship allowed Saul to go to the school of his choice, and American University would have been a convenient choice. However, Saul had also maintained contact with George Dantzig, who had joined Berkeley in 1960 to head its OR department. Saul chose Berkeley for his doctoral studies, and the Gass family drove to California in August 1963.

At Berkeley, Dantzig taught the linear programming course using notes that formed the basis of his famous text, *Linear Programming and Extensions*, which came out later in 1963. Because of Saul's substantial background in LP, he was not allowed to take this course for credit, but he audited it (in fact, Saul never took any courses for credit with his mentor.) There is an amusing story about how uneasy his classmates felt when they found out that Saul had already written the first text on LP!

His doctoral course work at Berkeley included network flows, discrete programming, theory of probability and statistics (I and II), mathematical economics (I and II), inventory theory, nonlinear programming, applied stochastic processes, and advanced statistical inference. In addition, he had to pass minor examinations in economics and probability/statistics, and two languages (French and German). Saul recalls the networks class given by Bob Oliver as one of his best courses at Berkeley. His best instructor was Elizabeth Scott, who taught probability and statistics. The Dantzig and Gass families socialized and often went to dinner together. He also socialized with Bob Oliver and Bill Jewell [99].

For his oral defense, Saul had to present a paper from outside his field. He was given a paper on busy periods in queueing written by Takacs. At the end of the presentation, he was asked only one question: Dantzig asked, "What's a convolution?" When Saul started to look for a dissertation topic, Dantzig suggested that he contact Roy Harvey at Esso. Harvey had a large-scale LP problem, for which Saul devised a novel decomposition scheme and algorithm. This was the dualplex algorithm, which constituted his Ph.D. dissertation [29]. Saul completed his Ph.D. in summer 1965. He was one of the earliest doctoral students of George Dantzig. Before him, Richard Cottle had completed his Ph.D. in 1964. Other students of Dantzig who were Saul's contemporaries include Earl Bell, Mostafa el-Agizy, Ellis Johnson, Stepan Karamardian, and Richard van Slyke, all of whom earned their doctoral degrees in 1965.

Saul returned to IBM in the summer of 1965. IBM had already formed its Federal Systems Division with offices in Gaithersburg, Maryland. For the next decade, he was involved in projects. Saul was manager of Federal Civil Programs and responsible for applying information retrieval and other data procedures, advanced graphics techniques, and data analysis to urban problems. While most of his work at IBM did not have a heavy dose of OR or LP modeling, Saul did get a chance to apply OR thinking to urban problems as a full-time member of the Science and Technology Task Force of the President's Commission on Law Enforcement.

The Commission was created by President Lyndon Johnson in 1965, partly in reaction to the issue of "crime in the streets" that Barry Goldwater had raised in the 1964 election campaign. The Commission was mainly comprised of lawyers and sociologists. The Task Force was formed to augment the work of the Commission by bringing scientific thinking to bear on crime. The Task Force was led by Al Blumstein (see [1]), who recruited Saul to join in 1966. Other recruits were Richard Larson (who was completing his undergraduate degree in Electrical Engineering), Ron Christensen (a physicist and lawyer), the consultant Sue Johnson, the statistician Joe Navarro, and Jean Taylor. The Task Force was based at the Institute for Defense Analyses (IDA), where Al Blumstein and Jean Taylor worked at the time. Saul was responsible for developing the Task Force's approach to how science and technology can best serve police operations.

From 1969-70, Saul was Senior Vice-President of World Systems Laboratories, Inc. This was a Washington-based consulting firm with five key principals. He then joined Mathematica, the well-known OR and economics consulting firm headquartered at Princeton, New Jersey. Tibor Fabian was President, and Harold Kuhn and Oscar Morgenstern were on the board. Saul headed the Bethesda office of the firm and worked on several government projects. These included the development of an educational student aid model for the U.S. Department of Education; the establishment and analysis of an educational data bank for the Appalachian Regional Commission; the development for the Corporation for Public Broadcasting of a procedure to evaluate the effectiveness of a series of telecasts on environmental issues; consulting to the systems group of the Chief of Naval Operations; the development of a simulation model of the dispatch/patrol functions of the Washington Metropolitan Police Department; the development of operational planning materials for the National Center for Educational Statistics common core data system; and principal investigator on the NSF project to evaluate policy-related research in police protection. He also organized an unclassified symposium for the CIA that focused on techniques for analyzing intelligence information.

One of the projects Saul undertook at Mathematica was a contract from the Environmental Protection Agency to conduct a survey of modeling in the non-military governmental area. This resulted in the volume *A Guide to Models in Governmental Planning and Operations,* which Saul edited along with Roger L. Sisson [124]. This book was privately published by its editors in 1975. A total of 2,000 copies were printed and distributed out of Saul's basement. The name of the publisher – Sauger Books – indicates this upon closer inspection [97]. Saul's chapter in this volume devoted 45 pages to a review of modeling efforts in law enforcement and criminal justice and lists 103 references. Among the models reviewed were patrol beat design, the police emergency response system, and court models [34].

5 Academic Home Found

Long before starting his professorial career, Saul had revealed his academic bent. In addition to doing research and writing the first text on LP, he also taught the subject regularly at the US Department of Agriculture (USDA), American University, and George Washington University. In 1973 and 1974, he taught an evening course in operations research for the business department of the University of Maryland. In 1973, the business administration department became the College of Business and Management. Rudy P. Lamone was appointed dean. Dean Lamone, who had received a Ph.D. in OR from the University of North Carolina, was interested in building a high-quality OR department. He persuaded Saul to join the University of Maryland in September 1975 to become the chair of the Management Science and Statistics Department. Saul was to spend the next 26 years at the university. As he puts it in an interview: "I had found a home." [97]

Saul was Professor and Chairman of the Faculty of Management Science and Statistics from 1975 to 1979. The faculty of this department already included Gus Widhelm and Stan Fromovitz in OR. Saul lost no time in building up the department. He hired Larry Bodin at the full professor rank and Bruce Golden as a fresh assistant professor in 1976. In the next two years, he recruited Frank Alt, Mike Ball, and Arjang Assad as assistant professors. While Saul stepped down as department chair in 1979, he remained closely involved with its development and growth for the next 22 years. During these years, he taught LP and OR subjects at doctoral, MBA/MS, and undergraduate levels. He also supervised doctoral and masters students and sat on numerous thesis and dissertation committees. Saul was the dissertation advisor of eight students, which we list in chronological order: Stephen Shao and Jeffrey Sohl (1983), Rakesh Vohra (1985), Noel Bryson (1988), Hiren Trivedi (1990), Anito Joseph and Pablo Zafra (1993), and Pallabi Guha Roy (1999).

As a respected citizen of the University of Maryland, Saul was asked to participate in important committees, especially when sensitive issues needed to be tackled. Two of his contributions are still in effect at the Robert H. Smith School of Business: As the chairperson for the committee that designed the faculty pre-tenure and post-tenure reviews, Saul prepared the "Gass Report," which continues to govern the review process at the Smith School. Also, as a repeat member of the annual merit review committee, Saul suggested a framework for ranking the faculty reports and is reputed to have advocated the use of AHP for this task!

Saul garnered many university honors in the course of his academic career. He was designated a University of Maryland Distinguished Scholar-Teacher in 1998. He held the Westinghouse Professorship during 1983-1992, and was appointed Dean's Lifetime Achievement Professor in 2000. In July 2001, he was appointed Professor Emeritus.

Saul's professional honors also make for a long list. He served as the 25th President of the Operations Research Society of America (ORSA) in 1976-77 and was elected an INFORMS Fellow in 2002. In 1991, he was awarded the Kimball Medal for service to ORSA and the profession, followed by the INFORMS Expository Writing Award in 1997. Saul received the 1996 Jacinto Steinhardt Memorial Award of the Military Operations Research Society (MORS) for outstanding contributions to military operations research.

Saul served as President of Omega Rho, the international operations research honor society in 1985-1986, Vice President for international activities of the Institute for Operations Research and the Management Sciences (INFORMS), and Vice President for the North American Operations Research Region of the IFORS Administrative Committee. He was general chairman of the 1988 TIMS/ORSA meeting held in Washington. Saul was invited to deliver the plenary address at the May 1996 INFORMS Washington, DC conference and the San Francisco TIMS/ORSA meeting in 1984. In 1994, Saul gave the third E. Leonard Arnoff Memorial Lecture at the University of Cincinnati.

While at the University of Maryland, Saul maintained a close relationship with the National Institute of Standards and Technology (NIST – formerly the National Bureau of Standards or NBS). Aside from several consulting projects, Saul organized a number of conferences through NIST. The most recent such conference, which he organized and co-chaired with Al Jones, was a workshop on Supply Chain Management practice and research co-sponsored by the NIST, the National Science Foundation, and the Robert H. Smith School of Business, University of Maryland. Selected papers from this conference were collected in a special issue of *Information Systems Frontiers* [135].

6 The OR Scholar

In this section, we focus on Saul's contributions to OR methodology and applications. We review the methodological contributions under two broad categories: the theory of LP and its extensions and decision making tools. We also describe Saul's work as a builder and user of OR models developed for specific applications. His work on the modeling process will be covered in the next section.

6.1 Linear Programming and Extensions

Saul's first major and lasting contribution to the theory of linear programming was his work on the parametric objective function with Thomas Saaty [121, 122, 144]. The idea arose within Project SCOOP in 1952. Walter Jacobs introduced Saul to this problem in the context of production smoothing. In production planning problems, one faces the dual objectives of minimizing the monthly fluctuations in production *and* the inventory carrying costs. By attaching weights to the two objectives, one can express this as a single objective LP, where the key parameter reflects the ratio of the cost of a unit increase in output to the cost of carrying one unit of inventory (see [51, pp. 353-358]).

Saul first solved this transformed parametric problem by hand on some test problems using a modified simplex tableau. When Thomas Saaty joined SCOOP in the summer of 1952, he and Saul worked out the details with some help from Leon Goldstein and Alan Hoffman. This resulted in three well-known papers by Gass and Saaty that address the parametric problem

$$\begin{aligned} &\text{Min } (c + \lambda d)\, x \\ &\text{s.t.} \quad Ax = b, \\ &\qquad\quad x \geq 0, \end{aligned}$$

where c and d reflect the cost vectors of the two conflicting objectives and λ is the parameter to be varied. The first paper [144] described the case where some components of the new costs $c + \lambda d$ are linear functions of λ and described how each basic optimal solution remains optimal for a range of values that defines a closed interval of values for λ. Moreover, by tracking these contiguous intervals, a finite number of optimal solutions can be obtained to account for all possible values of λ. Gass and Saaty [121] specified the algorithmic steps of the parametric problem that is described in Saul's [26] and other LP texts. Gass and Saaty also published a companion paper [122] that considered parametric programming when the costs depended on two independent parameters λ_1 and λ_2. For a historical view of the development and impact of parametric programming and Saul's seminal role, see Gal's historical reviews [20, 21].

The conceptual link between parametric programming and Multi-Objective Linear Programming (MOLP) problems was present in Saul's mind. Recalling how Walter Jacobs gave him the task of solving the parametric version, Saul writes:

> This led to the parametric programming algorithm in which we balanced off two competing linear objectives by the single parameter. We recognized that the scheme could be generalized to more objectives and described a multi-parameter approach where two objectives meant one parameter, three objectives, two parameters and so on. [83]

Saul's interest in goal programming dates back to the mid 1970s. He traces its development to his consulting days at Mathematica, where he encountered goal programming features in most planning models for the government [83] and used this model in his work on personnel planning models [9, 67]. Such models are typically large-scale goal programming problems involving thousands of deviation variables. Saul has addressed the problem of setting the objective function weights for these variables in a consistent way [53, 57]. Also related to this area is Saul's critique of preemptive goal programming [57].

In a string of papers, Saul and Moshe Dror have proposed an interactive approach to MOLP [14, 15, 16, 107]. In a more recent paper with Pallabi Roy, Saul proposes the use of a compromise hypersphere to rank efficient extreme point solutions to an MOLP [120]. In a vector maximization problem with q objectives, the utopian solution that simultaneously maximizes all q objectives is typically unavailable. There are various ways of defining a *compromise solution* that attempts to strike a balance among the q objectives. The approach proposed by Gass and Roy is to find an annulus of minimum width that encloses the efficient solutions in the q-dimensional objective space. We discuss this below, when we review Saul's work on fitting circles (or spheres) to a collection of points [130].

Encounters with Degeneracy: Among the topics of interest to Saul within LP are degeneracy and cycling. Describing his "encounters with degeneracy," Saul [71] traces the roots of this interest to his days at Project SCOOP and provides a proof for an unpublished result due to Leon Goldstein. The result states that a basic feasible solution with a single degeneracy cannot cause a cycle and appeared as an exercise in the first edition of Saul's text [26] (problem 2, p. 70). Saul made the useful distinction between *classical cycling* and *computer cycling* [40]. The former is what we usually see in textbooks of LP and refers to cycling when the computations of the simplex algorithm are carried out accurately without round-off errors. Computer cycling refers to cycling encountered when solving the LP with a computer system, and hence is "*a function of the mathematical programming system being used*" [40]. Neither concept logically implies the other: A problem can exhibit classical cycling but not computer cycling. In fact, recently Gass and Vinjamuri [128] performed a test of 11 LP problems that cycle classically but are solved successfully by three popular simplex solvers. Saul also studied the effect of degeneracy in solving transportation problems [63]. It is worth noting that Dantzig [11] and Magnanti and Orlin [140] have shown how parametric programming can be used to avoid cycling, thus bringing together two strands in Saul's research program.

Other early work of Saul's on linear programming includes his short note on an initial, feasible solution for a linear program [24], and a transportation-based algorithm for meeting scheduled manhour requirements for a set of projects [25]. Saul's next major algorithmic work in linear optimization was in the area of large-scale systems and constituted his doctoral dissertation.

The Dualplex Method: Saul introduced and studied the Dualplex algorithm in his doctoral dissertation [29, 32]. The problem was motivated by an application with a staircase structure in the technology matrix. The problem may be conceptualized as involving K stages, coupled by a set of "tie-in" constraints. In a decomposition approach, it is natural to handle the coupling constraints in such a way as to fully exploit the block structure of the individual stages. Saul used this approach focusing on the dual problem for handling the complicating variables. The following account, which is necessarily very brief, is meant to outline the approach.

Assume that the LP problem can be put into the form:

$$\begin{aligned} &\text{Min} \quad c\,x + d\,y \\ \text{s.t.} \quad & w + A\,x + B\,y = b \qquad (1) \\ & w, x, y \geq 0 \end{aligned}$$

where w is the vector of basic variables, and the non-basic variables (x, y) are partitioned in such a way that the activities corresponding to the x variables appear in only one stage, while those for y appear in more than one stage and serve to couple the various stages. The matrix A therefore exhibits block-diagonal structure: it consists of the submatrices A_1 , A_2 , ..., A_K on the diagonal and zeros elsewhere. Correspondingly, we partition x by stage as $x = (x_1 , x_2 , \ldots, x_K)$. We rewrite constraint (1) as follows for stage k $(k = 1, \ldots, K)$.

$$w_k + A_k\, x_k = b_k - B_k\, y^0 \, . \qquad (2)$$

Now suppose that the dual problem

$$\text{Min } \pi b \quad \text{s.t.} \quad \pi B \geq d \;\; , \;\; \pi \geq 0 \qquad (3)$$

is solved to obtain the multipliers $\pi^0 = (\pi_1{}^0 , \pi_2{}^0 , \ldots, \pi_K{}^0)$ and an associated set of values y^0. We construct the solution $(w^0, x^0 = 0, y^0)$ to the original problem and test it for optimality by computing the reduced costs $c_k - \pi_k{}^0 A_k$. If this vector has any strictly positive components, then the optimality condition does not hold and the solution can be improved by introducing a variable with positive reduced cost from stage k into the basis. A key attractive feature of the dualplex method is that up to K such variables (one for each stage) can be pivoted into the basis at the same time. Once this is accomplished, the form given in (1) can be recovered with new values for the quantities A_k, B, b, c_k, and d, and the dual system (3) can be resolved again. For this approach to be effective, the previous basis for (3) should be exploited in full. This is where most of the technical details of the procedure have to be worked out. These are presented in [29], together with proof of the correctness of the overall algorithm.

Apart from the proceedings article [32], Saul did not publish anything on the dualplex method for over 20 years. He returned to this algorithm in his joint work with doctoral students at the University of Maryland. The algorithm is applied to the knapsack problem with generalized upper bounding (GUB) constraints and the piecewise linear approximation to the separable convex minimization problem [123]. In [4], the method is proposed for solving discrete stochastic linear programs.

Fitting Circles to Data Points: How does one fit a circle to a given set of points in the plane? This simple geometric question led to a collaboration among Saul, Christoph Witzgall, and Howard Harary [130]. To clearly define the optimization problem, one must specify a measure of fit. The criterion Saul and his coworkers use for fit is a modified Chebychev minimax criterion. To define it, suppose that *n* points P_i with coordinates (x_i, y_i), $i = 1, \ldots, n$ are fixed on the plane. Consider a circle of radius r_0 with its center located at (x_0, y_0). Let r_i denote the distance from the center to the point P_i with a radial line. If $r_i = r_0$, then P_i lies on the circle constructed and a perfect fit obtains. Otherwise, we consider the difference of the squared radial distances $| r_i^2 - r_0^2 |$ as the error term. The objective is therefore

$$\text{Min Max}_{i=1,\ldots,n} | r_i^2 - r_0^2 |,$$

or

$$\text{Min Max}_{i=1,\ldots,n} | (x_i - x_0)^2 + (y_i - y_0)^2 - r_0^2 | .$$

Since the (x_i, y_i) are fixed for $i = 1, \ldots, n$, the decision variables are (x_0, y_0) and r_0. These are the variables for which the outer minimization problem is solved. This problem can be formulated as a linear program [129]. Extensive computational experience with this problem is reported in [130], and these results show that the squared formulation above provides a very good approximation to the minimax criterion without squares, that is Min Max $| r_i - r_0 |$. The paper by Witzgall in this volume provides further details and developments of this approximation problem.

As described in [130], this problem arose from a manufacturing setting where coordinate measuring machines calibrate circular features of manufactured parts. Once the center of the fitted circle is determined, one can use it to define two concentric circles that are the inscribed and circumscribed circles for the *n* points. This defines an annulus of minimum width that contains all *n* points and is checked against tolerances in the manufacturing setting. Saul has adapted this basic idea to his research on MOLP [120]. The basic idea of a minimum-width annulus is used, now extended from circles in the plane to hyperspheres in $\mathbf{R}^q$. The given points correspond to vector-valued objectives of the available efficient points. Gass and Roy [120] describe how to use the minimum-width annulus to rank efficient points in the MOLP.

Modified Fictitious Play: Early in his career, Saul was exposed to the elegant results that established the equivalence of matrix games and LP. He has since expressed his appreciation for this result (see for example, p. 60 of [97]). He has also described how Alex Orden used the fictitious play method as one of the solution methods for LP in his computational work on the SEAC [81, 97]. Saul returned to this early interest in his work with Pablo Zafra [131,132]. The method of fictitious play was proposed by Brown [3] as an iterative method where the players take turns and at each play, each player chooses "*the optimum pure strategy against the mixture represented by all the opponent's past plays*" [3]. The convergence of this method, while guaranteed theoretically, can be extremely slow.

To speed up convergence, Gass and Zafra [131] modify the fictitious play method by using a simple restart method based on the existing lower and upper bounds on the value of the game. The modified fictitious play (MFP) procedure is then tested to assess its value as a computational procedure for finding initial solutions to LP problems. This MFP start is tested in combination with simplex-based or interior point LP solvers and found to be useful for certain types of linear programs. Gass, Zafra, and Qiu [132] show that MFP can achieve the same accuracy as regular fictitious play with 40-fold reductions in the number of iterations and significant savings in computational times.

In several publications, Saul and his coworkers Anito Joseph and K. Osei-Bryson have studied integer programming problems and proposed bounds, heuristics, and problem generation issues. This stream of research has resulted in several publications [136, 137, 138, 139] that detail the procedures and provide computational experience.

6.2 The Analytic Hierarchy Process (AHP)

Saul has maintained an interest in AHP [18, 143] since its inception. As he mentions in [95], he taught the subject at the University of Maryland since the early 1980s [2] and was the first author to discuss it in a text (chapter 24 of [50]). His expository article on AHP co-authored with Ernie Forman [18] covers the basics and describes 26 applications of AHP in different domains. In [95], Saul reviews the arguments of critics who fault AHP for violating the axioms of multiattribute utility theory (MAUT) and concludes that AHP is an alternative approach to MAUT that offers its own advantages.

Saul has also proposed the use of AHP in several new areas. In large-scale goal programming models for personnel planning, the decision maker must assign weights to thousands of deviation variables in the objective that measure the differences from the desired target values. In one realistic example, 13,900 such variables are present. Saul proposes the use of AHP to determine the priorities and weights in such models [53]. With Sara Torrence, Saul [127] has described the use of the AHP to rate the complexity of conferences for the Public Affairs Division of the National Institute of Science and Technology (NIST), which plans and coordinates approximately 100 conferences a year. The complexity of each conference is determined based on two AHP hierarchies used to provide ratings for both the time required and the level of expertise needed from the staff assigned to the conference. Saul has also proposed using AHP to provide a numerical rating for model accreditation [70].

Saul's most interesting methodological contribution to the AHP appears in his work with Tamás Rapcsák. Consider the pairwise comparison $n \times n$ matrix $A = (a_{ij})$ as constructed in Saaty's AHP and denote its maximum eigenvalue by λ_{max} [143]. It is well known that the vector **w** of weights or priorities of the alternatives in Saaty's AHP is the normalized right eigenvector of A corresponding to the largest eigenvalue λ_{max}, so that $A\,\mathbf{w} = \lambda_{max}\,\mathbf{w}$ and the sum of components of **w** is unity. Gass and Rapcsák [118, 119] propose a different derivation of the weights that makes use of the *singular value decomposition* (SVD) of A. If the $n \times$

n matrix A has rank k, the singular value representation is given by $A = U D V^T$, where D is a $k \times k$ diagonal matrix and U and V are matrices that satisfy $U^TU = I$ and $V V^T = I$. The diagonal entries of D, which must be positive are called singular values; we arrange them so that $\alpha_1 \geq \alpha_2 \geq \ldots \geq \alpha_k$. Let $\mathbf{u}_i$ and $\mathbf{v}_i$ be the columns of U and V for i = 1,..., k. The main result from singular value decomposition is that for any $h \leq k$, the matrix

$$A_{[h]} = \sum_{i=1}^{h} \alpha_i \quad u_i \quad v_i^T \tag{4}$$

constructed from the h largest singular values of A is the best rank h approximation to the original matrix A in the sense of minimizing the Frobenius (matrix) norm $\| A - G \|$ among all matrices G of rank h or less. (The Frobenius norm of a matrix is simply the Euclidean norm of the vector defined by the n^2 entries of the matrix.)

If the matrix A is *consistent* (i.e., $a_{ik} = a_{ij} \; a_{jk}$ for all i, j, k), then it is of rank 1 and its SVD consists of only the first term or diad of (4). In AHP, however, the pairwise comparison matrix A is typically not consistent. Gass and Rapcsák [119] argue that the use of the matrix $A_{[1]}$ is still justified as the best rank-one approximation to A and provide a simple expression for the weights **w** in terms of the singular vectors $\mathbf{u}_1$ and $\mathbf{v}_1$ corresponding to the largest singular value α_1 and prove that these weights are identical to the standard AHP weights if A is consistent. In addition, they provide a measure of consistency based on the Frobenius norm. In this way, they provide an alternative approach to the computation of priorities with certain appealing theoretical underpinnings, but acknowledge that further investigation of the relative merits of this approach is warranted.

Saul has also investigated the occurrence of intransitive relationships in pairwise comparison matrices [84]. An intransitive relation occurs when we have A > B > C > A where A > B means that item A is preferred to B. Given a pairwise comparison matrix $A = (a_{ij})$, we can construct a binary $n \times n$ preference matrix $P = (p_{ij})$ with zeros on the diagonal, where $p_{ij} = 1$ if item i is preferred to item j, in which case $p_{ji} = 0$. The preference graph corresponding to P is a directed graph with an arc from i to j if $p_{ij} = 1$.

Clearly, an intransitive relation among three items corresponds to a cycle of length three or a *triad.* It can be shown that triads are present if any cycles of higher order exist. Thus, searching for triads as the elemental representatives of intransitivity is appropriate. In [84], Saul reviews the known results for the number of triads in preference graphs and proposes using a transshipment algorithm to identify triads.

One might ask how frequently intransitive relations occur in the context of the AHP. The empirical study of Gass and Standard [125] sheds some light on this question. They consider 384 instances of positive reciprocal comparison matrices taken from real-world AHP studies and consider the distribution of the numbers in the basic 1-9 comparison scale. They also investigate the incidence of intransitive relations in such matrices.

6.3 OR Applications

In this section, we review Saul's work as a builder and user of OR models developed for public or governmental planning and analysis.

Design of Patrol Beats: One of the earliest applied modeling studies conducted by Saul was his work on the design of patrol beats: Given k patrol units to be assigned during a patrol shift, the problem is to design k patrol beats so as to equalize workload [30]. The area assigned to each patrol beat must have desirable geometric properties: it must be contiguous and avoid shapes (such as long and narrow) that would make patrolling difficult or inefficient. As such, the problem has some similarities to the well-known political districting problem. The computation of the workload for a given area requires historical data on the incidence of various types of incidents by census tract. The problem is solved with a heuristic developed for political districting that uses a transportation subproblem. The computations of the design study were carried out using 1966 data for the City of Cleveland, which had 58 beats and 205 census tracts.

Traffic Safety: Together with Nancy David and Robert Cronin, Saul [105] conducted a simulation study on the role played by citizens band (CB) radio in traffic safety for the National Highway Traffic Safety Administration (NHTSA). The main task of the simulation model is to compare the response times for the case where the highway patrol system has CB installed to the case when CBs are not used. The simulation model tracks the movement of vehicles and the occurrence of incidents along a single road link with two-way traffic. It is assumed that a vehicle with CB can report an incident to a patrol car with CB, or to the highway patrol base station. As an example of the summary statistics produced, the model indicated that the time to accident notification with the use of CB is 47% of the time without CB, and that the time to actual response to the accident with CB was 75% of the time to response without CB. Similar percentages were developed for other incidents that compromise traffic safety (e.g., roadway hazards).

In another project for the NHTSA, Gass, David, and Levy [106] describe a system flow model that captures the common structure of NHTSA traffic safety demonstration projects. This common structure involves the flow of people through a network of stages where the stages correspond to activities of a traffic safety program. For example, the flow might track convicted DWI offenders and a program might be a special treatment for a subset of such offenders. The stages can be modeled as queueing subsystems with sojourn times and delays. The model tracks the flows between successive stages, exit flows, and recidivism. The authors describe the model details and illustrate the structure with a case study on DWI probation.

Personnel Planning Models: Another class of models that can also be viewed as flow models are personnel planning systems. The basic personnel planning problem is to "*determine the* number *of personnel and their skills that best meets* *the future operational requirements of an enterprise*" [67]. In his review paper [67], Saul describes the basic structure of these models as integrating a Markov transition submodel with a network (or LP) optimization model. Saul's work in this area has focused on military manpower planning. In 1984, Saul was engaged as a consultant by Sigma Systems to extend and implement the Army Manpower Long Range Planning System (MLRPS). This model was originally designed in 1982-83 and moved to the Army computer in Washington, D.C. in August 1983.

U.S. Army personnel models are "*designed to determine by grade, skill, and/or years-of-service, the number of soldiers (or officers the Army can put in the field... so as to meet manpower goal over 7- to 20-year planning horizons.*" [104]. The flow model uses a Markov chain to project the flow of personnel accounting for transitions due to promotions, separations, skill migrations, and so forth. This is coupled with an optimization model that analyzes how the Army can best achieve a future force structure starting from its present state. The optimization goal programming (GP) model is driven by the goals the user inputs for skill-grade combinations by time period. The model allows the user to address such policy questions as "*what accessions, promotion and separation rates will best transform the Army's present force structure to the one that will be required 20 years from now?*" [104]

Personnel planning models are generally large-scale [49]. A typical model may have 7 grade classifications and 33 skill identifiers, which gives 7 x 33 = 231 grade-skill combinations to track over T years. If T = 10, the linear goal programming formulation of the MLRPS has 9,060 equations and 28,730 variables, of which 13,900 are deviation variables associated with the target goals. Saul's work with the MLRPS model led him to investigate procedures for setting the objective function weights for large-scale GP models [53] and exploiting the network structure within large GPs [79]. Saul has also studied the Accession Supply Costing and Requirements (ASCAR) model that determines the recruiting needs of an all volunteer Armed Forces to meet target goals [9].

In reviewing Saul's work on modeling, it is also important to mention his edited volumes where one can find comprehensive reviews of models in a given domain. The Gass and Sisson edited volume [124] is an early and important example of this category. This volume was prepared for the Environmental Protection Agency to review governmental, urban, and public modeling efforts. Environmental topics such as waste management and air pollution are discussed. The book has a much broader range, however, covering such areas as justice, education, health, and transportation planning. Saul's work on expert systems in emergency management [102, 103] is another example.

7 The Expositor of OR

Many individuals in the field of OR first came to know Saul through his linear programming text. Others may have first read one of Saul's articles in *Interfaces*. Today, we recognize Saul as one of the master expositors of OR and the recipient of the INFORMS Expository Writing Award for 1997. How did this dimension of Saul's career develop? To find the roots, *cherchez Project SCOOP*!

Saul wrote his first expository paper on LP at the request of Walter Jacobs at Project SCOOP. Jacobs asked Saul to prepare a non-technical pamphlet on LP aimed at an Air Force audience. The result was a guide entitled, "The Application of Linear Programming Techniques to Air Force Problems," published as an internal USAF paper in December 1954 [23]. This guide is 27 pages long and makes use of Air Force applications. For example, the transportation problem is introduced as shipping units of equipment required for the B-47 from three source Air Force bases to five destinations. Saul also describes a production smoothing problem and points out the conflicting objectives of minimizing the fluctuations in output and the excess monthly surpluses. The guide ends with a discussion of the contracts awards problem that arises when the Air Force procures items from civilian sources. Each bidder offers the unit at a known price and must observe minimum and maximum limits on its production quantity. The Air Force must award contracts in such a way as to minimize the total cost. This problem reappears in Saul's texts [26, 50].

The origin of Saul's *Linear Programming* text goes back to the introductory LP course George Dantzig taught at the US Department of Agriculture (USDA) Graduate School in 1950. When Dantzig left for RAND, George O'Brien – a part-time researcher at Project SCOOP – taught the course in Fall 1952. O'Brien, in turn, asked Saul to teach the course when he left the Washington area for Detroit. He then prepared a set of notes for the USDA course that he also taught to his coworkers at the Pentagon. This led to the notion of writing a text on LP. The material in Gass' text was originally prepared for a semester-long course with 16 lectures, each 2.5 hours in duration. In 1954-55, Saul sent a couple of chapters to a few publishers, until McGraw-Hill signed a contract to publish the text. He finished writing the text during his first year at IBM (1955-56). During this time, Saul went to the Library of Congress on Saturdays to do his writing. Appropriately, the dedication to Trudy Gass mentions "lost weekends."

Published in 1958, this was the first text on LP. In fact, the only book-length accounts of LP preceding Saul's text were the monographs by Charnes and Cooper [7] and Vajda [148]. The first edition of *Linear Programming* was translated into Russian in 1961 and was the first book on the subject in the Russian language. Later, the text was also translated into Spanish, Polish, Czechoslovakian, Japanese, and Greek, providing the first text on LP in these languages as well. Subsequent editions appeared in 1964, 1969, 1975, and 1985. The fifth edition of this text [51] was also reprinted as a Dover paperback in 2003.

The first edition of the text comprised 12 chapters. The first chapter introduced LP and gave three examples: the transportation problem, activity-analysis, and the diet problem. Chapter 2 provided basic mathematical background on linear algebra and convexity. Chapters 3-9 developed the theory and algorithmic procedures for LP. The last three chapters covered the transportation problem, general LP applications, and the relation between LP and the theory of matrix games. The book also included a bibliography of LP applications organized by application domain and based on the Riley-Gass bibliography [141]. A comparison between the first and fifth editions is given in Table 1.

Table 1. Comparison of the contents of the first and fifth editions of *Linear Programming.*

	First Edition	*Fifth Edition*
Publication year	1958	1995
Number of pages	223	532
Length (in pages) of chapter on LP applications (Ch. 11)	32	77
Number of references	102	736
Number of works in the applications bibliography	91	433
Number of exercises	43	380

Saul also published another major book and work of reference in May 1958. This was the compendium entitled *Linear Programming and Associated Techniques: A Comprehensive Bibliography on Linear, Nonlinear, and Dynamic Programming*, published by the Operations Research Office (ORO) at the Johns Hopkins University. This bibliography cited over 1000 items that included articles, books, monographs, conference proceedings, and theses. The cut off was set for June 1957 (Saul's LP text is cited as *in press*!). The book was divided into three parts. Part I provided the introduction and Part II covered the general theory. Part III of the bibliography, which was devoted to applications, accounted for 290 pages of the total 613 pages of the book.

Saul's co-author, Vera Riley, was Staff Bibliographer at ORO. While she had no training in OR or mathematics, she located the key references and was adept at reading a document and abstracting its main contributions. To expedite the work, Riley and Gass used the abstract provided by the work cited. However, when a cited work did not have an abstract that could be readily used (as with books), Saul wrote the annotation for the bibliography [99].

In 1961, Saul published a survey of recent developments in LP as a chapter in the prestigious series *Advances in Computers* [27]. The topics reviewed in this chapter include decomposition methods, LP applications, stochastic LP, integer programming, and nonlinear programming. Most of the research and references cited in this work were published during 1957-1960. Thus, in a sense, the work updated the Riley-Gass compendium [141] in the domain of LP. Of special historical interest is the section on LP codes and procedures, which comprises close to 40 of the 83 pages of the chapter. In this section, the LP codes are arranged by computing machine, and then by problem type. The reader will find many codes where the problem size is constrained by $m \leq 100$ or $m\,n \leq 1500$.

Among Saul's books, the primer entitled *An Illustrated Guide to Linear Programming* occupies a unique position [31]. The novelty lies in the illustrations and the lively and humorous expositional style. Not counting graphs and tables, there are 25 illustrations involving graphic characters conjured by the illustrator

William F. McWilliam to bring the concepts to life. Previously, Williams' primer on game theory [149] had made use of illustrations. But in the opinion of this reader, the illustrations in [31] are more elaborate and support the discussion in the text more effectively.

The first half of the *Illustrated Guide* is devoted to problem formulation. The reader encounters the classical LP problems: the transportation problem and traveling salesman problems, the caterer and trim problems, personnel assignment and activity analysis. The caterer problem, for example, is described as a management science consulting assignment addressing the issue of dirty napkins for the Mad Hatter's tea parties. The consultant's report appears in a different typescript under the title: *An Analytical Analysis of Interactive Activities as related to the Economics of Functional Gatherings: A preliminary linear programming model of a tea-party subsystem*. Clearly, Saul was writing as one who knew the consulting profession all too well!

Despite the introductory nature of the text, Saul takes the time to explain the historical origins of some of the military applications. A historical footnote explains that the caterer problem disguised the procurement of repaired aircraft engines. Another footnote recounts the origin of the contract-awards problem, which goes back to Saul's Project SCOOP days:

> The relationship between the contract-awards problem and the transportation problem was first discovered and exploited by mathematicians of the U.S. National Bureau of Standards (NBS), working with personnel from the Philadelphia quartermaster depot. Prior to the advent of linear programming, each problem was solved by submitting the bids to a series of evaluations conducted by different analysts. When no change could be found, the successful bidders would be announced, and everyone would hope for the best. When the first operational tests were conducted using the NBS computer, the SEAC, the quartermaster group continued to solve the problems with their analysts in order to build up the necessary confidence in the linear-programming approach. The computer solutions were always better than, or at least as good as, the quartermaster solutions. [31, pp. 107-108].

In 1985, Saul published a new textbook entitled *Decision Making, Models and Algorithms* [50]. The objective of this text was to expose the mathematically inclined undergraduate student to the decision sciences as used in OR/MS. Of the 22 chapters of this text, 16 are taken from the *Illustrated Guide*. Thus, this new text is partly a reincarnation of Saul's 1970 classic, complete with the illustrations that enlivened the *Guide*. However, *Decision Making* also has much new material, including chapters on modeling, decision trees, and the AHP. Of special pedagogical interest is the material collected in the five chapters that close the five parts of the book. These chapters reflect Saul's skills of exposition and his passion for explaining the methods and practice in an accessible way.

Saul's major book-length work in the 1990s is the *Encyclopedia of Operations Research and Management Science,* which he edited with Carl M. Harris [110, 111]. Saul was approached by the publisher to embark upon this project in 1994.

Saul invited Carl Harris to join him, and it took them two years to complete the *Encyclopedia*; the first edition was published in 1996.

The second edition [111], which appeared in 2001, is over 900 pages long and lists 1136 entries. The editors commissioned over 200 expository articles that run 3-6 pages in length. One of the noteworthy features of this work is its list of contributors. The editors succeeded in soliciting contributions from leading authorities in OR and management science. Having read a large number of the longer entries, I believe that the *Encyclopedia* is also an expository triumph: special care is taken to make the articles accessible and tutorial in nature. The book is dedicated to Carl Harris and Hugh Miser, *in memoriam*.

This section has mainly focused on Saul's book-length publications. Saul is also well-known for his expository or review articles. These works are not discussed in this paper but the following examples may be cited: AHP and rating [2, 18, 87, 95]; LP and extensions [52, 63, 71]. Modeling and applications [47, 59, 67, 68], and teaching OR [112, 2, 80].

8 Manager of the Modeling Process

8.1 Scrutinizing the Modeling Process

For close to thirty years, Saul has studied not just the technical contents of models, but the "*total environment of decision-making with models,*" which he has chosen to call "*managing the modeling process*" [56, 66]. Saul's interest in the area was an outgrowth of a series of studies sponsored by the National Institute of Standards and Technology (NIST), The Department of Energy (DOE), and the U.S. General Accounting Office (GAO). Saul also drew upon his experience with OR studies and projects in the public sector during his consulting years.

In the early 1970s, Saul became involved in the evaluation of police protection models as a principal investigator of the National Science Foundation grant to Mathematica. His task was to evaluate 50 models based on the documentation provided and the accompanying research papers. Saul was faced with the challenge of developing a framework for evaluation. Reflecting on the project, he writes:

> Our first problem was to determine what was meant by evaluation and how you do it. The literature gave little guidance, so we developed our own evaluative process. I quickly learned that analysts do not document, cannot, or will not write well, do not state their modeling assumptions, are unclear as to their data sources, maybe perform sensitivity analyses but do not tell you, and so on.... For me, the outcome was to start thinking about the problem of what we really mean by good modeling practices and implementation, and how do you evaluate model-based projects. [56]

Saul's next investigation of the modeling process was to help the U.S. General Accounting Office (GAO) develop a procedure for the evaluation of complex models. The historical background on the events that led to this effort is provided in [73] and [81] and is briefly summarized here.

In the mid-1970s, Federal agencies were using computer-based policy models to support the executive branch in addressing policy and legislative issues in such areas as energy and welfare. Congress wanted to know how these models worked and directed the U.S. Government Accounting Office (GAO) to evaluate the Project Independence Evaluation System (PIES) model developed by the Federal Energy Agency. In 1976, GAO published its review of PIES [145], marking the first federal effort in model evaluation. Soon afterwards, a provocative GAO report [146] suggested that model development activities can be improved in a host of different ways. In the face of such concerns, the question of model evaluation arose naturally: How does one conduct an evaluation of a complex computer-based policy model? Moreover, the evaluation of PIES caused GAO to recognize the need for a more formal process of model evaluation. It is important to recall that PIES was the first experience of GAO in assessing complex policy models and that in 1975-1976, the prior literature on this subject was *"basically non-existent."* [56].

In April 1977, Saul organized a workshop at NBS [39] to expose model developers and users to the GAO report [146] and to elicit reactions from this group. The main controversial topic was GAO's gated approach with five phases, each of which could potentially arrest further development of the model. Also discussed was Saul's questionnaire-based approach to model assessment [35, 36]. The discussions at the workshop reinforced Saul's belief in the need for a life-cycle approach to computer model development and documentation. Saul's framework defined thirteen phases starting from embryonic initiation, through development and validation, to implementation, maintenance, evaluation, and documentation [37, 38]. Along with Bruce Thompson, Saul also continued his involvement in shaping the framework GAO was preparing to guide model evaluation. The final document appeared in 1979 as the publication *Guidelines for Model Evaluation* [147]. As Saul [81] put it, *"the importance of this document is that if project personnel were constrained to furnish the evaluative information suggested by the 'Guidelines', the success rate of our modeling projects would increase greatly."* The GAO Guidelines identified five major criteria for model evaluation: Documentation, validity (theoretical, data, and operational), computer model verification, maintainability (updating and review), and usability. To bring its message to the attention of OR analysts, Gass and Thompson published a summary of the *Guidelines* in *Operation Research* [126].

Saul's perspective on managing the modeling process has drawn from his long involvement with the assessment of energy models. He has cited the case of DOE's Energy Information Administration (EIA) on several occasions for having *"put into place a quality assurance program that, except for nuclear and some defense activities, is probably the most advanced in the world"* [81]. Saul was an early contributor to the EIA quality assurance and evaluation program. In the mid-1970s, he was funded by EIA through NBS, along with parallel efforts at MIT (Edward Kuh and David Wood), Berkeley (David Freeman), and Stanford. Saul's work in this area resulted in his first publications on the subject [35, 36], followed by a review of different assessment frameworks for energy models [41, 43, 44].

8.2 Evaluation of Complex Models

In one of his first publications on the modeling process, Saul defines model assessment or evaluation as "*the process by which interested parties, who were not involved in the model's origins, development and implementation, can assess the model's results in terms of its structure and data inputs so as to determine, with some level of confidence, whether or not the results can be used in decision making*" [35]. This process is necessary because (a) the ultimate decision makers are typically far removed from the modeling process, (b) the applicability of the model to a new domain of use must be assessed, and (c) because the complex interactions between the model assumptions, inputs, structure, and results are best understood through a formal independent evaluation process. Saul states the basic philosophy behind model assessment and its relevance to the analyst in the following terms:

> In the development of any model, the model developers should assume that their model will be subjected to an independent assessment, and thus, it behooves them to impose the explicit discipline of an assessment methodology and related project management controls to ensure that acceptable and correct professional procedures are imposed on all aspects of the model structure and use. [19]
>
> The OR analyst should be particularly concerned with the model evaluation process because the outcome of an evaluation is really a recommendation to the decision maker whether or not to use the output of the analyst's model. [46]

Saul's approach to model evaluation appears in a string of publications [35, 36, 114, 126, 42, 43, 47] culminating in the comprehensive account provided in the *Operations Research* feature article [46]. Saul [43] reviews several frameworks for the assessment of energy policy models. His framework in this paper builds on and synthesizes previous proposals for evaluating computer-based and policy models. He adopts the distinction made by Fishman and Kiviat [17] between model verification and validity. Briefly stated, for computer-based models, "*the process of demonstrating that the computer program 'runs as intended' is termed verification.*" Model validation "*attempts to establish how closely the model mirrors the perceived reality of the model user/developer team.*" [46]

Verification must ensure that the computer program describes the model accurately, has no errors of logic, and that it runs reliably. As such, verification is chiefly the concern of programmers and must precede the validation process. Following the GAO framework [126] that Saul helped develop, validation comprises three major components: technical, operational, and dynamic validity. "*Technical validity requires the identification of all model assumptions, including those dealing with data requirements and sources, and their divergences from perceived reality.*" It can further be subdivided into model validity, data validity, mathematical, and predictive validity. The last element examines errors reflecting the difference between actual and predicted outcomes. Operational validity assesses "*the importance of errors found under technical validity*" and includes sensitivity analysis. Finally, dynamic validity examines "*how the model will be maintained during its life cycle so that it will continue to be an acceptable representation of the real system.*" [46]

Saul also uses the assessment framework to propose a questionnaire for the utility evaluation of a complex model [36]. The questionnaire uses thirteen criteria to assess model utility as follows:

1. Computer program documentation
2. Model documentation
3. Computer program consistency and accuracy
4. Overall computer program verification
5. Mathematical and logical description
6. Technical validity validation
7. Operational validity
8. Dynamic validity
9. Training
10. Dissemination
11. Usability
12. Program efficiency
13. Overall model

In another study related to the utility of complex models, Saul [142] sought expert opinion on how the utility of large-scale models can be improved by surveying. The study surveyed 39 modelers with diverse affiliations and application domains to obtain their reactions to a list of 18 key ideas for model improvement (e.g., model user training, verification and validation plan, and a model ongoing review panel).

The preceding brief account suggests that model evaluation and assessment is a multi-faceted topic with fluid boundaries and subject to different interpretations. Saul's path through this maze is marked by a level-headed consideration of past frameworks, avoidance of rigid requirements, and pragmatism. Based on [58, 60] and other sources cited above, I would summarize Saul's overall view of model assessment as follows:

- there is no single "correct" assessment process that works for all models
- the assessment process can and should be formally developed
- the assessment process should be informed by the valuable past experience with complex models, their use, and implementation
- the assessment framework should remain attentive to the intended use of the model and what is practical or helpful to the ultimate users
- effective project management requires that a life-cycle view of model development and assessment be adopted
- assessment should not be an afterthought; it is expensive and ineffective to conduct *ex post*

- ongoing evaluation is a mark of professional quality and results in an improved development process overall
- the OR analyst should maintain a keen interest in the processes of evaluation

Based on his long-standing scrutiny of complex models, Saul is emphatic on the importance of model evaluation. Here is how he brings the point home.

> From our perspective, good modeling practice assumes that someone, someday, will knock at your door and shout: "Open up, it's the modeling police force! We're here to take your model down to Headquarters, question it to see what makes it tick, and plug it into the lie detector machine to determine if it tells the truth. You have three minutes to call your analyst, programmer, and lawyer". ... If you were the poor soul behind the door, what would you wish you had done so that the evaluation of your model comes out excellent? [81]

8.3 Model Documentation

The preceding account of model evaluation indicates the pivotal role played by model documentation in the process of independent or third-party assessment of policy models. Often, the analyst conducting such an assessment must often rely on the documentation provided for the model as the primary source of information. Moreover, "*it is clear that the lack of documentation hinders both the dissemination and use of models, especially models for analyzing policy decisions*" [113]. This makes model documentation a critical element of model usability. As Saul puts it:

> The evaluator must review the model documentation that will be made available to the decision makers, computer system operators, analysts, other possible users, and interested researchers. This review must establish the value of every type of documentation in terms of their specific purposes. The understanding of a complex model rests on the clarity of its documentation and its associated training program. [48]

> Documentation of a model is extremely important. A management plan for the production of documentation is an essential component of the management plan for a model... This must be understood by sponsors and developers and should be addressed (and funded) in contractual arrangements. [113]

In 1979, Saul and his coworkers conducted an assessment of a major modeling effort at the Energy Information Administration (EIA) of DOE. They evaluated a large-scale model called MOGSMS that provided forecasts of oil and gas supply and proposed guidelines to DOE on the organization of model documents [113]. Their hierarchical view of documentation has four levels and calls for twelve specific documents. The levels are (1) rote operation of the model, (2) model use, (3) model maintenance, and (4) model assessment. The relevant documents for each level are described and placed on a four-shelf "model bookcase" for visual effect.

In 1979, Saul prepared a report for the Institute for Computer Sciences and Technology of the National Bureau of Standards in which he proposed guidelines for the documentation of computer-based decision models of DOE. This report prescribed a total of 13 documents that corresponded to different phases of the life cycle of the model [38]. Saul has also summarized his guidelines for model documentation in a paper in *Interfaces* [48]. The outcome of the documentation process is four manuals directed at the analyst, the user, the programmer, and the manager. For each of these, Saul suggests a detailed table of contents.

Saul summarized the guiding theme of his approach to documentation as follows:

> The documentation of computer-based models should provide specific and detailed information organized and presented in a manner that will satisfy the needs of each segment of the model's audience. The audience consists of the model's sponsors and users (possibly non-technically oriented), the model's analysts, programmers, and computer operators; other users, analysts, programmers and computer operators; and independent model evaluators. [48]

8.4 Model Credibility

Suppose that a set of procedures for model assessment is agreed upon and followed. What is the ultimate result of following such procedures? Gass and Parikh [116, 117] discuss the notions of baseline analysis and credible analysis for complex policy models. Ultimately, a judgment is made on "*the measure of confidence or credibility a user should give to the model's results*" [46]. Saul reminds us of the subjective element in the notion of model confidence:

> We emphasize that model confidence is not an attribute of a model, but is an information-based opinion or judgment of a particular user for a given decision environment,... The level of confidence may vary from user to user because of differences in application requirements, and subjective judgmental preferences... Model confidence is subjective, each decision maker internalizes the available information by means of an imprecise algorithm for evaluating model confidence. [46]

While there is no precise procedure for determining this level of confidence, Gass and Joel [114] propose an approach and provide a set of criteria that an independent observer can use to rate (score) the model under evaluation. Building on this work, Saul suggests a modified approach for rating model accreditation based on the AHP. The criteria for the AHP are: specifications, verification, validation, pedigree, configuration management, usability, and documentation, each with its own list of subcriteria.

Together with several coworkers from the U.S. GAO, Saul also adapted the model assessment framework to evaluate simulation models and tested the approach on three Army simulation models [19]. The three simulation models were used in two antiaircraft defense systems—the portable surface-to-air Stinger missile and the division air defense gun (DIVAD). The objective of this study "*was to demonstrate that it is possible to systematically collect and analyze information about a simulation that would permit an assessment of the credibility of that simulation to be made*" and to identify the steps DOD had taken to ensure this credibility [19].

For each of the three simulation models evaluated (ADAGE, Carmonette, and COMO III), Fossett et al. [19] describe the type and key features of the model as well as its intended use. They assess the credibility of each model based on theory, model design, input data, correspondence to the real world, organizational support structures, documentation for users, and reports of strengths and weaknesses. Fosset et al. [19] acknowledge that "*of all OR methodologies, simulation has always been in the forefront of verification and validation research and stressed the necessity of applying verification and validation tests.*" The assessment framework they provide suggests that OR analysts may have focused on just a subset of the full list of assessment components that relate to validation and verification (e.g., input data quality, statistical representation, and sensitivity). One contribution of this study is to bring the challenges of assessment into sharper focus for a class of models that form an integral part of the OR toolkit.

Based on his assessment work on simulation models, Saul was invited to participate in the model validation, verification, and accreditation (VV&A) working group of MORS- the Military OR Society. A brief account of model accreditation and the relevant activities of this group is given in [81]. Other model assessment studies in which Saul participated include the evaluation of the Dynamic General Equilibrium Model, a dynamic model of the U.S. economy used to understand the impact of mobilization on the economy [6]. Finally, Saul has also participated in the development of guidelines for emergency management models [5].

9 The OR Professional, Statesman, and Ambassador

In 1996, in the course of a discussion of academics and practice as the two sides of OR, Saul summarized his career as follows.

> My career spans both sides of the OR Equation. For 25 years I worked as a mathematician and an OR analyst, and I directed OR for a couple of consulting firms; I had the good fortune to work in some important areas: Linear programming, the first man-in-space program, criminal justice, energy modeling and manpower systems. I have been there. For the last 20 years, I have been an academic. I have been there, too! [78].

If we add 10 years to the numbers cited, it remains an accurate description of Saul's 55-year long career in OR. Saul's experience base and his blend of academics and practice place him in a select group among the leading members of our profession. As a scholar and teacher, Saul has published extensively. His publications include six books, 80 journal articles, nine book chapters, at least 12 proceedings articles, 4 edited volumes and reports, and a dozen other occasional pieces. The counts given are based on the references given in this article and should be viewed as lower bounds. While reasonably comprehensive, this list leaves out some items and does not account for multiple editions, translations, and so forth.

Saul has written about the "three P's of OR: Practice, Process, and Professionalism" [58]. Remarkably, another facet of Saul's contributions emerges when one considers his involvement in the profession as an active and vocal citizen. This section focuses on this facet and its relation to the three P's of OR.

9.1 The OR Professional as Concerned Citizen

Saul's care and concern for the well-being of the OR profession has been a theme expressed in numerous articles, plenary addresses, position statements and other outlets. Chief among these is his collection of "Model World" articles in *Interfaces*. In these articles, Saul expressed his views on the full range of issues in our profession in an accessible and direct style. Twelve such articles have appeared during the period 1990-2005 addressing such issues as models and the modeling process [62, 64, 65, 112], the profession and its ethics [77, 82, 115], the history of OR [65, 89, 101], the meaning of such rankings as the *Business Week* survey of business schools [87], and the publication practices of OR/MS journals [78].

In addition to "Model World," Saul has expressed his views on the profession in various plenary addresses, invited articles, or special feature articles. A review of his writings on these occasions shows that Saul returns to several key themes. I take these to be Saul's professional *credo*. Using Saul's article for the President's Symposium in *Operations Research* [54] as a starting point, I will try to summarize these themes.

OR: its past, present and future. Saul has presented his view of "*what OR has done and should do*" in [54]. Saul states that "*OR has arrived,*" in the sense that it has successfully solved a wide variety of operational problems that the OR pioneers took as their challenge. While OR should take pride in its accomplishments, the operational outlook is too "*restrictive a view of what OR can and should be.*" In the future, OR will have to tackle complex organizational problems, meet the challenge of decision-making in real time, and contribute to policy analysis [82].

Professional identity and the OR process: On several different occasions, Saul has sounded a note of alarm on how the status of OR as a profession runs the risk of being diluted as diverse professions adopt and use OR techniques [54, 64]. For Saul, this risk is heightened by the identification of OR by its methods alone and calls for a shift in perspective.

> Unless we bring structure to our profession, that is develop and promulgate guidelines of technical conduct — what may be termed the process of Operations Research — we will soon not have much to claim as our specific professional domain. In the eyes of technical compatriots and those in management who support us, we must be something other than methods. [58]
>
> There has not been any improvement in what I term "managing the modeling process." I think it is a serious concern; one, that if not corrected, will see the profession of OR/MS being subsumed by the other disciplines that are managed better (or at least appear to be better managed). [56]

Professional Quality: As a profession, OR must not only develop "*high standards, guidelines and management procedures,*" but also demonstrate to management that OR professionals can manage a complex project and complete it "*to specifications, on time and within budget.*" Such questions as "*how does the total modeling effort fit into the life-cycle of the project?*" must be addressed [54]. For Saul, the broad issues of model evaluation discussed in Section 8 are an integral part of this integration.

The Science of Modeling: Saul has challenged the OR profession to develop *a science of modeling.* [54, 58]. He commends computer science for making the study of what it does an object of inquiry and believes that OR should do the same. "*Unlike those working in the field of computer science, we have not attracted the behavioral and psychological researchers to the study of the practice and implementation of our professional endeavors.*" [66]

Ethics: Saul has articulated his position on ethics in MS/OR clearly:

> It is essential for the future well-being of the MS/OR profession that its ethical concerns and problems be investigated and discussed in a more demanding fashion, especially by our professional societies. The problems will not go away... MS/OR needs a code of ethics and standards for professional practice. [77]
>
> The reader can rightly ask, "Do modelers need a code of ethics?" My answer is a resounding "Yes!" ... That most important ethical concern [that we as OR analysts face] is adhering to proper professional practices in the development and reporting of our work. [72]

Saul's interest in professional ethics and code of conduct in OR is of long standing. He took a keen interest in the *Guidelines for Professional Practice* that appeared in *Operations Research* in September 1971 [8], participated in the debate surrounding the *Guidelines* [33], and reviewed its history for the next generations of OR professionals [66, 69]. Saul supports the original 1971 *Guidelines* and has regularly cited this effort in his writings on ethics [66, 76]. He suggests that the guidelines are most appropriate when combined with the framework he offered in

[56]. In two articles [66, 77], Saul reviews other examples of codes of professional conduct and gives an interesting account of his presentation to (and interactions with) the doctoral students at ORSA doctoral colloquia on the subject of professional ethics.

In his historical review, Saul reminds us that the *Guidelines* were written in the aftermath of a controversial study of the antiballistic missile system (ABM). Because the techniques of the study drew upon military OR, the Operations Research Society of America was drawn in. This brings up the thorny issue of the appropriate code of conduct for analysts when they find their models entangled within an adversarial process. Saul reminds us that "*models have a life of their own and are subject to use beyond the original intent; they are becoming tools of advocacy*" [66]. Saul presents two interesting case studies of this situation in [66, 69, 73].

9.2 Ambassador to the OR World

Globalization may be very much in vogue nowadays, but for Saul it has been second-nature to view MS/OR as a "*problem-solving discipline that crosses geographical boundaries*" [62] . His extensive international travels have served to build personal and professional relations, for sure, but Saul has also actively sought to learn about OR practice in other countries and has chosen to spend his sabbaticals outside the United States. A brief review of his international contacts will indicate Saul's passion for worldwide travel.

In 1977, under the US/USSR Academy of Sciences Exchange Program, Saul spent one month in the Soviet Union visiting scientific institutions in Moscow, Kiev, Tbilisi, and Novosibirsk. This led to his participation in other US-USSR exchanges. One such exchange was a workshop on large-scale optimization, in which researchers from the Central Economic Mathematical Institute of the USSR Academy of Sciences (Moscow) participated. Saul organized this workshop in College Park in January 1990. In June 1990, Saul led the U.S. delegation that visited Moscow. In May 1993, he led a delegation of 15 Operations Research professionals to Russia and Hungary under the auspices of the Citizen Ambassador Program.

In 1981, Saul was invited to present a seminar on Operations Research in the U.S. for the International Institute of Technology in Tokyo. In 1983, he lectured in England on model validation and assessment under the auspices of the British Science and Engineering Council and the Operational Research Society. In 1988, Saul spent his sabbatical at the University of Anadolu, Eskisehir, Turkey and lectured at universities in Ankara and Istanbul. In 1985, the Beijing University of Iron and Steel Technology and the Chinese Academy of Sciences invited Saul to visit China, where he lectured in Beijing, Xian, and Shanghai. In 1986, he was an invited lecturer at universities in Brisbane, Australia and Auckland, New Zealand. In 1988, he was a plenary speaker at the First International Symposium on the Analytic Hierarchy Process, Tianjin, China.

Saul spent two months at the Computer and Automation Research Institute, Hungarian Academy of Sciences as a Fulbright Scholar for 1995-96. He was an invited speaker at the First (1995) International Conference on Multi-Objective Programming and Goal Programming (MOPGP) held in Southhampton, England [79]. He presented the first Abraham Charnes Lecture at the second MOPGP conference held in Torremolinos, Spain in May 1996 [83].

In 2001, Saul was selected for a five-year term as a Fulbright Senior Specialist by the Fulbright Program administered by the Council for International Exchange of Scholars and has visited several countries as part of this program. More recently, he was selected as the IFORS Distinguished Lecturer plenary speaker for the joint IFORS/EURO conference held in Reykjavik, Iceland, July 2-5, 2006.

In his capacity as an observer of the international practice of OR, Saul has discussed OR technology transfer to developing countries and the practice of OR around the world. In 1987, Saul was the keynote speaker at the 11th Triennial Conference of the International Federation of Operational Research Societies' (IFORS), held in Buenos Aires. At this meeting, Saul addressed MS/OR technology transfer and stated:

> I believe that each country must develop its own approach to the practice of MS/OR, a practice that fits within and is part of the country's cultural and managerial decision-making framework. A country's unique ethos must define its approach to the practice of MS/OR. [62]

In September 1990, Saul returned to this theme when he delivered the opening plenary address at the national meeting of the British Operational Research Society in Bangor, Wales [66]. He reviewed some of the reasons why projects involving OR technology transfer failed in developing countries. Commenting on the challenges faced by OR analysts in these projects, Saul wrote:

> Operations researchers in developing countries have a most difficult task. Their management wants results now; they want pay-offs similar to those acclaimed in the developed countries. But the successes in the developed countries were not easy to come by; they took 40 years of research and application, and an evolving management style before they bore fruit.... Operations researchers in developing countries know the science of OR, but they must develop their own culture of OR that can grow and bear fruit in their soil. The developing countries will benefit if they do diverge from the way OR is practiced in the developed countries. I think they can do a more efficient job of it by applying the discipline of a modeling life-cycle approach to their OR projects. [66]

9.3 The Chronicler of OR

In his reflections on the 50th anniversary of the founding of ORSA [89], Saul recalls the 71 persons who attended the founding meeting of ORSA on May 26 and 27, 1952 at the Arden House, Harriman, New York. Saul calls this group, together with a dozen pioneers who were not founding members, the first generation of OR professionals. Thirteen members of this group served as ORSA Presidents through

1974. This places Saul, who was President of ORSA in 1976, in the second generation. He remarks:

> One might say that starting in 1975, the administrative and organizational aspects of ORSA were managed by a new, second generation of OR professionals... My emphasis on the generational aspects of OR lets me segue into my main theme: the training and experiences of my generation of OR professionals were shaped by the early decades of remarkable scientific and management advances by the now somewhat forgotten first generation. [89]

The remarkable (some would call it explosive) achievements of these pioneers of OR is what Saul has tried to convey in his various historical writings. He believes that the insights of these founding OR scholars and professionals continue to be instructive today. This is one reason why I have included Saul's historical writings as part of his expository *opus*.

Saul's historical papers fall into two groups. The first group has to do with key periods of historical and scientific interest in which Saul was involved personally. Project SCOOP and the origins of LP is covered in [61, 65, 81, 88]. Saul's Project Mercury experience appears in [27, 85]. The Washington OR scene is described in [81]. Other works in this category are Saul's appreciations of George Dantzig [93, 96] and the memorial article Saul co-authored with Don Gross on their friend Carl Harris [109]. Saul has also written short biographies of George Dantzig, A. W. Tucker, and John von Neumann for the Hall of Fame section of the *International Transactions in Operational Research* [93, 94, 98].

The second group consists of historical pieces that cover specific OR/MS pioneers or a given period of the OR/MS profession. Saul recalls and reflects on the founding of ORSA [89], reviews the history of the definition of OR [101], and the early history of LP [61] as a response to the article by Robert Dorfman on the same subject [13].

The work of Saul with Susan Garille on the diet problem [22] offers an interesting blend of history and practice; one might refer to this work as old wine in a new bottle! Garille and Gass consider the original diet problem posed by Stigler in 1945: Given 77 foods and nine nutrients (including calories), find the diet that meets the recommended dietary allowances (RDAs) for the nutrients at minimum cost. Garille and Gass recount how Stigler's diet cost $39.93 using 1939 data, as compared to the optimal solution obtained with the simplex method in 1947 at a cost of $39.69. They go on to discuss the subsequent history for the diet problem and solve an updated version using 1998 prices and RDAs.

In 2002, Saul published several articles to commemorate the 50th anniversary of the founding of ORSA [88, 89, 90, 91, 92]. One of these was a timeline of key events in OR history [91]. It listed 241 events that captured the development of the field. Together, Saul and Arjang Assad expanded this list into a book with 417 annotated entries published in 2005 as *An Annotated Timeline of Operations Research: An Informal History* [100]. Saul dedicated the book to his grandchild, Arianna Gass.

Saul's humor and flair for showmanship have made OR history fun at national meetings of our profession. Starting in 1990, he organized and ran three Knowledge Bowls held in conjunction with national meetings of ORSA, TIMS and INFORMS. In these contests, two teams of prominent OR/MS citizens competed to answer questions that tested their OR/MS "cultural literacy." I was a judge at two of these events and witnessed the pleasure Saul took in preparing and pitching the questions. Sample questions appear in [92].

10 Conclusion

This article has reviewed Saul's career to date as an OR scholar, teacher, and professional. In the introduction to this paper, I indicated that Saul has been a leader in SPPP – Scholarship and the three P's of OR. On all four scores, through his extensive writings and his personal example, he has given us much to cherish and reflect upon.

Saul has taken his own advice on full documentation to heart by making a rich record of his career available to us. From this record, we can see the roots of much of Saul's research interests extending back to his first 10-15 years in OR. His interests in LP, multi-objective optimization, military OR, public sector planning, and policy models all go back to this period. From Saul's accounts of the early days of OR, it is evident that Saul's professional identity is nurtured and fortified by his remarkable exposure to the first generation of OR pioneers. To his credit, his awareness of the past has never compromised his forward-looking perspective. He has taken up new interests himself and challenged the OR profession to shake off restrictive outlooks, stake out new areas of interest, and establish standards of practice [54, 60, 82]. Nearly two decades ago, Saul was a member of the Committee on the Next Decade in OR [10]. In November 2006, at the INFORMS National meeting at Pittsburgh, Saul will chair a cluster on "The Great Problems of OR," in which prominent citizens of the OR community will try to delineate the challenges for the next generation of OR researchers. This is just one example of Saul's continuing alertness to the future course of OR.

As a committed and vocal citizen of the OR community, Saul has never shied away from expressing his opinion on key issues of the OR profession. (As his colleague, I can attest that he has done the same at the university.) When he is moved to state his opinion, he does so directly and forcefully, clearly stating his credentials and relevant background as needed. At times, Saul has gone against the grain of majority opinion [74, 75, 33, 112]. In such cases, his conduct sets an example of how professional debate can be carried out with equanimity and integrity. He is a capable organizer of professional gatherings and events and the perfect master of ceremonies. Finally, Saul has a strong sense of humor, which finds its way into his writings and enlivens his speeches.

I would like to close with a personal remark. I was hired by Saul 28 years ago and have been his colleague ever since. My appreciation of Saul's role as an OR professional has been monotonically increasing during this period. I remember clearly how, in the course of a brief exchange in the parking lot, I approached him with the idea of expanding the timeline [91] into an annotated book. That was in Winter 2002, and we thought we could knock it off in less than a year. The book [100] took us close to 26 months to finish. During this period, as Saul's co-author, I had an opportunity to work closely with him and learn more about him. I remain grateful for this.

Five years ago, I was pleased to read Peter Horner's tribute to Saul Gass on the occasion of his 75th birthday [134]. Given Saul's "high-octane" energy level, the accomplishments listed in that tribute are now badly out of date! I suspect the same will be true of this article before too long. Nonetheless, in keeping with the occasion feted by this volume, I offer this review as a small tribute to a great colleague.

Acknowledgments

This article makes liberal use of the writings of Saul Gass. I am indebted to Saul for making some of his earlier papers available to me and for answering certain queries I put to him. I acknowledge my debt to the excellent interview with Saul published by MORS [97]. Given Saul's superior powers of exposition, I have chosen to quote him directly throughout the paper. Where references to his works are less specific, it is to avoid the excessive clutter that referencing by source and page would have caused. I thank Bruce Golden for inviting me to contribute to this volume and for his patience, flexibility, and helpful comments as this article grew much beyond its original scope and length. I am grateful to Ruth Zuba for her valuable suggestions and assistance in the final stages of the manuscript preparation.

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Appendix: Reminiscences of Saul Gass

On the occasion of the 80th birthday of Saul Gass, I invited a group of his friends and colleagues to contribute brief reminiscences of their interactions with him. My objective was to add first-hand and personal observations of Saul to my overview article in this volume. I was very grateful to receive the contributions that follow. For each piece, I have indicated the author and the date on which I received the contribution. Except for minor edits, I have reproduced the original writings. I extend my sincere thanks to all contributors who responded to my request.

Arjang Assad

Al Blumstein
Alfred Blumstein is University Professor and the J. Erik Jonsson Professor of Urban Systems and Operations Research at the Heinz School, Carnegie Mellon University
2/19/06

I got to know Saul when I arrived in Washington in 1961. Saul was then already a key player in the OR community there. As I recall, Saul was working for a very strong consulting firm named CEIR. We must have met at a meeting of the local Washington Operations Research Council, or WORC. There were lots of members and lots of good folks who were serious about OR, especially as it applied to government problems – of course, this was Washington. Most of us were working with the military, some in DoD, some in the think tanks like IDA, RAND, ORO, CNA, and many in the various consulting firms around before the term "Beltway Bandits" became known – mostly because the Beltway wasn't built until the late 1960s. In 1965, Lyndon Johnson's President's Crime Commission decided to establish a Task Force on Science and Technology – presumably because science and technology was sending a man to the moon, so it certainly must be able to solve the urban crime problem. Somehow, I got recruited to lead that effort, and Saul was a natural candidate to join, and so I called him to see if he could become available. He was working for IBM at the time, and he was able to arrange for part-time participation without leaving IBM.

The project he took on was finding out how to stem the then-growing rate of auto theft, and he discovered that a very large fraction of stolen cars had their keys left in them. That led to a variety of proposals to get people to remove their keys from the cars. Our favorite was to have the key spring-loaded so that it would pop out into the driver's hand as soon as he turned the car off. The auto manufacturers claimed that the keys would too often land on the floor, so they settled for just making a lot of noise whenever the car was turned off and the keys were left in the ignition. And that led to a whole variety of noisy sounds in cars whenever the driver and other occupants weren't doing what they were supposed to – keys, doors, seatbelts. So you can blame Saul Gass for all that noise.

Don Gross
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2/12/06

I have known Saul since the 1960s when I first came to the DC area. While most of our interaction has been professionally through ORSA and now INFORMS, my wife and I have been at several social events with Saul and Trudy. About two years ago, we were at a wedding where a lot of dancing took place. It was a pleasure to watch Saul and Trudy on the dance floor. They outperformed even the youngsters (20 and 30 somethings). My advice to Saul is to compete for the "Dancing with the Stars" TV program. If he *optimizes* the choreography, I think he could win hands down!

Tom Magnanti
Thomas L. Magnanti is the Dean of the School of Engineering and Institute Professor at MIT
2/20/06

I first encountered Saul Gass, like I imagine many others, through his pioneering textbook, *Linear Programming: Methods and Applications*. At the time I was an undergraduate student studying chemical engineering and his book opened my eyes to an entirely new world – optimization and operations research – that has consumed my professional life ever since. It is fair to say that I am an operations researcher because of Saul Gass.

Later, my first professional research grant was for a DOT program called TARP, the Transportation Advanced Research Program. Other grantees included such luminaries as Saul and George Dantzig. At the end of a day of a grant review meeting held in Boston, my wife and I drove Saul, George and Robert Dorfman to dinner in our aging Oldsmobile, equipped with very poor shock absorbers. Upon hitting one of Boston's finest potholes, Saul, George, and Bob all levitated, seemingly hitting their heads on the car roof. Later that night my wife said she feared that we might have put an end to the field of linear programming.

Saul and my professional lives have been interwoven ever since. As but a few examples: (i) we both served as President of the Operations Research Society of America (ORSA), (ii) several years ago, I contributed an article to the *Encyclopedia of Operations Research and Management Science* that he so expertly edited (including careful and thoughtful editing of my modest contribution), (iii) he invited me to participate in one of the famous Knowledge Bowls that he has organized for our professional meetings (my team was pretty dismal!), (iv) on a couple of occasions, we participated in celebratory sessions that Saul organized in honor of our common thesis advisor, the great George Dantzig (and so, by virtue of our common thesis advisor, Saul and I are academic brothers), and (v) as the current President of the International Federation of Operational Research Societies (IFORS), I had the privilege recently of inviting him to be the IFORS

Distinguished Lecturer at the 2006 EURO meeting. The later of these examples provides just one indication of Saul's professional preeminence. Items (i)-(iv) provide a glimpse into the enormous impact that he has had in serving the profession with singular creativity, flair, and distinction. Indeed, he has always seemed to be everywhere; I marvel at his endless energy and at his steadfast commitment to the profession — unlike any other.

Heiner Müller-Merbach
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2/20/06

When I was a student in the late 1950s, we used Saul's textbook, which was published prior to George Dantzig's textbook. During 1963-64, I spent a post-doctoral year at the Operations Research Center of the University of California-Berkeley. The center was at the "Richmond Field Station," far away from the campus. George Dantzig was the director. He told me to share the office with Saul. I was quite surprised to meet him working for his Ph.D. - since he was so far ahead of me in linear programming. It was a great year.

After my return to Germany Saul and I met on many occasions. Saul and Trudy visited us once or twice. It may have been sometime around 1980 that they came from Russia, almost starving. We organized some good stuff to feed them to gain some energy again, which he depends on for his 10k races. I also remember that Saul attended the 1981 IFORS Conference in Hamburg. At the general assembly, Saul - on behalf of the US delegation- nominated me for the next IFORS President. The other candidate was my friend Hans-Jurgen Zimmermann, also from Germany; he was supported by several European OR societies. The voting process in the following year was in my favor, and I became President of IFORS for the three year period 1983 through 1985. In 1984, we had the triennial IFORS Conference in Washington DC, where we celebrated the 25th anniversary of IFORS. [*Dr. Muller-Merbach has also written an appreciation entitled "Saul Gass: 80 Years" for the German OR newsletter.*]

Graham Rand
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2/17/06

It is a great pleasure and an honour to be asked to contribute some reflections on my association with Saul on the occasion of his 80th birthday. It is hard to believe that he has reached that milestone. I remember the years when he was competing in the Saul Gass 10k runs at conferences: even then I was never fit enough to follow in his footsteps. Nevertheless, I have been greatly privileged to count Saul as a friend, whom it has been a delight to meet at INFORMS and IFORS meetings over the years. The pleasure has frequently been enhanced by Trudy's company. I recall a lovely dinner in San Antonio on the evening of Bush Junior's first election "victory". The British contingent were joined by John Little and Saul. Saul kept disappearing to catch up on the latest news: well at least we knew the result was going to be close!

Saul is, of course, a very welcome visitor to the UK. I was involved a little in the organisation of the Operational Research Society's annual conference held in Bangor, Wales in 1990, when Saul gave the opening address on "The many faces of OR". The Welsh members present were probably not too impressed when the Chairman welcomed him to England. Most of our professional collaboration has concerned the history of OR. In my role as the organiser of the IFORS' Operational Research Hall of Fame, Saul has given invaluable help, suggesting possible citation authors, and contributing citations himself for George Dantzig, Albert Tucker, and John von Neumann. His contributions, as would be expected, were interesting and delivered on time. Although I made a small contribution to his encyclopedia, and have fielded several questions about British OR history, the balance of debt is greatly in my favour. From my perspective, this particular Anglo-American relationship is very special.

Rick Vohra

Rakesh V. Vohra is John L. and Helen Kellogg Professor of Managerial Economics and Decision Science at Northwestern University
2/11/06

I have Margaret Thatcher to thank for becoming a Ph.D. student of Saul's. In the spring of 1980 while she ran for government, I campaigned for Labor and pondered what to do upon graduation. The fall of that year found me, a graduate student at the LSE, learning economics in the pubs and cafes. By December, Thatcher's program to shrink Government was in full swing. One consequence was deep cuts in University spending. My tutor, Ailsa Land, called me into her office and told me, because of the cuts, if I wanted an academic career, I should "go west." She pointed me to College Park and urged me to take up with Saul Gass.

In the fall of 1981 I joined the Mathematics department at the University. It was, I think, in the spring of 1982 that I made my first expedition (it took 15 minutes) from the Glenn Martin building (where Mathematics was housed) to Tydings Hall (where the Business school was housed) to meet Saul. To get there, one had to traverse the mall, which was criss-crossed by a series of concrete paths placed with no particular concern for symmetry or order. Legend has it that the mall was designed with no walkways but a great expanse of green. The planners would wait to see what paths were beaten into the grass to decide where to locate concrete paths.

Saul's office was dark, at least that is what I recall. He was surrounded by piles of books and papers. From the perspective of a regular patron at the local pizza shop, he seemed awfully emaciated to me; I did not know then that he ran a lot. I told him of my interest in OR and something of my interests in using it to house the homeless, clothe the unclothed, and shod the shoeless. I'm pretty sure it was drivel. He was kind enough not to throw me out of the office and asked instead about courses I had taken and told me what courses I should take.

My next meeting with Saul was in his LP class. Saul taught three things. Some I absorbed right away, others have taken time to sink in. First, formulate everything as an LP. Second, pass to the dual. Now this is not always helpful, but when it is, it is. I tell my graduate students the same thing now. The third thing Saul taught, was the notion of the right level of generality. LP is useful not because it is the most general of all classes of optimization problems. It is useful because it is just general enough to model a rich enough variety of situations and structured enough that one can say useful things about the phenomena being modeled. Saul was by no means an obvious match for an advisor. He knew and took an interest in the activities of the basketball coach Lefty Driesell; I did not. When the urge to exercise would come upon me, I would lie down, Saul would not. Saul was interested in real models that would support real decisions. I wanted to prove theorems. Nevertheless, it worked out!

Chris Witzgall
Christoph Witzgall has retired as Research Mathematician from the National Institute of Standards and Technology (NIST)
3/15/06

Traveling with the Gass family in Russia 1990, we visited an art museum. Afterwards, gleaming with a mathematician-father's joy, Saul recounted to whoever would listen how his son, the lawyer, had recognized a Möbius band among the decorations and pointed it out to him.

Larry Bodin
***Laurence D. Bodin is Professor Emeritus of Management Science at the Robert H. Smith of Business of the University of Maryland professor* 2/9/06**

Saul Gass introduced me to Operations Research in 1962 through his book, *Linear Programming*, the first edition. I saw Saul's book in the bookstore and convinced the chair of the Mathematics Department at Northeastern University to offer me a reading class. Nobody in the Mathematics Department at Northeastern University knew anything about Operations Research in 1962.

I met Saul for the first time at IBM in Bethesda in 1964. We were introduced by Ed Brown, a mutual colleague. Saul started his Ph.D. program in Operations Research at the University of California, Berkeley in 1963, and I became a student in the same program in 1964. Our paths intertwined for the next 10 years – graduate school, IBM, consulting companies and a faculty position at a university. I joined Saul Gass in the Business School at the University of Maryland in 1976. We had many rewarding experiences together. We introduced AHP into the graduate and undergraduate programs in the mid-90s and co-authored two papers on the teaching of the AHP, began writing the "definitive OR text for MBA students" (parts were written and used in the classroom, but the book was never completed). I fondly remember looking forward to Saul's presentations at the College's faculty assembly. His use of Dilbert to emphasize a point was terrific. Saul and I retired on July 1, 2001 and are now roommates in Van Munching Hall. Carol and I look forward to our continued association with Saul and Trudy Gass.

Ed Baker
Ed Baker is Professor of Management Science at the School of Business, University of Miami
2/10/06

One of things that has always impressed me about Saul Gass has been his openness and willingness to talk with and mentor students. In November of 1976, ORSA-TIMS held its fall meeting in Miami Beach. I was a second year doctoral student at the University of Maryland, and Saul Gass was the department chair. Saul was also the President of ORSA that year and, as a result, he had a large suite overlooking the ocean. He also, as I came to learn, would be hosting a cocktail party of ORSA-TIMS officials in his suite.

I was thrilled to be attending my first ORSA/TIMS conference and looked forward to hearing a number of papers. What a wonderful surprise it was for me to also receive an invitation to come to a reception in Saul's suite. I went to the event not knowing what to expect, but found Saul and Trudy, as gracious as ever, talking to a small group of people. Saul welcomed me and proceeded to introduce me to the group that included David Hertz, Art Geoffrion, and Jack Borsting, all ORSA luminaries. I was duly impressed with the company, and particularly with Saul's kindness and gracious nature in including me in the group.

I am sure that no one in that group remembers my introduction, but the meeting proved fortuitous for me. In 1984, I would become a colleague of David Hertz and Jack Borsting at the Business School at the University of Miami. Jack was serving as dean of the School of Business, and David was a University Professor. As it happened, I came up for promotion under Jack's deanship, and I know that he called upon Art Geoffrion, David Hertz, and Saul Gass to write letters reviewing my work. I don't know what they said, but promotion came through. I am certainly indebted to each of them, but I am especially grateful to Saul Gass for giving me that introduction.