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The mathematics of Peter L. Hammer (1936–2006): graphs, optimization, and Boolean models

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1 Preface

This volume of the *Annals of Operations Research*, contains a collection of papers published in memory of Peter L. Hammer (1936–2006).

As we recall further down, Peter made substantial contributions to several areas of operations research and discrete mathematics, including, in particular, mathematical programming (linear and quadratic 0–1 programming, pseudo-Boolean optimization, knapsack problems, etc.), combinatorial optimization (transportation problems, network flows, MAXSAT, simple plant location, etc.), graph theory (special classes of graphs, stability problems, and their applications), data mining and classification (Logical Analysis of Data), and, last but not least, Boolean theory (satisfiability, duality, Horn functions, threshold functions, and their applications).

The Call for Papers invited authors to submit research papers in all of these areas. We were very happy to receive a large number of high quality submissions along the lines explored by Peter, and eventually we selected 22 original contributions to appear in this special

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volume. We have no doubt that he would have been very proud of this collection of papers, and we are happy to dedicate it to him.

We would like to thank all authors of this special volume for their contributions, all our enthusiastic experts who served as volunteer referees for their help in selecting and improving these submissions, and Ms. Katie D'Agosta, the Managing Editor of the journal, for her continuous support and help with this volume.

Unfortunately, shortly before the volume was completed, fate struck again: On October 10, 2010, our dear friend and co-editor Bruno Simeone (born in 1945) passed away unexpectedly. Bruno was one of Peter Hammer's first doctoral students, and one of his closest and most faithful friends. He obtained his Ph.D. at the University of Waterloo in 1979, with a thesis entitled *Quadratic 0–1 Programming, Boolean Functions and Graphs*. Throughout the years, he remained in continuous contact with Peter, and together they co-authored about 30 scientific papers. Besides being a creative and dedicated researcher, Bruno was a friendly and cheerful person. He is deeply missed by all those who knew him.

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2 Peter L. Hammer (1936–2006)

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Peter Ladislaw Hammer was born in Timisoara, Romania, on December 23, 1936. He earned his doctorate in mathematics under Academician Grigore C. Moisil at the University of Bucharest in 1966. He defected to Israel in 1967 where he became a professor at the Technion in Haifa. After moving to Canada, he taught from 1969 to 1972 at the University of Montréal, and from 1972 to 1983 at the University of Waterloo. In 1983, he moved to the USA and became a professor at Rutgers University, where he founded RUTCOR—the Rutgers Center for Operations Research. He remained the director of RUTCOR until his untimely death in a tragic car accident on December 27, 2006.

For more than 40 years, Peter Hammer ranked among the most influential researchers in the fields of operations research and discrete mathematics. He made numerous major contributions to these fields, launching several new research directions. His results have influenced hundreds of colleagues and have made a lasting impact on many areas of mathematics, computer science, and statistics.

Most of Peter Hammer's scientific production has its roots in the work of George Boole on propositional logic. More than anyone else, Peter Hammer used and extended Boole's *machina universalis* to handle questions relating to decision making, analysis, and synthesis as they arise in natural, economic, and social sciences. Over the span of his scientific career, he conducted eclectic forays into the interactions between Boolean methods, optimization, and combinatorial analysis, while adapting his investigations to the most recent advances of mathematical knowledge and of various fields of application. Among the main research topics which received his attention, one finds an impressive array of methodological studies dealing with combinatorial optimization, some excursions into logistics and game theory, numerous contributions to graph theory, to the algorithmic aspects of propositional logic, to artificial intelligence and to the development of innovative data mining techniques. We include a complete bibliography at the end of this Preface.

At the onset of his career, as a researcher at the Institute of Mathematics of the Academia of Romania, Peter Hammer wrote several important articles on transportation problems, jointly with Egon Balas. At the same time his advisor, Grigore Moisil, directed him to the study of Boolean algebra. In this field, a central role is played by functions depending on binary variables, and taking either binary values (i.e., Boolean functions) or real values (i.e., pseudo-Boolean functions). In a series of papers, Peter Hammer demonstrated that a large variety of important problems of operations research, combinatorics, and computer science can be reduced to the optimization of pseudo-Boolean functions under constraints described by a system of pseudo-Boolean inequalities. A further main conceptual step in his work was the characterization of the set of feasible solutions of the above system as solutions of a single Boolean equation (or, equivalently, of a satisfiability problem). This led him, in joint work with Ivo Rosenberg and Sergiu Rudeanu, to the development of an original approach inspired from classical Boolean methods for the solution of a large variety of discrete optimization problems.

This research project culminated in 1968 with the publication of the book *Boolean Methods in Operations Research and Related Areas* (Springer-Verlag, 1968), co-authored by Sergiu Rudeanu. This landmark monograph, which founded the field of pseudo-Boolean optimization, has influenced several generations of students and researchers, and is now considered a "classic" in operations research.

In a sense, Peter Hammer's early work can be viewed as a forerunner of subsequent developments in the theory of computational complexity, since it was in effect demonstrating that a large class of combinatorial optimization problems is reducible to the solution of Boolean equations. However, this purely "reductionist" view of his work would be quite narrow. In fact, Peter Hammer systematically used the "canonical" representation of various

problems in terms of Boolean functions or Boolean equations to investigate the underlying structure, the "essence" of the problems themselves. More often than not, this goal is met through a simplifying process based, once again, on the tools of Boolean algebra. This approach provides, for instance, a simple way to demonstrate that every system of linear inequalities in binary variables is equivalent to a set of inequalities involving only $0, 1, -1$ coefficients, as observed in a joint paper by Frieda Granot and Peter Hammer (1972). It also led Peter Hammer, Ellis Johnson, and Uri Peled (1975) to early investigations into the facial structure of knapsack polyhedra.

In a related stream of research, Peter Hammer established numerous fruitful links between graph theory and Boolean functions. In a famous joint paper with Vašek Chvátal on the aggregation of inequalities in integer programming (1977), he introduced and characterized the class of threshold graphs, inspired by threshold Boolean functions. Threshold graphs have subsequently been the subject of scores of articles and of a book by N.V.R. Mahadev and Uri Peled, two of Peter Hammer's former doctoral students. Other links between graphs and Boolean or pseudo-Boolean functions were explored in joint work with Claude Benzaken, Dominique de Werra, Christian Ebenegger, Stephan Foldes, Toshihide Ibaraki, Alex Kelmans, Vadim Lozin, Frédéric Maffray, Bruno Simeone, and others.

Quadratic 0-1 optimization was one of Peter Hammer's main fields of investigation. The theory of roof-duality (1984), jointly developed with Pierre Hansen and Bruno Simeone, builds on concepts from linear programming (linear relaxations), Boolean theory (quadratic Boolean equations) and networks flows (maximum flow problems) to compute best linear approximations of quadratic pseudo-Boolean functions and tight bounds on their maximum value. Further research along similar lines was conducted by Peter Hammer in collaboration with Endre Boros, Jean-Marie Bourjolly, Yves Crama, Michel Minoux, David Rader, Gabriel Tavares, Xiaorong Sun, and others.

Peter Hammer was also interested in the application of Boolean models in artificial intelligence and related fields, as witnessed by numerous papers or edited volumes coauthored with Gabriela and Sorin Alexe, Martin Anthony, Tiberius Bonates, Endre Boros, Yves Crama, Oya Ekin, Marty Golumbic, Vladimir Gurvich, Lisa Hellerstein, John Hooker, Toshihide Ibaraki, Alex Kogan, Miguel Lejeune, Irina Lozina, Kaz Makino, and other coworkers. His contributions bear on automatic theorem proving, compression of knowledge bases, algorithms for special classes of satisfiability problems, etc. About 20 years ago, he launched an innovative approach to data mining based on a blend of Boolean techniques and combinatorial optimization. The basic tenets of this approach were presented in a joint paper with Yves Crama and Toshihide Ibaraki (1988) and were subsequently developed by Peter Hammer and his co-workers into a new broad area of research, which he dubbed *Logical Analysis of Data*, or LAD for short. The effectiveness of the LAD methodology has been validated by many successful applications to data analysis problems. In particular, some front-of-the-line medical centers use LAD in the practice of medical diagnosis for a variety of syndromes.

Many aspects of Peter Hammer's contributions to the study of Boolean functions and their combinatorial structure can be found in a monograph entitled *Boolean Functions: Theory, Algorithms, and Applications* (Cambridge University Press, New York, 2011), coauthored with Yves Crama and containing contributions by several other close collaborators.

Beside his scientific production, Peter Hammer will undoubtedly be remembered for his vigorous contribution to and promotion of discrete mathematics and operations research. He was the founder and editor-in-chief of several highly-rated professional journals, including *Annals of Discrete Mathematics*, *Annals of Operations Research*, *Discrete Applied Mathematics*, *Discrete Mathematics*, *Discrete Optimization*, and the *SIAM Monographs on Discrete Mathematics and Applications*. At Rutgers University, Peter Hammer was the founding

Director of the operations research program, and he was largely responsible for developing RUTCOR into an internationally recognized center of excellence and an open institute, where seminars, workshops, graduate courses, and a constant flow of visitors create a stimulating research environment. He was also a tireless organizer of professional conferences and workshops, where he always made sure to provide opportunities for interactions between experienced scientists and younger researchers.

The importance of Peter Hammer's scientific contribution was acknowledged by the award of numerous international distinctions, including the "George Tzitzeica" prize of the Romanian Academy of Science (1966), the Euler Medal of the Institute of Combinatorics and its Applications (1999), and honorary degrees from the Swiss Federal Institute of Technology in Lausanne (1986), the University of Rome "La Sapienza" (1998), and the University of Liège (1999). He was a Fellow of the American Association for the Advancement of Science since 1974, and a Founding Fellow of the Institute of Combinatorics and its Applications. Several conferences were organized in his honor, including the First International Colloquium on Pseudo-Boolean Optimization (Chexbres, Switzerland, 1987), the Workshop and Symposia Honoring Peter L. Hammer (Caesarea Rothchild Institute, University of Haifa, 2003), and the International Conference on Graphs and Optimization (GO V, Leukerbad, Switzerland, 2006).

Peter Hammer was not only an outstanding scholar and a tireless organizer, but also a kind, generous, and humorous human being. He relished the interaction with students and colleagues, and made everybody feel comfortable to work with him, be it on a mathematical question (which he was always keen to formulate) or on planning a conference. He had a talent for enrolling and motivating non-mathematicians to collaborate with him, which often led to original and innovative results, as illustrated by his joint work with economists, management scientists, and medical doctors. He supervised numerous graduate students with respect and fatherly understanding, considering each one of them as his "best student."

Peter Hammer was also a true "citizen of the world": born in Romania to a Hungarian family, he subsequently took Canadian citizenship, followed by US citizenship, wrote joint papers with coauthors from about 30 different countries, fluently spoke 6 languages (or more), traveled the world extensively, spent extended periods of time in Belgium, France, Israel, Italy, Russia, Switzerland, and many other countries, and developed an extended network of friends and coworkers on all continents.

3 List of publications of Peter L. Hammer

3.1 Books

1. Pseudo-Boolean Programming and Applications. Lecture Notes in Mathematics, Vol. 9, Springer Verlag, Berlin/Heidelberg/New York, 1965, 50 pages.
2. Boolean Techniques for Bivalent Programming (with S. Rudeanu). Lecture Notes in Mathematics, Vol. 23, Springer Verlag, Berlin/Heidelberg/New York, 1966, 120 pages.
3. Boolean Methods in Operations Research and Related Areas (with S. Rudeanu). Springer Verlag, Berlin/Heidelberg/New York, 1968, 330 pages. Edition française: Dunod, Paris, 1970.
4. Boolean Models and Methods in Mathematics, Computer Science, and Engineering (Editor with Y. Crama), Cambridge University Press, New York, NY, 2010, xviii + 759 pages.
5. Boolean Functions: Theory, Algorithms, and Applications (with Y. Crama). Cambridge University Press, New York, NY, 2011, xxii + 675 pages.

3.2 Forthcoming book

6. Pseudo-Boolean Functions (with E. Boros and Y. Crama). Cambridge University Press, forthcoming 2012.

3.3 Edited volumes

7. Mathematical Programming in Theory and Practice (Editor, with G. Zoutendijk). North Holland Publishing Co., Amsterdam, 1974, 480 pages.
8. Studies in Integer Programming (Editor with E.L. Johnson, B. Korte and G. Nemhauser). North Holland Publishing Co., Amsterdam, 1977, 562 pages.
9. Discrete Optimization I II (Editor with E.L. Johnson and B. Korte). North Holland Publishing Co., Amsterdam, 1979, 299 & 453 pages resp.
10. Horn Logic, Search and Satisfiability. Annals of Mathematics and Artificial Intelligence, Volume 1, 1990 (Editor with M. Golumbic, P. Hansen and T. Ibaraki). J.C. Baltzer Scientific Publishing Co., Switzerland, 372 pages.
11. Boolean Functions. Discrete Applied Mathematics, Volumes 96–97, 1999 (Editor with E. Boros), Elsevier Publishing, Amsterdam, 236 pages.
12. Boolean Functions and Related Problems. Discrete Applied Mathematics, Volume 107, 2000, Elsevier Publishing, Amsterdam, 262 pages.
13. Discrete Optimization DO'99: Surveys on the State of the Art. Discrete Applied Mathematics, Volume 123, 2002, and Topics in Discrete Mathematics 11, 2003 (Editor with E. Boros), Elsevier Publishing, Amsterdam, 580 pages.
14. Contributions to Discrete Optimization. Discrete Applied Mathematics, Volume 124, 2002 (Editor with E. Boros), Elsevier Publishing, Amsterdam, 142 pages.
15. Boolean and Pseudo-Boolean Functions. Discrete Applied Mathematics, Volume 142, 2004. Elsevier Publishing, Amsterdam, 205 pages.
16. Discrete Mathematics and Data Mining. Discrete Applied Mathematics, Volume 144, 2004 (Editor with M. Anthony, E. Boros, and A. Kogan). Elsevier Publishing, Amsterdam, 227 pages.
17. Boolean and Pseudo-Boolean Functions. Discrete Applied Mathematics, Volume 149, 2005. Elsevier Publishing, Amsterdam, 218 pages.
18. Discrete Mathematics and Data Mining II. Discrete Applied Mathematics, Volume 154 (7), 2006 (Editor with M. Anthony, E. Boros, and A. Kogan), Elsevier Publishing, Amsterdam, pp. 1037–1156.
19. Discrete Mathematics and Data Mining II, Discrete Applied Mathematics, Volume 156 (6), 2008 (Editor with M. Anthony, E. Boros, and A. Kogan), Elsevier Publishing, Amsterdam, pp. 823–984.

3.4 Published papers

20. Groups with Finite Classes of Conjugate Elements. Diploma Work. (Appro = M.Sc. Thesis). University of Bucharest, Dept. of Mathematics and Mechanics, 1958.
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22. Mathematics and the Planning of Transportations. Probl. Automatica, 2, 1960, 47–55 (with E. Balas).
23. Linear Programming and Transportation. Rev. Statistica, 9, 1960, No. 7, 43–61 (with E. Balas).
24. Transportation Problems with Related Centres. Stud. Cerc. Matem., 11, 1960, No. 2, 439–450 (with E. Balas).

25. Applications of Mathematics to Economics. Gazeta Matem Fiz, Ser. A, 12 (65), 1960, No. 11, 569–576.
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28. Transportation Problems with Parameters. Stud. Cerc. Matem., 12, 1961, No. 2, 413–427 (with E. Balas).
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30. A Method for Solving Transportation Problems. Com. Acad. RPR, 11, 1961, No. 9, 1047–1049 (with E. Balas).
31. Transportation Problems for Nonhomogeneous Products. Stud. Cerc. Matem., 13, 1962, No. 1, 97–105 (with E. Balas).
32. Semilinear Spaces. Com. Acad. RPR, 12, 1962, No. 12, 1267–1272 (with G. Godini).
33. On the Egerváry Method for Solving Transportation Problems. II. Stud. Cerc. Matem., 14, 1963, No. 1, 59–67 (with S. Rudeanu).
34. Stability of the Optimal Solutions of Transportation Problems with Variable Costs. Com. Acad. RPR, 13, 1963, No. 3, 249–251 (with E. Balas).
35. Soviet Works on Operations Research. Gazeta Matem. Fiz., Ser. A, 15(68), 1963, No. 2, 102–103.
36. On the Minimization of Pseudo-Boolean Functions. Stud. Cerc. Matem., 14, 1963, No. 3, 359–364 (with I. Rosenberg and S. Rudeanu).
37. Applications of Boolean Algebra to Economics. Stud. Cerc. Matem., 17, 1965, No. 4, 583–598.
38. Romanian Research on Mathematical Programming. Progresele Stiintei, 1, 1965, No. 5, 137–142.
39. A Theory of Binary Decisions. I. The Linear Case. Stud. Cerc. Calcul Economic si Cibern. Econom., 1, 1966, No. 2, 105–126 (with S. Rudeanu).
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41. Shefferian Algebras. Bull. Math., 3(51), 1959, 289–303.
42. Transportation Problems with Variable Data. Rev. Math. Pures et Appl., 6, 1961, 713–734 (with E. Balas).
43. Applications de la programmation linéaire dans les transports roumains. Etudes Economiques, 1962, No. 140 (with E. Balas).
44. On the Transportation Problem. Cahiers du Centre d'Etudes de Recherche Opérationnelle, Part I: 4, 1962, No. 2, 98–116; Part II: 4, 1962, 131–160 (with E. Balas).
45. Applications of Discrete Linear Programming to the Minimization of Boolean Functions. Rev. Math. Pures et Appl., 8, 1963, No. 3, 459–475 (in Russian; with I. Rosenberg and S. Rudeanu).
46. On a Problem in Coding Theory. Bull. Math., 7(59), 1963, Nos. 3, 4, 149–150 (with A. Deleanu).
47. Programmation polynomiale en nombres entiers. C.R. Acad. Sci. Paris, 258, 1964, 424–427.
48. On the Generalized Transportation Problem. Management Science, 11, 1964. No. 1, 188–202 (with E. Balas).
49. Applications of Pseudo-Boolean Programming to the Theory of Graphs. Zeitschrift für Wahrscheinlichkeitstheorie, 3, 1964, 163–176 (with I. Rosenberg).

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