MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 4/1993

Combinatorial Optimization

17. – 23.01.1993

Die Tagung fand unter Leitung der Professoren Martin Grötschel (Technische Universität Berlin / Konrad-Zuse-Zentrum für Informationstechnik Berlin) und William R. Pulleyblank (IBM Research Center, Yorktown Heights) statt.

An der Tagung nahmen 59 Teilnehmer aus 11 Ländern teil, die in 51 Vorträgen über neueste Forschungsergebnisse aus dem Bereich der Kombinatorischen Optimierung berichteten. Die Zusammensetzung des Teilnehmerkreises aus jungen und erfahrenen Forschern, sowie Vertretern aus Europa und aus Nordamerika garantierte, daß ein breites Spektrum der Theorie, der Algorithmik und der Anwendungen der Kombinatorischen Optimierung abgedeckt wurde. Signifikant war, daß viele der Teilnehmer über Forschungsarbeiten berichteten, die zur Lösung großer und schwieriger praxisrelevanter Probleme aus Gebieten beitrugen, zu denen die Kombinatorische Optimierung lange Zeit keinen Zugang hatte.
Die bewährte Konzeption des Hauses ermöglichte es in den Pausen zwischen den täglichen 4 Vortragssitzungen oder am Abend die vorgetragenen Gedanken in kleinen Arbeitsgruppen zu vertiefen, gegenseitig neue Ideen auszutauschen, sowie sich in geselliger Runde näher kennenzulernen. Es wurden Kontakte geknüpft, die die eigene Forschungsarbeit positiv beeinflussen werden. Das Institut bot für alle Teilnehmer einen idealen Rahmen, um in freundschaftlichem Miteinander Forschung betreiben zu können.
Ein kleiner mathematischer Wettbewerb forderte von den Teilnehmern auch in den Pausen oder am Abend einiges an Gedankenarbeit. Die Aufgabe bestand darin zwei Max-Cut Probleme auf einem Gittergraphen von 64 Knoten zu lösen. Von den Teilnehmern des Wettbewerbs wurden durchweg sehr gute Lösungen abgegeben, die ohne Zuhilfenahme von technischen Hilfsmitteln (Computer) erarbeitet werden mußten. Von zwei Gruppen wurden beide Probleme optimal

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gelöst. Ihre Mühen wurden mit T-Shirts belohnt, die vom IBM Research Center und vom Konrad-Zuse-Zentrum gestiftet wurden.
Die Veranstalter sowie die Teilnehmer danken dem Hause für die freundliche Aufnahme und hervorragende Betreuung während der Tagung.

Die folgenden Vortragszusammenfassungen geben einen Überblick über die in dieser Tagung behandelten Themen.

VORTRAGSAUSZÜGE

N. Ascheuer
Online Hamiltonian path problems

We present the results of a joint project with industry that had the aim to optimize the movements of a stacker crane of an automatic storage system. This question leads to the solution of online Hamiltonian path problems. The comparison of the online behaviour of several heuristics is presented. The question of determining a lower bound for a good online strategy then leads to offline combinatorial optimization problems such as Hamiltonian path problems with and without additional constraints (time windows, precedence constraints). Modellings and preliminary computational results are presented.
Partially joint work with A. Abdel-Hamid, M. Fischetti, M. Grötschel, M. Jünger, G. Reinelt.

A. Bachem
A parallel implementation of an interior point method

In this talk we report on a parallel implementation of a primal-dual interior point method for linear programming. We started with the sequential implementation of the OB1-Code of Lustig, Marsten and Shanno and used a fan-in algorithm to parallelize the numerical factorization of the Cholesky factor. We show that a balanced subtree mapping yields a good load balancing on a message passing computer. For a transputer cluster speed ups of 3-5 on 6 processors give the best relative efficiency. Numerical results on the Netlib examples are presented.
Joint work with M. Strietzel, M. Wottawa.

E. Balas
On the monotonization of polyhedra

In polyhedral combinatorics one often has to analize the facial structure of less that full dimensional polyhedra. The presence of implicit or explicit equations in the linear system defining such a polyhedron leads to technical difficulties when analyzing its facial structure. It is therefore customary to approach the study of such a polytope P through the study of one of its (full dimensional) relaxations (monotonizations) known as the submissive and the dominant of P. Finding sufficient conditions for an inequality that induces a facet of the submissive or the dominant of a polyhedron to also induce a facet of the polyhedron itself has been posed in the literature as an important research problem. Our paper goes a long way towards solving this problem. We define a generalized monotonization of a polyhedron P, $g - mon(P)$, that subsumes both the submissive and the dominant, and give a sufficient condition for an inequality that defines a facet of $g - mon(P)$ to define a facet of P. For the important

case of the travelling salesman polytope P, in both its symmetric and asymmetric variants, we give sufficient conditions trivially easy to verify, for a facet of the monotone completion of the TS polytope to define a facet of the TS polytope itself. The upshot of this research is that all cases in which facets of the monotonized polyhedron do not correspond to facets of the polyhedron itself are pathological in a well defined sense.
Joint work with M. Fischetti.

M. L. Balinski

Rounding proportions: rules of rounding

Failure to add to 1 – to be "justified" to 1 – occurs frequently in reported sets of rounded data. The probabilities for different rules of rounding vectors and tables to give "justified" results under varying assumptions concerning the probabilistic structure of the data are computed.
This extends the pioneering work of Mosteller, Youtz and Zahn (1967) and Diaconis and Freedman (1979) who assessed the probability that conventionally rounded proportions add to 1. It is shown that other rules of rounding can improve upon the conventional rules in various contexts that depend upon the distribution of the original data and in the measure of "best".
Joint work with S. T. Rachev.

M. Ball

Integer programs with reliability constraints

This work focuses on the formulation and solution of integer linear programs which contain constraints on the reliability of some system. Typically expressions for system reliability are complex non-linear functions. The first part of this work presents cases for which bounds on system reliability are derived which can be converted into linear constraints by taking logarithms. One of the results used is a bound on the probability that a random vector is a member of a polymatroid. The second part of this work involves the use of preprocessing and reformulation strategies for the resultant integer programs.

F. Barahona

Computing image distances by network flows

We present experiments with the Kantorovitch/Hutchinson metric for images. We use network flow methods to compute it in the case of digital images. We show examples when this metric gives the right answer, we also show cases when a different metric is needed.
Joint work with C. Cabbrelli, U. Molter

D. Bertsimas

A polyhedral approach to stochastic optimization

We formulate classical stochastic optimization problems (multi-armed bandits, branching bandits, multiclass queueing systems) as linear programming problems over extended polymatroids, polyhedra that strictly extend polymatroids. Optimization of a linear objective over an extended polymatroid is solved by an

adaptive greedy algorithm and leads to optimal solutions with an indexability property. Interesting consequences of our new characterization include a deeper understanding of Gittins indices for multi-armed bandit problems, the fastest known algorithm to compute these indices, unexpected connections between different problems, sensitivity analysis to name a few.
Joint work with J. Ninõ-Mora.
We next provide a new method based on potential functions to obtain polyhedral and non-linear relaxations of more complicated (typically PSPACE-complete) stochastic optimization problems (for example, sequencing and routing of multiclass queueing networks). We optimize over these relaxations in polynomial time using techniques from semi-definite programming and thus obtain strong lower bounds on the optimal solution. In the class of systems which can be formulated as extended polymatroids our characterization is exact. Moreover, our approach leads to reformulation of extended polymatroids using a polynomial number of variables and constraints.
Joint work with J. Pascalidis and J. Tsitsiklis.

R. E. Bixby
Solving TSP's

In this talk a summary of the results of an approximately five year computational study of the traveling salesman problem are reported. The results of this work include the solution of 16 previously unsolved real-world instances from "TSPLIB," among them an example with 3038 nodes. The computational effort to solve this problem was estimated as equivalent to approximately 1 1/2 years of CPU time on a SPARC station 2. This instance is by far the most difficult solved to date and demanded numerous theoretical and practical improvements in the methods used for obtaining exact solutions to NP-hard combinatorial optimizations problems.. Parallelism was crucial to the computation as were major improvements in our ability to solve hard linear programming problems. However, undoubtedly the most important new developments were theoretical and involved new separation routines. In one of these, we used the PQ-tree data structure to examine the collection of all tight subtour constraints for the current solution vector. In the case that this collection does not have the consecutive ones property, we can derive a violated comb inequality from a theorem of Tucker.
Joint work with D. Applegate, V. Chvátal, W. Cook.

R. E. Burkard
Bottleneck Monge matrices and their role in combinatorial optimization

A matrix $C = (c_{ij})$ fulfills the bottleneck Monge property, if

(1) $\max(c_{ip}, c_{jk}) \leq \max(c_{iq}, c_{jp})$ for all $1 \leq i < j \leq m,\ 1 \leq p < q \leq n$.

1. If the cost matrix of a time transportation problem fulfills the bottleneck Monge property, then the North West Corner Rule yields an optimal solution.

2. If C is the matrix of processing times of an m machine flow shop problem where $-C$ fulfills (1), then the job sequence $(n, n-1, n-2, \ldots, 1)$ minimizes the makespan.

3. If the distance matrix of a bottleneck TSP fulfills (1), then there is an optimal solution which is pyramidal.

Finally we comment on the recognition of bottleneck Monge matrices.

S. Chopra
Capacitated multi-commodity flows

Given a graph $G = (V, A)$, a set of commodities K (each with a source and sink) consider the problem of designing a minimum cost network where there are flow costs on each arc and capacity on each arc can be purchased in batches of size C at a cost w_a. This problem is shown to be NP-hard even on series-parallel graphs. For the case with a single commodity (single source and sink) we give a polynomial time algorithm and a complete inequality description of the polyhedron for the case where flow required is at most the batch-size. For the general case we describe a family of valid inequalities and discuss how these can be used computationally.

G. Cornuejols
Balanced $0, \pm 1$ matrices

A $0, \pm 1$ matrix is balanced if, in every submatrix with exactly two nonzero entries per row and column, the sum of the entries is a multiple of four. This concept introduced by Truemper, generalizes the notion of balanced $0, 1$ matrix defined by Berge. In joint work with Michele Conforti we extend the notion of bicoloring to $0, \pm 1$ matrices and we prove that a $0, \pm 1$ matrix is balanced if and only if all of its submatrices have a bicoloring. This generalizes a theorem of Berge about bicoloring $0, 1$ matrices. We also extend to the $0, \pm 1$ case results of Fulkerson, Hoffman and Oppenheim on the total dual integrality of the set packing and set covering problems when the constraint matrix is balanced.

W. H. Cunningham
Matchings, matchable sets, Hilbert bases

A *matchable set* of a graph $G = (V, E)$ is the set of end nodes of some matching of G. If $P(G)$ is the matching polytope of G and $Q(G)$ is the matchable set polytope, then $Q(G) = \{A_y : y \in P(G)\}$, where A is the incidence matrix of G. A rational polytope P has the $\frac{1}{m}$ Hilbert property if each $x \in P$ has an expression as a convex combination of vertices of P with coefficients λ such that λ is $\frac{1}{m}$ as discrete as x. (That is, qx integral implies $mq\lambda$ integral.) For $m = 1$, this is equivalent to $\{(v, 1) : v \text{ a vertex of } P\}$ being a Hilbert basis. We prove that for any $G, Q(G)$ has the $\frac{1}{2}$ Hilbert property, and moreover λ can be chosen with at most $3(|V| - 1)/2$ nonzeroes. A general result on the $\frac{1}{m}$ HP implies only that λ need to have at most $m|V|$ nonzeroes. We conjecture that the correct number for $Q(P)$ is $|V| + 1$. The proof uses the result that for any

$x \in Q(G)$ there exists $y \in P(G)$ with y $\frac{1}{2}$ as discrete as x and with y having at most $3(|V|-1)/2$ nonzeroes.
Part of this is joint with J. Green-Krótki.

S. Fekete
Minimum area polygons

The "Minimum Area Polygon" problem (MAP) asks for a simple polygon with a given planar set of vertices for which the enclosed area attains the minimum. Pick's theorem provides a relation between the area of a simple polygon and the number of grid points it meets; this yields a combinatorial lower bound for the area of a polygon. Considering this bound leads to the "Grid Avoiding Polygon" problem (GAP), which asks for a simple polygon with a given set of (grid) vertices that does not meet any additional grid points. We prove that GAP is NP-complete, implying NP-completeness of MAP. This result answers a question stated by Suri in 1989. We also show that the respective maximization problems are NP-complete and closely related to MAP and GAP. We give upper and lower bounds on approximation factors for the "Maximum Area Polygon" problem. Finally, we show that it is NP-hard to minimize the volume of the k-dimensional faces of a simple d-dimensional polyhedron with a given set of vertices. This answers a generalization of a question of O'Rourke.

M. Fischetti
Odd cycles and $0, \frac{1}{2}$-cuts

Given the polyhedron $P := conv\{x \in Z^n : Ax \leq b,\ x \geq 0\}$, where A is a $m \times n$ integer matrix and $b \in Z^m$, a *Chvátal-Gomory (C-G) cut* is a valid inequality for P of the type $\alpha^\lambda x \leq \alpha_0^\lambda$, where $\lambda \in R_+^m$, $\alpha_j^\lambda := \lfloor \sum_{i=1}^m \lambda_i a_{ij} \rfloor$ $(j = 1, \ldots, n)$, and $\alpha_0^\lambda := \lfloor \sum_{i=1}^m \lambda_i b_i \rfloor$. In this paper we study *0-1/2 C-G cuts*, arising for $\lambda \in \{0, 1/2\}^m$. We show that the associated separation problem, 0-1/2 SEP, has a pleasant combinatorial structure, and can be solved efficiently in the special cases in which A has at most 2 odd coefficients per row, or at most 2 odd coefficients per column. This generalizes a result of Padberg and Rao. We also describe reduction procedures for 0-1/2 SEP, and outline two heuristic algorithms. One of the two heuristics turns out to be exact for a subclass of 0-1/2 C-G cuts, which often contains wide families of strong inequalities for P. Applications to the Node Packing, Clique Partitioning, Asymmetric Traveling Salesman, and Plant Location polytopes are briefly discussed. Finally, we present in the appendix a new efficient algorithm for finding a minimum-weight odd cycle in a digraph.
Joint work with A. Caprara.

A. Frank

Preserving and augmenting edge connectivity

Generalizing a theorem of J. Edmonds, we prove the following:

Theorem 1: Let $D = (V, A)$ be a directed graph with a special node r, called root, and a subset T of target nodes so that the in-degree of each other node is at least its out-degree. There is a family $\mathcal{F}$ of k edge-disjoint r-arborescences in D so that each member of $\mathcal{F}$ contains every element of T if and only if $d_{in}(X) \geq k$ holds for every $X \subseteq V - r$ for which $X \cap T \neq \emptyset$.

Theorem 2: If D is a pre-flow digraph (i. e. $d_{in}(v) \geq d_{out}(v)$ for every $v \in V - r$) then for any k there are k edge-disjoint arborescences rooted at r so that each vertex v belongs to $\min(k, \lambda(r, v))$ of them where $\lambda(r, v)$ denotes the maximun number of edge-disjoint paths from r to v.

These results are derived with the help of a splitting theorem that generalizes an earlier result of W. Mader.

B. Gerards

Disjoint paths on the Möbius strip

Theorem 1: Let $G = (V, E)$ be a graph embedded on the Möbius strip $\mathcal{M}$ such that the collection $d_1, d_2, \ldots, d_{2k}$ of odd degree nodes lies, in that order, on the boundary of $\mathcal{M}$. Then the following hold:

a) There exist k edge disjoint paths $P_1, \ldots, P_k$ such that P_i goes from d_i to d_{i+k} for $i = 1, \ldots, k$ if and only if for each $U \subset V$ the number of indices $i = 1, \ldots, k$ with $| \{d_i, d_{i+k}\} \cap U |= 1$ is at most the cardinality of $\delta(U) = \{uv \in E \mid u \in U, v \notin U\}$.

b) There exist k edge disjoint paths $P_1, \ldots, P_k$ such that P_i goes from d_i to d_{2k-i} for $i = 1, \ldots, k$ if and only if for each $U \subset V$ the number of indices $i = 1, \ldots k$ with $| \{d_i, d_{2k-i}\} \cap U |= 1$ is at most the cardinality of $\delta(U)$.

Similar results have been derived for the plane disk (Okamura and Seymour (1991)) and for the annulus (Okamura (1983), Schrijver (1989)). These three results by Okamura, Seymour and Schrijver can be combined with statement a) of Theorem 1 into one, unifying, result.

Theorem 2: Let G be a graph embedded on the Klein Bottle such that all faces of G are bounded by even circuits. Then for each $w \in \mathbb{R}_+^E$ with $w(\delta(v))$ even if $v \in V$ we have that

$$\begin{array}{llll} \min & w^T x & = \max \sum_{C \text{ odd circuit}} & y_C \\ s.t. & x(C) \geq 1 \quad (C \text{ odd circuit}) & s.t. \sum_{C \text{ odd circuit}, C \ni e} & y_C \leqq w_e \quad (e \in E) \\ & x \in \mathbb{Z}_+^E & & y_C \in \mathbb{Z}_+ \quad (C \text{ odd circuit}) \end{array}$$

E. Girlich
Combinatorial classification of polymatroids

We investigate the combinatorial structure of polymatroids

$$P(r) = \{x \in R_n^+ : \sum_{i \in I} x \leq r(I),\quad I = N\},\ N = \{1, 2, \ldots, n\}$$

where the rank function $r(I) : 2^N \longrightarrow R^+$, is a submodular, isotone and normalized function. Edmonds describes the minimal system of facets of a n-dimensional polymatroid. By $R(r)$ we denote the facet-poset, where the sets $I \in R(r)$ are r-closed and r-inseparable. Two polytopes P_1, P_2 are combinatorial equivalent, iff there exists an isomorphism with

$$F_1 \subseteq F_2 \subseteq P_1 \Longleftrightarrow \mu(F_1) \subseteq \mu(F_2) \subseteq P_2 \quad .$$

Combinatorial equivalent polytopes have the same structural vectors $f(P) = (f_0(P), f_1(P), \ldots, f_{n-1}(P))$, where $f_i(P)$ denote the number of i-faces of the polytope P.
By $H(n)$ we denote the cone of all rank-functions $r(I)$, which are a positive combination of Boolean rank-functions. $H(n)$ is a simplicial cone. All polymatroids $P(r)$, where r is an element of a faces of $H(n)$ are combinatorial equivalent. For all $r \in int(H(n))$ the polymatroid $P(r)$ is combinatorial equivalent with the permutation-polymatroid.

M. X. Goemans
Approximation through uncrossing

We consider the class of combinatorial optimization problems which can be formulated by an integer program of the following type:

$$Min \sum_{e \in E} c_e x_e$$

subject to:

$$(IP) \qquad \begin{array}{ll} x(\delta(S)) \geq f(S) & \emptyset \neq S \subset V \\ x_e \in \{0,1\} & e \in E \ , \end{array}$$

under some restrictions of the function $f : 2^V \longrightarrow \mathbb{N}$. This class includes classical problems such as the Steiner tree, T-join or survivable network design problems. We present a primal-dual algorithm with a provable worst-case performance guarantee. In the case of *uncrossable* functions with range $\{0, 1\}$, the ratio between the values of the primal integral solution and the dual feasible solution is at most 2. In many cases, the algorithm can be efficiently implemented (given an oracle for f).
The (implementation of the) algorithm as well as the structure of the integer program itself raise a number of interesting issues. For example, we have derived a generalization of Padberg and Rao's characterization of minimum odd cuts to minimum uncrossable cuts.
Based on joint work with D. Williamson, H. Gabow, M. Mihail, V. Vazirani.

M. Grötschel
Packing Steiner Trees

In this talk I report about joint work with A. Martin and R. Weismantel (Konrad-Zuse-Zentrum, Berlin) on the problem of packing Steiner trees into a capacitated undirected graph. This problem arises in VLSI design and models several versions of the routing problem of nets. We transform the Steiner tree packing problem into a minimization problem over a polyhedron and investigate the facet structure of this polyhedron. The results of this polyhedral approach are employed in a cutting plane algorithm. I also report on computational experiences with this method.

M. Hartmann
Finding minimum cost-to-time ratio cycles

Let $G = (V, E)$ be a digraph; for each $e \in E$ there is an associated integral cost c_e and a non-negative integral transit time t_e. The minimum cost-to-time ratio cycle problem is to find λ^*, the minimum of $c(\Gamma)/t(\Gamma)$ over all directed cycles Γ of G. We present a new algorithm for finding λ^* whose running time is dominated by $O(\Sigma_{u \in V} \max\{t_{uv} : uv \in E\})$ minimum cost paths calculations on a digraph with non-negative arc costs. Further, we consider early termination of the algorithm and a faster implementation in case $t(\Gamma) > O$ for all directed cycles Γ. The algorithm can be viewed as an extension of the $O(|V||E|)$ algorithm of Karp for the minimum cycle mean problem. Our algorithm can also be modified to solve the related parametric minimum cost paths problem with the same bound on the running time.
Joint work with J. B. Orlin.

D. Hartvigsen
Generalizing the all-pairs min-cut problem

The all pairs min cut (APMC) problem on a nonnegative edge weighted graph is to find, for each pair of nodes, a min cut that separates the pair. Gomory and Hu (1961) presented a structural characterization of collections of cuts that solve the APMC problem. We show how the APMC problem can be generalized to matroids and we present several theorems that characterize the structure of solutions to this more general problem. The result of Gomory and Hu is a special case of one of these theorems. In particular, we find that the APMC problem is a matroid optimization problem.

E. Johnson
Optimum crew pairing

The problem considered is to partition the flight legs into pairings (tours of duty beginning at a crew base and returning) for a monthly airline problem. Work has been done with Ranga Anbil, Rajan Tanga and V. S. Ramakrishnan at American Airlines Decision Technologies on the domestic daily problem. First, a linear program is solved over several million columns and then an integer program is solved over a subset of 15,000 columns. The new methodology has been in use for 1 1/2 years with a resulting saving of about $ 2 million/year. A long-haul problem has been solved in joint work with Levent Hatay and Cynthia Barnhart for a small package carriage. Exact linear programming solutions are obtained using column generation techniques combined with shortest path. Better deadheads are chosen using dual information.

R. Kannan
Optimizing with a membeship oracle

In certain stochastic optimization problems, the feasible convex set is given by a natural membership oracle which returns for any point x in space whether x is feasible. However a separation oracle (which can be obtained under general conditions using a Theorem of Yudin and Nemirovski) is very expensive. We give a randomized polynomial time algorithm to minimize approximately linear functions over up-monotone convex sets $K(x \in K, y \geq x \Rightarrow y \in K)$ in the positive octant. The algorithm puts an exponential bias function on K and does a random walk to sample according to the function. The fast convergence of the random walk is the central issue.
Joint work with J. Mount, S. Tayur.

P. Kleinschmidt
Improvements in chromosome classification

The process of classifying human chromosomes (karyotyping) can be modelled by a transportation problem. We demonstrate how previous attempts in this direction can be substantially improved by better cost functions for the transportation problem.

M. Laurent
Box integral clutters

Let $\mathcal{L}$ be a clutter on E. $\mathcal{L}$ is said to be $\frac{1}{d}$-integral if for all $\frac{1}{d}$-integral bounds a, b, all vertices of the polyhedron $Q(\mathcal{L}) \cap \{x : a \leq x \leq b\}$ are $\frac{1}{d}$-integral. The case $d = 1$ corresponds to the classical notion of weak Max-Flow-Min-Cut property (or Q_+-MFMC, or ideal). A binary clutter is the port of a binary matroid. We prove (with B. Gerards) that a binary clutter $\mathcal{L}$ is $\frac{1}{d}$-integral for some (or for all) $d \geq 2$ iff $\mathcal{L}$ has no Q_6, no Q_7 minor. (Q_6 is the port of F_7, Q_7 is the port of a series extension of F_7).
Given a graph $G = (V, E)$, the polytope $S(G) = \{x : x(F) - x(C - F) \leq \mid F \mid -1$ for $F \subseteq C, C$ cycle of $G, \mid F \mid$ odd$\}$ is a linear relaxation of the cut polytope of G. As a consequence of the above result, $S(G)$ is box $\frac{1}{d}$-integral for $d \geq 2$ if and only if G is not contractible to K_4. We also have some results on $\frac{1}{3}$-integral graphs G, i. e. such that all vertices of $S(G)$ are $\frac{1}{3}$-integral (with S. Poljak). Namely, the 1-sum of two $\frac{1}{3}$-integral graphs is $\frac{1}{3}$-integral; the 2-sum of an integral graph and a $\frac{1}{3}$-integral graph is $\frac{1}{3}$-integral. Also, the 3-sum of an integral graph with a $\frac{1}{3}$-integral graph such that the common triangle carries at least one equality for each vertex, is $\frac{1}{3}$-integral. Serveral minimal excluded minors for $\frac{1}{3}$-integrality are known. They suffice for characterizing $\frac{1}{3}$-integral graphs on $n \leq 7$ nodes.
Joint work with B. Gerards, S. Poljak.

Th. Lengauer
Research problems in bioinformatics

Molecular bioinformatics is a notion describing an interdisciplinary research area between biochemistry/molecular biology on the one hand and computer science/mathematics on the other hand. The aim of this area is to develop computer-aided methods for analyzing and, eventually, designing large biopolymers, especially proteins.
The function of proteins is governed by the three structural aspects:

- sequence,
- 3d structure,
- dynamics.

The talk gives an introduction into all three structural aspects. Then it surveys existing computer-aided methods for the analysis of proteins and exhibits their limitations.
Finally, the talk poses a few algorithmic problems in the area of the analysis of protein structure. Among them is a problem of aligning a protein sequence into a (different) protein structure. The aim is to evaluate how likely the sequence is to fold up into the given structure.

T. M. Liebling
Placement of telecom satellites on the GSO

Placing telecom satellites on the geostationary orbit is becoming an increasingly sensitive issue since that orbit is getting quite crowded and satellites interfere with each other.
The solution of the underlying optimization problem is the basis for the discussions at the International Telecommunication Union for the allotments of service arcs to the various member countries.
Our formulation of that problem is

$$max(z \mid w_i \leq v_i \leq E_i; \quad min(|v_j - v_i|, 2\pi - |v_j - v_i|) \geq z d_{ij} \quad \forall i, j) .$$

This problem is solved using a partial enumeration heuristic, since it is NP-Hard. For a fixed order of the satellites on the GSO, it becomes the dual of the LP consisting in finding a circuit of minimum cost to weight ratio in a graph. Each arc of the graph is associated with a cost and a weight (possibly negative). This LP is efficiently solved using a version of the simplex method "à la Cunningham".
Talk based on S. E. Bickerstaff-Spältli's Ph. D. thesis.

L. Lovász
The cocycle lattice of binary matroids

We study the lattice (grid) generated by the incidence vectors of cocycles in a binary matroid. It is shown that in the dual of this lattice, every denominator is a power of 2. Matroids for which the dual lattice is $\frac{1}{2}$-integral are characterized : they are those matroids that, when embedded in the projective space over $GF(2)$, contain a member of the (punctured) Reed-Müller code. This gives a polynomial time algorithm to recognize such matroids.
Joint work with A. Seress.

T. Magnanti
Heuristics, LPs and trees on trees

We study a class of models, known as overlay problems with two sets of variables x and y, related by linking constraints $x \leq y$. For example, in some telecommunication settings y corresponds to a spanning tree and x to an embedded Steiner tree (or a path). For the general problem, we describe a heuristic solution procedure and establish a worst-case performance guarantee for this heuristic as well as for the linear programming relaxation of the model. For certain models, these performance guarantees are 33%. We also develop heuristic and linear programming performance guarantees for specialized models, a dual path connectivity model with a worst-case guarantee of 25% and an uncapacitated network design model with a worst-case performance guarantee (approximately) proportional to the square of the number of commodities.
Joint work with A. Balakrishnan, P. Mirchandani.

A. R. Mahjoub
Two-connected spanning subgraphs and polyhedra

We study the problems of finding a two-edge (two-node) connected spanning subgraph of minimum weight. These problems are closely related to the widely studied traveling salesman problem and have applications to the design of reliable communication and transportation networks. We discuss the polytopes associated with the solutions to these problems. We give complete descriptions of these polytopes for the class of Halin graphs. We show that when the graph is series-parallel, the polytope associated with the two-edge connected spanning subgraphs is completely described by the trivial constraints and the so-called cut constraints. We also discuss some classes of facet defining inequalities of these polytopes and other polyhedral aspects when the graph is general.

F. Margot
Polyhedral characterizations
A new method for proving integrality of polytopes corresponding to the convex hull of the characteristic vectors of solutions to some combinatorial problems on graphs defined by compositions is presented. The method is illustrated with the Maximum Cut on 2-trees and has been used to derive complete linear characterizations for the Independent Set, Strong Connectivity Orientation and Strongly Connectivity problems on series parallel graphs.

R. Möhring
Path- and treewidth of some perfect graphs

We show that the pathwidth of a cocomparability graph equals its treewidth. The proof is based on a new notion, called *interval width*, for a partial order P, which is the smallest width of an interval order contained in P, and which is shown to be equal to the treewidth of its cocomparability graph (plus 1). We observe that determining any of these parameters is $\mathcal{NP}$- hard and develop approximation algorithms for interval width of P whose performance ratios depend on the dimension of P. Applying similar proof techniques, we also show that the treewidth of a graph without asteroidal triple equals its pathwidth.
Some of the results are joint work with M. Habib.

C. Moll
The inverse shortest path problem

We consider the following problem: Given a graph $G = (V, E)$, some pairs of nodes $E' \subset V \times V$ and distances $D(v, w)$ for every pair $(v, w) \in E'$. Are there weights for the edges $e \in E$ such that the induced distances d_w on the graph correspond to the given distances $(d_w(v, w) = D(v, w)\ \forall(v, w) \in E')$. We show that this problem is $\mathcal{NP}$-complete even in very restricted cases (planarity of $G(V, E \cup E')$, $E' \subset \{v_1, v_2\} \times V$). On the other hand, we present polynomial time algorithms for the following cases ($E' = \{v_1, ..., v_k\} \times V$, $E' \subseteq \{v_o\} \times V$). If we fix paths for every pair in E', we have to consider the problem of finding weights such that these paths are shortest paths of given distances. This problem can be formulated as a linear program. We use this observation for a heuristical approach.
Joint work with A. Bachem, H. Haugs, S. Fekete, W. Hochstättler.

D. Naddef
Using path inequalities in a branch and cut code for the symetric TSP-polytope

In this joint work with Jean Maurice Clochard we present evidence that path inequalities can be useful in solving symmetric traveling salesman problems by branch and cut. Moreover they are the key of a branching strategy based on subtour elimination inequalities rather than on variables. The problem of the high density of these inequalities can be dealt with in various manners.

G. L. Nemhauser
The fleet assignment problem : solving large scale IP

Given a flight schedule and set of aircraft, the fleet assignment problem is to determine which type of aircraft should fly each flight segment. This paper describes a basic daily, domestic fleet assignment problem and then presents chronologically the steps taken to solve it efficiently. Our model of the fleet assignment problem is a large multi-commodity flow problem with side constraints defined on a time-expanded network. These problems are often severely degenerate, which leads to poor performance of standard linear programming

techniques. Also, the large number of variables can make finding optimal integer solutions difficult and time consuming. The methods used to attack this problem include an interior point algorithm, cost perturbation, model aggregation, branching on set-partitioning constraints and prioritizing the order of branching. The computational results show that the algorithm finds solutions with a maximum optimality gap of 0.22% and is more than two orders of magnitude faster than using default options of a standard LP-based branch and bound code.
Joint work with C. A. Hane, C. Barnhart, E. Johnson, R. E. Marsten, G. Sigismondi

S. Poljak
Local maximum cuts

Let $G = (V, E)$ be a cubic graph, and $x = (x_e)$ variables associated with the edges. Consider a system of linear inequalities consisting of $|V|$ blocks, where each block corresponds to a vertex. Every block may have one or two possible forms :

either	$x_e > x_f + x_g$	(1 inequality)
or	$x_e \leq x_f + x_g$	
	$x_f \leq x_e + x_g$	(3 inequalities)
	$x_g \leq x_e + x_f$	

where e, f, g are edges incident to a common vertex. In addition we assume

$$x_1, x_2, \ldots, x_{|E|} \geq 0.$$

We prove that the system is feasible if and only if it has a bounded integer solution such that $1 \leq x_e \leq 2n$ for every e. The solvability of the system is characterized by a combinatorial condition.
As a corollary, we prove that any local search for max-cut on weighted cubic graphs requires at most $O(n^2)$ steps.

W. R. Pulleyblank
Depot scheduling

We discuss a model of the depot operation of a large food seller in the United Kingdom. We discuss the formulation as well as computational results. The model was run on a network of nineteen RS/6000's.
This was joint work with J. Forrest

P. Raghavan
Fun with random walks

We introduce a two-person "cat and mouse" game played on n points in a space. We give a tight characterization of this game in terms of a synthesis problem for a random walk on the points. We show that this synthesis problem can be solved by invoking electric network theory. We apply these results to obtain an optimal randomized algorithm for the server problem on a class of metric spaces.

G. Rinaldi
Vehicle Routing Problems

We consider the problem of finding a minimum length k-tour in a complete graph. A k-tour is the edge set of the union of k circuits that cover all nodes of the graph and all meet at the same node. We consider both the capacitated and uncapacitated version of the problem. In the capacitated case a demand function is defined on the nodes and the total demand of the nodes of each of the k circuits is required not to exceed a given capacity.
We show how the LP relaxation of an integer programming formulation of the capacitated problem is polynomially solvable by means of a separation procedure for the capacity constraints. An extension of these constraints leads to the class of the *generalized capacity inequalities*. We show conditions for these inequalities to be facet defining. (*This is joint work with F. Harche.*)
We describe several new classes of valid inequalities that can be viewed as extensions of TSP comb inequalities, obtained by taking into account the capacity constraints. These inequalities turned out to be very effective in a computational study where some difficult medium sized problems could be solved to optimality without resorting to enumeration. (*This is joint work with Y. Pochet, L. Wolsey, P. Augerat, J.M. Clochard, D. Naddef, E. Benavent, V. Campos, A. Corberan, E. Mota.*)
Finally, we address the uncapacitated problem. Two operations are described that, when applied to any facet defining inequality for the TSP, produce facet defining inequality for the polytope associated with the problem. For some of the inequalities obtained with these operations we show how the separation problem can be solved in polynomial time.

G. Rote
The mice-collecting traveling salescat problem

In the traveling salesman problem for moving points we have given n objects which move in fixed directions with given fixed constant speeds in some Euclidian space, and a salesperson with an upper bound on her speed wants to visit all objects as fast as possible. Besides the application suggested by the metaphor in the title, possible applications include the refueling of planes during flights (approximately a two-dimensional problem) and a man who wants to look at each of n ladies strolling along a street (a problem in $\mathbb{R}^1$).
We present a dynamic programming algorithm that solves the one-dimensional version of the problem (all points move on a single line) in $O(n^4)$ time and $O(n^3)$ space.
We also give some ideas that might lead to a heuristic algorithm for the two-dimensional problem with a constant performance guarantee factor.

A. Sassano
The p-median polytope

A spanning p-star of a digraph $G = (V, E)$ is a subset F of E with $|F| = |V| - p$ and with the property that each arc of $|F|$ goes from a node in a subset $S \subseteq V$ with p elements to a distinct node of the set $V - S$.
The p-median polytope $M_k(G)$ is the convex hull of the incidence vectors of the spanning p-stars of G. We show that $M_k(G)$ has dimension $|V| - 1$ and it is a "slice" of the vertex packing polytope $P(H_G)$ associated with a suitable graph H_G derived from $G(M_k(G)) = conv(P(H_G) \cap \{x \in \{0,1\}^{|E|} : \sum_{e \in E} x_e = k\})$. In addition, we exhibit some basic classes of facet defining inequalities for $M_k(G)$ and for two of them we describe exact separation algorithms with a polynomial running time.
Joint work with P. Avella.

A. Sebö
Minimally non-greedy structures

In a common paper with Y. Caro and M. Tarsi we study when various classes of problems can be solved in a greedy or - with the terminology of some predecessors - in a "random" way. The results we give are sometimes polynomial algorithms to recognize greedy instances, for other problems we also give structural characterizations, for yet others we provide $\mathcal{NP}$-completeness proofs.
In the talk I speak in details about a structural characterization of minimal hypergraphs in which the greedy algorithm does not necessarily lead to maximum matching, and about minimal "not-jump-system".

P. D. Seymour
Graph 5-colouring

H. Hadwiger conjectured in about 1940 that for any integer $p \geq 0$, every graph not contractable to K_{p+1} is p-colourable. For $p \leq 3$ this is easy, but for $p = 4$ it is extremely difficult and is equivalent to the four-colour problem, as K. Wagner showed in 1937. In joint work with N. Robertson asn R. Thomas, we show that also for $p = 5$ the conjecture is equivalent to the four-colour problem (and hence true, assuming the 1978 proof of the four-colour problem by Appel and Haken). Indeed, without using the four-colour problem, we show that every minimal counterexample is "apex", that is, it has a vertex whose deletion leaves a planar graph. Our method is roughly as follows. Let G be a minimal counterexample. We prove first that G is 7-connected (almost) and has a perfect matching (almost). The graph obtained by contracting the edges in the 1-factor has average valency < 8 (for otherwise it would be contractable to K_6, by a result of Mader) and so a random edge of the 1-factor is in several circuits of length 3 or 4. Since these short circuits cannot be converted to a K_6 it follows that G is apex as required.

B. Sheperd
Lehman's theorem and stable set polyhedra

We consider a transformation of covering polyhedra to polytopes which preserves the dimensions of faces. This is used together with results of Lehman about contraction-minimal matrices to give a linear description for the stable set polytopes of *near-bipartite* graphs. These are graphs for which $G - N(v)$ is bipartite for each node v. This class contains the complements of line graphs. The description results in several new classes of minimal non-t-perfect graphs.

D. Shmoys
An approximation algorithm for the generalized assignment problem

The generalized assignment problem can be viewed as the following problem of scheduling parallel machines with costs. Each job is to be processed by exactly one machine; processing job j on machine i requires time p_{ij} and incurs a cost of c_{ij}; each machine i is available for T_i time units, and the objective is to minimize the total cost incurred. Our main result is as follows. There is a polynomial-time algorithm that, given a value C, either proves that no feasible schedule of cost C exists, or else finds a schedule of cost at most C where each machine i is used for at most $2T_i$ time units.
We also extend this result to a variant of the problem where, instead of a fixed processing time p_{ij}, there is a range of possible processing times for each machine–job pair, and the cost linearly increases as the processing time decreases. We show that these results imply a polynomial-time 2-approximation algorithm to minimize a weighted sum of the cost and the makespan, *i.e.*, the maximum job completion time. We also consider the objective of minimizing the mean job completion time. We show that there is a polynomial-time algorithm that, given values M and T, either proves that no schedule of mean job completion time M and makespan T exists, or else finds a schedule of mean job completion time at most M and makespan at most $2T$.
Joint work with É. Tardos.

M. Stoer
Survivable network design problem involving multicommodity flows

The problem is to extend the capacities of a given network such that the traffic demands can be met in each failure situation (single edge or single node failure), and such that the extension cost is minimal. A cutting plane algorithm using Benders decomposition and some polyhedral results are presented.
Joint work with G. Dahl.

S. Thienel
Implementation of a branch and cut algorithm for the TSP

We resemble the implementation of Padberg and Rinaldi (1991) of a branch and cut algorithm for the TSP, yet there are some differences.
Fractional LP-solutions are not only used for the computation of lower bounds, but also to compute good tours. The set of active variables is generated and managed differently. The reduced costs of nonactive variables are computed

in a hierarchical fashion. Since our algorithms for the separation of comb and clique tree constraints are less sophisticated, we cannot solve as large problems to optimality as Padberg and Rinaldi could. Because the computation of upper and lower bounds is integrated, we can find a tour with prespecified guaranteed quality and give satisfiable solutions and lower bounds even if there is only a limited amount of CPU-time available. Finally we show how this implementation for the TSP can be used as a framework for other combinatorial optimization problems.
Joint work with M. Jünger and G. Reinelt.

D. Wagner
A linear-time algorithm for edge-disjoint paths in planar graphs

We consider the problem of finding edge-disjoint paths in a planar graph, s. t. each path connects two specified vertices on the outer face boundary. We focus on the case where the eveness condition is satisfied. The "classical" result for that problem is the theorem of Okamura & Seymour, which says that a problem is solvable iff the cut condition is fulfilled. Several algorithms solving this problem which are based on this result are known from the literature. The best one receives a running time of $O(n^{\frac{5}{3}}(loglogn)^{\frac{1}{3}})$.
In this talk a new algorithm is presented which requires only $O(n)$ time. The approach also yields an alternative proof for the theorem of Okamura & Seymour.
Joint work with K. Weihe

E. Welzl
Two frameworks for optimization problems

We present two frameworks for solving optimization problems including linear programming (n constraints, d variables), computing the smallest enclosing ball of n points in $\mathbb{R}^d$, or computing the distance between two n-vertex (or n-facet) d-polytopes. The algorithm developed in the framework can be shown to use a subexponential number of arithmetic operations in the unit cost model

$$\text{expected } O(nd^2 + e^{\sqrt{d \cdot logd}}), \text{ randomized}$$

(This bound relies on work by Clarkson, Kalai, Matoušek/Sharir/Welzl, and Gärtner).
Here is Gärtner's framework. Suppose we are given an n-element set H with a linear ordering $\prec$ on 2^H. Our goal is to find the minimal element in 2^H. $(H, \prec)$ is given implicitely by the following oracle : for $F \subseteq G \subseteq H$, the oracle either reports that F is optimal in 2^G (i.e. $F = min(2^G)$), or it provides a set F', $F' \subseteq G$, $F' \prec F$. (No conditions on $(H, \prec)$ are required!). Every deterministic algorithm requires $2^n - 1$ oracle queries in the worst case, while a randomized algorithm can solve every such problem with expected $e^{O(\sqrt{n})}$ oracle queries.

L. A. Wolsey
Polyhedra for lot-sizing with Wagner-Whitin costs

We examine the single-item lot-sizing problem over an n period horizon with Wagner-Whitin costs, i. e. $p_{t-1}+h_{t-1} \geq p_t$, $p_{t+1}+g_t \geq p_t$ for all t, where p_t, h_t and g_t are the unit production, storage and backlog costs respectively.
For the uncapacitated problem with backlogging (BLS) abd the constant capacity problem (CLS), an explicit description of the convex hull of solutions in the basic stock, backlog and set-up variables is not known for either model. Here we describe integral polyhedra which which solve the two problems with Wagner-Whitin costs. In addition we obtain combinatorial separation algorithms that are $O(n^2)$ for CLS and $O(n^3)$ for BLS, as well as extended formulations with $O(n^2)$ constraints and variables in both cases.
Joint work with Y. Pochet

G. M. Ziegler
Constructing the Permuto-Associahedra

We construct a family of polytopes KPA_{n-1}, the "Permuto-Associahedra". Here KPA_{n-1} is an $(n-1)$-dimensional polytope, whose vertices correspond to the complete bracketings of permutations of $\{1,2,\ldots,n\}$, with a natural notion of adjacency. Our proofs yield integral coordinates, with all vertices on a sphere, and include a complete description of the facet-defining inequalitites.
This solves a problem of M. M. Kapranov (Northwestern U.), who had defined KPA_{n-1} as a combinatorial object and showed that it corresponds to a cellular ball.
Joint work with V. Reiner

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