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V. N. Shevchenko

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Qualitative Topics in Integer Linear Programming

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КАЧЕСТВЕННЫЕ ВОПРОСЫ ЦЕЛОЧИСЛЕННОГО ЛИНЕЙНОГО ПРОГРАММИРОВАНИЯ

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ABSTRACT. Integer solutions are considered for systems of linear inequalities, equations, and congruences, along with the construction and theoretical analysis of integer programming algorithms. The complexity of algorithms is analyzed in dependence on two parameters: the dimension, and the maximal modulus of the coefficients describing the conditions of the problem. The analysis is based on a thorough treatment of the qualitative and quantitative aspects of integer programming, in particular, on bounds obtained by the author for the number of extreme points. This makes progress possible in many cases when the traditional approach, in which complexity is regarded as a function only of the length of the input, leads to a negative result. The book is intended for mathematicians and other specialists in the theory and applications of discrete optimization, as well as for students and post-graduates specializing in mathematical cybernetics and information science.

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Contents

Notation

$\mathbf{R}$	the field of real numbers,
$\mathbf{Q}$	the field of rational numbers,
$\mathbf{Z}$	the ring of integers,
P^n	the set of n-dimensional arithmetic vectors with components in P,
$P^{m\times n}$	the set of matrices with m rows and n columns with elements in P,
A_+	the set of nonnegative elements of a set A,
$\lvert A\rvert$	the cardinality of a set A,
$\operatorname{Co} A$	the convex hull of a subset A of $\mathbf{R}^n$,
$\dim A$	the dimension of a set $A \subset \mathbf{R}^n$, that is, the maximal number of linearly independent vectors in A,
$\lceil\alpha\rceil$	the maximal integer not exceeding the number α,
$\lfloor\alpha\rfloor$	the minimal integer not less than α,
$\{\alpha\} = \alpha - \lceil\alpha\rceil$	the fractional part of α,
$\lceil\alpha\rfloor$	the integer closest to α: $\lceil\alpha\rfloor = \lceil\alpha\rceil$ if $\alpha - \lceil\alpha\rceil \leq 1/2$, and $\lceil\alpha\rfloor = \lfloor\alpha\rfloor$ otherwise,
$\operatorname{res}_a b$	the residual after division of $b \in \mathbf{Z}$ by $a \in \mathbf{Z}$, $a \neq 0$,
$\log\alpha$	the logarithm of α to the base 2,
$x \equiv y \ (d)$	means for nonzero $d \in \mathbf{Z}$ and $x, y \in \mathbf{Z}^n$ that each component of the vector $x - y$ is divisible by d,
$\lVert x\rVert$	the Euclidean norm of a vector x,
A^{T}	the transpose of a matrix A,
$\operatorname{rk} A$	the rank of a matrix A,
e_j	the vector in $\mathbf{Z}^n$ with jth coordinate 1 and the other coordinates 0 ($j = 1, \ldots, n$),
$\binom{m}{n}$	the number $\frac{m!}{n!(m-n)!}$ of combinations of m things, taken n at a time.

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Foreword

The main object of investigation in this book is the set M of integer solutions of a system of linear inequalities, equations, or congruences, and its convex hull $\operatorname{Co} M$. Such mathematical objects arise in integer programming, which is the sufficiently universal language of discrete optimization, an area with a large sphere of applications in mathematical cybernetics, economics, and other disciplines.

We pose the following problems: 1) determine whether M is nonempty; 2) give a description of $\operatorname{Co} M$, that is, find the set of its extreme points and (or) a list of its faces; 3) solve the integer linear programming problem (ILPP), that is, find in M a point x at which a specified linear function attains a maximum; 4) estimate the complexity of algorithms giving answers in the preceding cases.

It is presently common to estimate the complexity as a function of the length l of the input, the function being interpreted as the number of binary digits required to store all the input parameters of the problem. In our case these are the coefficients a_{ij} on the left- and right-hand sides of the system describing the set M. We assume them to be integers unless otherwise stated, and then $l = \sum\lceil 2 + \log|a_{ij}|\rceil$, where the sum is over all coefficients. It is common to regard an algorithm as efficient if its complexity is bounded above by a polynomial in l (then one says that it is a polynomial algorithm, and that the problem solved by it is polynomially solvable).

No polynomial algorithms are known at present for even the first of the problems posed. Moreover, if we accept the well-known hypothesis that P$\neq$NP, where P and NP are the classes of problems polynomially solvable on a determinate and indeterminate Turing machine, respectively (precise definitions and an exposition of these questions can be found, for example, in [**50**]), then there are no such algorithms.

The problem P_1 of determining whether a system of linear equations in nonnegative integers is consistent is a universal or NP-complete problem, that is, any problem P_0 in the class NP can be polynomially reduced to it, and hence the polynomial solvability of the problem P_1 would mean the existence of a polynomial algorithm also for any problem P_0.

The approach regarding the complexity as a function only of the single parameter l is apparently too general. In integer linear programming it is expedient to consider two parameters, the dimension n and $\alpha = \max|a_{ij}|$, which it is natural to take as guides for distinguishing efficiently (polynomially) solvable subclasses of problems. It is known that polynomial algorithms for the problem P_1 exist for the two subclasses described by the respective conditions: a) n increases without bound, while α and the number m of equations are arbitrary but fixed; b) n is fixed, while α increases without bound. The first of these is easy to get by the dynamic

programming method, and the second was obtained by Lenstra; it is the latter that will receive most of our attention.

The foregoing gives the reader some idea of what this book covers. To make this idea more concrete we go through the contents by chapters.

In Chapter 1 we consider the intersection of a convex polyhedral cone with the integer lattice $\mathbf{Z}^n$ and prove that it is finitely generated. This provides a theoretical basis for the subsequent constructions. Here we pose the question of conditions on the right-hand side of a system of linear equations that are necessary and sufficient for the system to be consistent in the nonnegative integers $\mathbf{Z}_+$.

In Chapter 2 we solve the problem posed in Chapter 1 by presenting a discrete analogue of the Farkas theorem and solving the closely related problem of aggregation of a system of linear equations $Ax = b$. The latter problem consists in finding a linear equation whose set of nonnegative integer solutions coincides with the set $\mathfrak{M}(A, b)$ of nonnegative integer solutions of the original system. We derive necessary and sufficient conditions for the existence of such an equation, and we prove that its coefficients must grow exponentially with respect to m.

The central part of the book is Chapter 3, in which we consider the intersection M of a polyhedron with the integer lattice $\mathbf{Z}^n$ or with a sublattice of it. For various ways of specifying the polyhedron we prove that M and its convex hull $\operatorname{Co} M$ are finitely generated, and we present bounds for the number of vectors in generating sets and their components. On the basis of the properties obtained for the set N of extreme points of $\operatorname{Co} M$ we then give a method for obtaining upper bounds for their number $|N|$. In particular, it is shown that $|N|$ is bounded above by a polynomial in $\log \alpha$ for any fixed dimension n, that is, $|N|$ is essentially less than $|M|$, and this difference can be increasingly significant, the larger α is. For some important special cases, for example, for the knapsack problem, it is shown that our upper bounds cannot be improved with respect to order, and examples are given in which $|N|$ grows exponentially with n.

In Chapter 4 we use the results of Chapter 1 on decomposion of cones to analyze the existing cut methods in integer programming from a unified point of view, and we present new ones. We reveal the role of the asymptotic or elementary ILPP (in which the constraints are given by a square system of linear inequalities $Az \leq b$, where $\Delta = |\det A| \neq 0$), which is equivalent to the group minimization problem (GMP; introduced by Gomory) consisting in the minimization of a linear function on the set of nonnegative integer solutions of the equation $\sum_{j=1}^{n} g_j x_j = g_0$, where the g_j are elements of an additive Abelian group of order Δ. The equivalence of these two problems allows methods for solving each of them to be carried over to the other, and gives two natural parameters n and Δ as a function of which the complexity of various algorithms can be estimated. In this connection we investigate the mean values of the minors of various classes of matrices.

Complexity questions of linear programming are examined in Chapter 5. In particular, it is shown that the asymptotic ILPP and the knapsack problem (more precisely, the problem P_1 for $m = 1$) are NP-complete. An algorithm that is polynomial for a fixed dimension is constructed for finding all the extreme points and faces of $\operatorname{Co} \mathfrak{M}(A, b)$. Analogous results are presented also for the case when the polyhedron is described by a system of inequalities if their number is bounded by a polynomial in n. It is shown that if the growth of n is bounded above by a quantity proportional to $(\log \log \alpha)^{1/2}$, then the polynomial property of all the estimates

is preserved. It is also shown that all the estimates can be made independent of the right-hand sides. These results enable us to distinguish new subclasses of polynomially solvable ILPP's.

The appendices contain some facts about solving systems of linear equations and congruences in integers (references to such assertions in Appendix 1 are given by the letter A with a corresponding number), a combinatorial-statistical analysis of determinants and permanents of certain (0-1)-matrices, some functions of many-valued logic connected with the ILPP (in particular, a solution of the problem of deciphering threshold functions), models of certain practical problems reducing to the ILPP, and methods for solving them.

Since 1970 the author has been head of the Department of Mathematical Logic and Higher Algebra at Nizhni Novgorod State University and has worked on integer programming problems. In this monograph broad use is made of results obtained by the author and his students and colleagues. The author cannot, of course, claim completeness for his presentation of the topics touched upon here, and the bibliography reflects his tastes and, to a greater extent, his opportunities. In particular, the list of publications contains a series of auxiliary textbooks for graduate courses given yearly by the author for students in the Department of Computational Mathematics and Cybernetics.

The author is grateful to his department colleagues S. I. Veselov, A. P. Il'ichev, and A. Yu. Chirkov, who took part in the writing of some sections of the book, as well as to V. A. Talanov for useful discussions, and to M. Yu. Preobrazhenskaya and I. V. Suslova for the technical preparation of the manuscript for printing at the publishing house "Nauka" in 1991. Unfortunately, well-known changes in our country hindered publication of the book, which has become possible only thanks to the support of the Russian Foundation for Fundamental Research, to which the author expresses his gratitude.

The insertions in the text reflecting recently obtained results necessitated an extra list of references, beginning with [**333**].

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