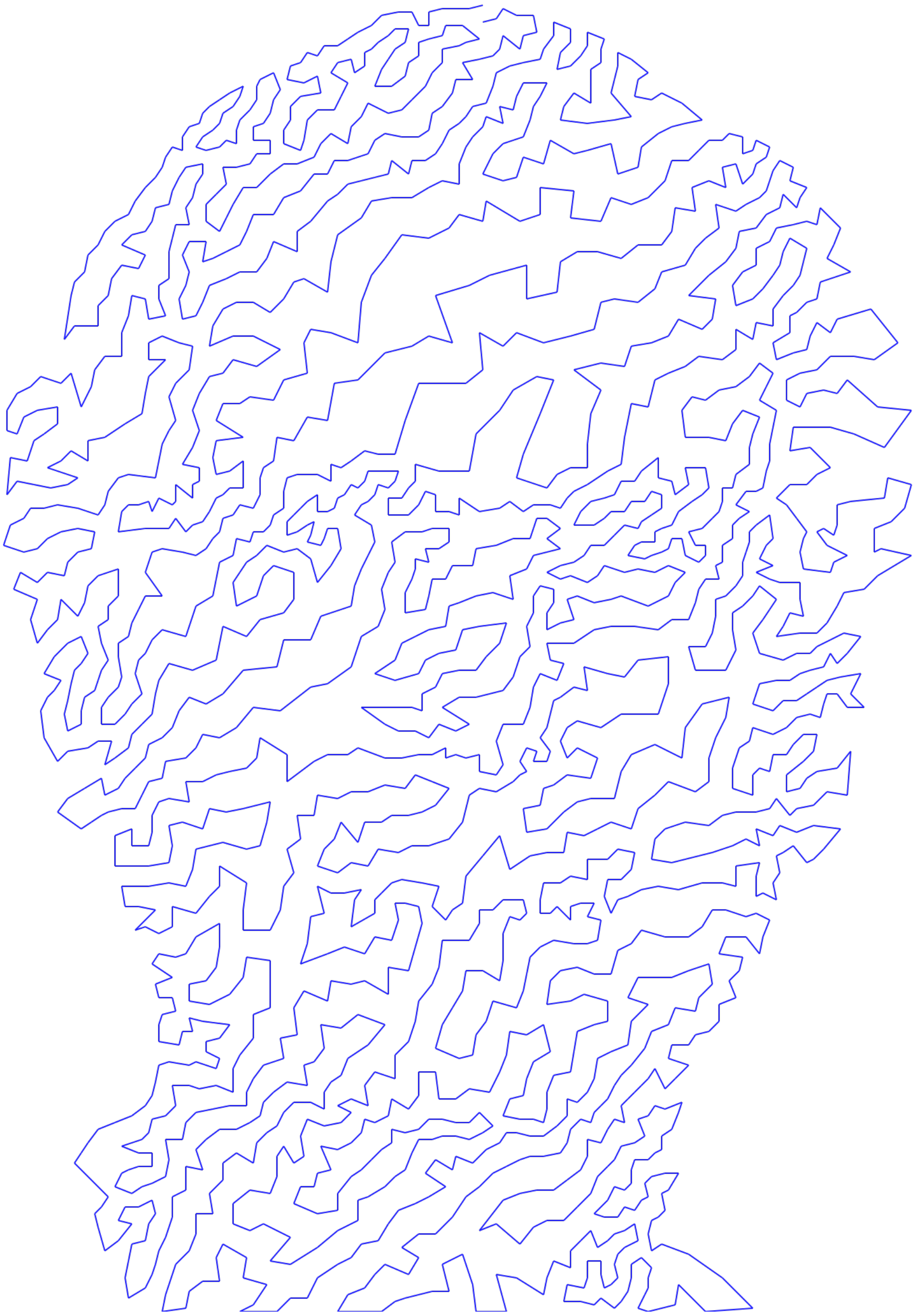
Bonn Workshop on Combinatorial Optimization

Celebrating the 65th Birthday of Bill Cook

October 17-21, 2022



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1 General information

Organizers

David Applegate	Daniel Espinoza	Stephan Held	Bernhard Korte

Plenary Speakers

David Applegate	Daniel Bienstock	Robert Bixby	Sylvia Boyd
Vašek Chvátal	Sanjeeb Dash	Michel Goemans	Laura Sanità
Alexander Schrijver	Jens Vygen		

Arithmeum

The Arithmeum presents the history of mechanical calculating machines, as well as the computing of today, in an aesthetically pleasing environment. Many demonstration models invite the visitor to discover the historical milestones of mechanical calculating, and at interactive multimedia stations the visitor can develop small microprocessors in a playful way. Early highlights in the development of computers are also exhibited. You are invited to join a **guided tour on Wednesday, 17:45 - 18:45**.

WiFi

SSID dm-guest **Key** GuestPW22!

2 Schedule

Monday, October 17, 2022

08:30 – 08:55	Registration
08:55 – 09:00	Opening

Chair: Bernhard Korte

09:00 – 10:00	**Alexander Schrijver** On the Shannon capacity of sums and products of graphs
10:00 – 10:30	Coffee break

Chair: Laura Sanità

10:30 – 11:00	**Laurence Wolsey** On path lengths of undirected binary trees
11:00 – 11:30	**Bruce Reed** The speed and bias of the Hamilton cycle maker-breaker game
11:30 – 12:00	**Linda Cook** Detecting a long even hole
12:00 – 14:00	Lunch break

Chair: Alexander Martin

14:00 – 15:00	**Sylvia Boyd** The 4/3 conjecture: Is it true or false?
15:00 – 15:30	**Rico Zenklusen** Approximating weighted connectivity augmentation below factor 2
15:30 – 16:00	Coffee break — conference photo

Chair: Michael Jünger

16:00 – 16:30	**Vera Traub** Reducing Path TSP to TSP
16:30 – 17:00	**Nathan Klein** Analyzing the max entropy algorithm for TSP
17:00 – 17:30	**Niklas Schlomberg** Packing cycles in planar and bounded-genus graphs

Tuesday, October 18, 2022

Chair: Alexander Schrijver

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10:00 – 10:30	Coffee break

Chair: Martin Grötschel

10:30 – 11:00	**Joseph Cheriyan** The traveling tournament problem: Complexity aspects
11:00 – 11:30	**Martin Skutella** Quickest minimum cost transshipments
11:30 – 12:00	**László Végh** Approximating Nash social welfare for submodular valuations
12:00 – 14:00	Lunch break

Chair: Daniel Espinoza

14:00 – 14:30	**Ricardo Fukasawa** A fast combinatorial algorithm for the bilevel knapsack problem with interdiction constraints
14:30 – 15:00	**Ambros Gleixner** Certified Gomory mixed integer cuts in a numerically safe MIP framework
15:00 – 15:30	**Daniel Dadush** Interior point methods are not worse than Simplex
15:30 – 16:00	Coffee break

Chair: Vašek Chvátal

16:00 – 16:30	**Robert Bixby** Some TSP stories
16:30 – 17:30	**Ina Prinz** About traveling salesmen and unicorns
17:45	Birthday dinner departure

Wednesday, October 19, 2022

Chair: Robert Weismantel

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Choose your witnesses wisely

10:00 – 10:30 Coffee break

Chair: Sylvia Boyd

10:30 – 11:00 **Meike Neuwohner**
The Limits of Local Search for Weighted k-Set Packing

11:00 – 11:30 **Gyorgy Turan**
On machine learning and discrete mathematics: A case study for error-correcting codes

11:30 – 12:00 **Illya Hicks**
May the forts be with you

12:00 – 14:00 Lunch break

Chair: Michel Goemans

14:00 – 15:00 **Vašek Chvátal**
Dear William, bash on regardless!

15:00 – 15:30 **Hang Zhou**
Capacitated vehicle routing

15:30 – 16:00 Coffee break

Chair: Petra Mutzel

16:00 – 16:30 **Volker Kaibel**
Steiner cut dominants

16:30 – 17:00 **Daniel Blankenburg**
Resource sharing revisited

17:00 – 17:30 **Eduardo Uchoa**
Advances in exact algorithms for vehicle routing

17:45 – 18:45 **Arithmeum Tour**

Thursday, October 20, 2022

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10:00 – 10:30 Coffee break

Chair: Gerhard Reinelt

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The Cook et al. proximity question: Improvements and future directions

11:00 – 11:30 **Stefan Hougardy**
How fast is k-Opt?

11:30 – 12:00 **Marcos Goycoolea**
New integer programming ideas for solving large-scale RCPSPs

12:00 – 14:00 Lunch break

Chair: Giovanni Rinaldi

14:00 – 15:00 **Jens Vygen**
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15:00 – 15:30 **Karen Aardal**
Branching on general disjunctions based on lattice information

15:30 – 16:00 Coffee break

Chair: Britta Peis

16:00 – 16:30 **Petra Mutzel**
Quantum annealing versus digital computing: An experimental comparison

16:30 – 17:00 **Zoltán Szigeti**
Recent results on packing arborescences

17:00 – 17:30 **Martin Nägele**
Congruency-constrained optimization

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Chair: Stefan Hougardy

09:00 – 10:00	**Daniel Bienstock** Exact versus approximate solution for QCQPs
10:00 – 10:30	Coffee break

Chair: Stephan Held

10:30 – 11:00	**Thomas McCormick** Parametric min cut complexity
11:00 – 12:00	**David Applegate** PDLP: A large-scale LP solver
12:00	Ending

3 Abstracts

Branching on general disjunctions based on lattice information

Karen Aardal

There has been enormous progress in the branch-and-bound methods in the past couple of decades. In particular, much effort has been put into the so-called variable selection problem, i.e. the problem of choosing which variable to branch on in the current search node. Recently, many researchers have investigated the potential of using machine learning to find good solutions to this problem by for instance trying to mimic what good, but computationally costly, heuristics do. The main part of this research has been focused on branching on so-called elementary disjunctions, that is, branching on a single variable. Theory, such as the results by H.W. Lenstra, Jr. and by Lovász & Scarf, tells us that we in general need to consider branching on general disjunctions, but due in part to the computational challenges to implement such methods, much less work in this direction has been done. A notable exception is the implementation of the Lovász-Scarf method by Cook and co-authors. In addition some heuristic approaches have been suggested and implemented.

In this talk we discuss both theoretical and heuristic results when it comes to branching on general disjunctions with an emphasis on lattice based methods. A modest computational study is also presented.

The talk is based on joint work with Lara Scavuzzo and Laurence Wolsey.

Some progress on Woodall's Conjecture on packing dijoins in digraphs

Ahmad Abdi

Let $D = (V, A)$ be a digraph. A dicut is the set of arcs in a cut where all the arcs cross in the same direction, and a dijoin is a set of arcs whose contraction makes D strongly connected. It is known that every dicut and dijoin intersect. Suppose every dicut has size at least k. Woodall's Conjecture, an important open question in Combinatorial Optimization, states that there exist k pairwise disjoint dijoins. We make a step towards resolving this conjecture by proving that A can be decomposed into two sets B and C, where B is a dijoin, and C intersects every dicut in at least $k - 1$ arcs. We prove this by a Decompose, Lift, and Reduce (DLR) procedure, in which D is turned into a sink-regular $(k, k+1)$-bipartite digraph. From there, by an application of Matroid Optimization tools, we prove the result. The DLR procedure works more generally for weighted digraphs, and exposes an intriguing number-theoretic aspect of Woodall's Conjecture. In fact, under natural number-theoretic conditions, Woodall's Conjecture and a weighted extension of it are true. By pushing the barrier here, we expose strong base orderability as a key notion for tackling Woodall's Conjecture.

This is joint work with Gérard Cornuéjols (CMU) and Michael Zlatin (CMU).

PDLP: A large-scale LP solver

David Applegate

To quote Bill, "There's always a bigger TSP. That's a great thing about computational work on the traveling salesman problem." (`https://www.math.uwaterloo.ca/tsp/star/index.html`). A current target is based on the Gaia DR2 star catalog, providing a TSP instance with 1,331,906,450 points. To obtain a strong lower bound on the optimal tour length, we'd like to solve a cutting plane linear program (LP) for this instance. However, traditional LP solvers rely on a factorization of the constraint matrix, requiring significantly more memory than required to record the instance.

I will present an alternative approach to solving LPs, whose core computational operation is instead matrix-vector multiplications. Compared with factorization-based approaches, matrix-vector multiplications are less likely to run out of memory on large-scale problems and are more easily parallelized. Our method, PDLP (PDHG for LP) is based on primal-dual hybrid gradient, popularized by Chambolle and Pock (2011), with several important enhancements, both theoretical and practical.
This talk is based on joint work with: Mateo Diaz, Oliver Hinder, Haihao Lu, Miles Lubin, Brendan O'Donoghue, and Warren Schudy.

Exact versus approximate solution for QCQPs

Daniel Bienstock

In recent years much attention has been directed at QCQPs (Quadratically Constrained Quadratic Programs) which arise in several important engineering applications and are usually nonconvex, and possibly quite large. Addressing QCQPs requires a number of very distinct methodological techniques. Some of these techniques have a clear linear integer programming heritage, and this is reflected in bounding techniques, and, generally speaking, in the language used to describe the solution process. Typically, software systems used to handle QCQPs will report a relaxation bound, as well as an incumbent 'solution' (there is a reason for the quotes). When the difference between bounds is close enough the algorithms will stop. If indeed the difference is lower than a small tolerance, software systems may deploy the term 'optimal'. However, QCQPs differ in a fundamental form from linear problems. 'Solutions' are often computed by local solvers, such as Knitro or IPOPT. These are excellent packages that are expertly implemented and are supported by strong theory. Nevertheless, the vectors output by such codes can exhibit (very) small infeasibilities. And, unfortunately, in the QCQP setting even extremely small infeasibilities can give rise to arbitrarily large superoptimality. In this talk we will present some recent theoretical results concerning these points, and will also perform some simple numerical experiments that display these ideas.

Some TSP stories

Robert Bixby

I will relate some of the Concorde team's experiences working on the TSP.

Resource sharing revisited

Daniel Blankenburg

We revisit the (block-angular) min-max resource sharing problem, which is a well-known generalization of fractional packing and the maximum concurrent flow problem. It consists of finding an ℓ_∞-minimal element in a Minkowski sum $\mathcal{X} = \sum_{C \in \mathcal{C}} X_C$ of non-empty closed convex sets $X_C \subseteq \mathbb{R}^{\mathcal{R}}_{\geq 0}$, where $\mathcal{C}$ and $\mathcal{R}$ are finite sets. We assume that an oracle for approximate linear minimization over X_C is given.

We improve on the currently fastest known FPTAS in various ways. A major novelty of our analysis is the concept of local weak duality, which illustrates that the algorithm optimizes (close to) independent parts of the instance separately. Interestingly, this implies that the computed solution is not only approximately ℓ_∞-minimal, but among such solutions, also its second-highest entry is approximately minimal.

Based on a result by Klein and Young, we provide a lower bound of

$$\Omega\left(\frac{|\mathcal{C}| + |\mathcal{R}|}{\delta^2} \log |\mathcal{R}|\right)$$

required oracle calls for a natural class of algorithms. Our FPTAS is optimal within this class — its running time matches the lower bound precisely, and thus improves on the previously best-known running time for the primal as well as the dual problem.

The 4/3 conjecture: Is it true or false?

Sylvia Boyd

The well-known 4/3 Conjecture states that the integrality ratio of the subtour LP for metric TSP is at most 4/3 . This conjecture has been around for almost 40 years and has been the focus of much research, yet it remains unresolved. In this talk we survey the results that support the conjecture, as well as discuss the properties that a possible counter example would need to possess.

The traveling tournament problem: Complexity aspects

Joseph Cheriyan

The goal in the Traveling Tournament problem (TTP) is to generate a feasible schedule for a sports league such that the total travel distance incurred by all teams throughout the season is minimized. The TTP has attracted a variety of research over the last two decades, but several questions pertaining to the computational complexity of the problem and its variants remain open. The talk will discuss some of these questions and will present some recent progress.

This is based on joint work with Salomon Bendayan and Kevin Cheung, and Salomon's masters thesis covers some of these topics.

Dear William, bash on regardless!

Vašek Chvátal

The speaker will survey his interactions with the birthday boy since their first meeting at the Institut für Ökonometrie und Operations Research in early 1984.

Detecting a long even hole

Linda Cook

We call an induced cycle of even length in G an even hole. In 1991, Bienstock showed that it is NP-hard to test whether a graph G has an even hole containing a specified vertex v in G. In 2002, Conforti, Cornuéjols, Kapoor and Vušković gave a polynomial-time algorithm to test whether a graph contains an even hole by applying a theorem about the structure of even-hole-free graphs from an earlier paper by the same group. In 2003, Chudnovsky, Kawarabayashi and Seymour provided a simpler polynomial time algorithm that searches for even holes directly. We extend this result by presenting a polynomial time algorithm to determine whether a graph has an even hole of length at least k for a given $k \geq 4$.

This is joint work with Paul Seymour.

Interior point methods are not worse than Simplex

Daniel Dadush

Whereas interior point methods provide polynomial-time linear programming algorithms, the running time bounds depend on bit-complexity or condition measures that can be unbounded in the problem dimension. This is in contrast with the classical simplex method that always admits an exponential bound. We introduce a new polynomial-time path-following interior point method where the number of iterations also admits a combinatorial upper bound $\mathcal{O}(2^n n^{1.5} \log n)$ for an n-variable linear program in standard form. This complements previous work by Allamigeon, Benchimol, Gaubert, and Joswig (SIAGA 2018) that exhibited a family of instances where any path-following method must take exponentially many iterations.

The number of iterations of our algorithm is at most $\mathcal{O}(n^{1.5} \log n)$ times the number of segments of any piecewise linear curve in the wide neighborhood of the central path. In particular, it matches the number of iterations of any path following interior point method up to this polynomial factor. The overall exponential upper bound derives from studying the 'max central path', a piecewise-linear curve with the number of pieces bounded by the total length of $2n$ shadow vertex simplex paths.

This is joint work with Xavier Allamigeon (INRIA / Ecole Polytechnique), Georg Loho (U. Twente), Bento Natura (LSE), László Végh (LSE).

Cutting planes from extended formulations

Sanjeeb Dash

Cutting planes are essential tools for solving mixed-integer programs and split cuts — first studied by Cook, Kannan, and Schrijver (1990) — are among the most important cutting planes used in practical integer programming solvers. We discuss how to use extended formulations of the LP relaxation of a mixed-integer program to obtain stronger cutting planes than those that can be obtained from the original LP relaxation. In particular, we compare the effect of adding split cuts in the extended space to the effect of adding the same types of cuts in the original space. We observe that the Lovasz-Schrijver and Sherali-Adams lift-and-project operator hierarchies can be viewed as applying specific 0-1 split cuts to an appropriate extended formulation and demonstrate how to strengthen these hierarchies using additional split cuts. Finally, we discuss extended formulations of mixed-integer programs obtained by replacing integral variables by linear combinations of binary variables and compare the effect of split cuts applied to these extended formulations versus split cuts applied to the original formulation.

A fast combinatorial algorithm for the bilevel knapsack problem with interdiction constraints

Ricardo Fukasawa

We consider the bilevel knapsack problem with interdiction constraints, a fundamental bilevel integer programming problem which generalizes the 0-1 knapsack problem. In this problem, there are two agents, a leader and a follower. Both of them have their own knapsack constraints over the same set of items. The objective of the follower is just like the regular knapsack problem: maximize profits obtained by picking items that fit into the follower's knapsack. The leader, on the other hand, is allowed to pick items that fit into the leader's knapsack and, any item picked will be unavailable for the follower. The objective of the leader is to minimize the profit of the follower. Previous exact methods for solving this problem make use of mixed-integer linear programming (MIP) solvers. We present a simple combinatorial branch-and-bound algorithm which outperforms the current state-of-the-art solution methods by 4.5 times on average for all instances reported in the literature. Furthermore, our algorithm solved 53 of the 72 previously unsolved instances. Our result relies fundamentally on a new dynamic programming algorithm which computes very strong lower bounds. This dynamic program relaxes the problem from bilevel to $2n$-level by ordering the items and solving an online version of the problem.
This is joint work with Noah Weninger.

Certified Gomory mixed integer cuts in a numerically safe MIP framework

Ambros Gleixner

The presence of floating-point roundoff errors compromises the results of virtually all fast mixed integer programming solvers available today. In this talk we present recent advances in our endeavour to craft a performant mixed integer optimizer that is not only free from roundoff errors, but also produces certificates of optimality that can be verified independently of the solving process. We provide an overview of the entire framework, which is an extension of the open solver SCIP. We focus in particular on the exact generation of two types of valid inequalities: Gomory mixed integer cuts via mixed integer rounding and aggregations extracted from dual proofs of infeasibility at pruned nodes of the branch-and-bound tree.

This is joint work with Leon Eifler and Sander Borst.

The noncommutative rank of a matrix space

Michel Goemans

The noncommutative rank of a matrix space is a relaxation of Edmonds' problem for deciding whether there is a matrix of full rank in the span of a given set of matrices. The noncommutative rank can be formulated in several equivalent ways, and these have lead to a variety of algorithms, including an approach based on operator scaling by Garg et al. (2016) and another based on submodular function minimization on lattices by Hamada and Hirai (2021). In joint work with Cole Franks and Tasuku Soma, we modify the operator scaling approach to also provide an optimal shrunk subspace, which acts as a dual certificate of optimality. In this talk, I will describe the landscape, and also describe applications to the rank-2 Brascamp-Lieb polytope and fractional linear matroid matching.

New integer programming ideas for solving large-scale RCPSPs

Marcos Goycoolea

The resource constrained project scheduling problem (RCPSP) is well-known for being a very difficult problem in combinatorial analysis. To date, many small instances with 60 activities or less are still unsolved. Most academic papers focus on solving such small instances. To date it would seem that the most effective technique for this is Constraint Programming, which can solve most problems with 120 jobs or less, relatively fast. The RCPSP is an important problem in the context of underground mine planning, where activities describing a mining project must be scheduled over the life of the project in such a way as to maximize NPV. Problems of interest in mining can easily have tens of thousands of activities, and span thousands of time periods. Thus, they are well above in size as those commonly studied in the academic literature. Though they do enjoy sparser precedence structures, they are out of reach for standard RCPSP methodologies (CP and IP). In this talk we show how some simple aggregation schemes can be used to compute both strong upper and lower bounds for a range of large planning instances.

May the forts be with you

Illya Hicks

Zero forcing is a dynamic graph process in which an initial set of vertices in a graph is colored and, through a set of color-changing rules, may cause additional vertices to become colored through a series of iterations. Zero forcing sets are vertex sets that (when initially colored) cause all remaining vertices to become colored; the zero forcing number of a graph is the minimum cardinality of the graph's zero forcing sets. The zero forcing number is of particular interest as it provides a bound for the minimum rank problem for graphs; the minimum rank problem has applications to recommender systems. In this talk, we will explore zero-forcing and its variants as well as their corresponding obstruction sets which we call forts. In the end, we will explore how forts are related to the minimum rank problem.

How fast is k-Opt?

Stefan Hougardy

The k-Opt heuristic is a simple improvement heuristic for the Traveling Salesman Problem. It starts with an arbitrary tour and then repeatedly replaces k edges of the tour by k other edges, as long as this yields a shorter tour. There exist pivoting rules for 2-Opt that result in an exponential number of iterations, even for Euclidean TSP. It is an open problem whether there exists a pivoting rule that makes 2-Opt a polynomial time algorithm. In 1989 Krentel proved that for sufficiently large k such a pivoting rule cannot exist. The value of k arising from the proof is larger than $10,000$. We present a new reduction yielding a smaller value for k.

This is joint work with Hoang Phuc Hung.

Steiner cut dominants

Volker Kaibel

For a subset of terminals T of the nodes of a graph G a cut in G is called a T-Steiner cut if it subdivides T into two non-empty sets. The Steiner cut dominant of G is the Minkowski sum of the convex hull of the incidence vectors of T-Steiner cuts in G and the nonnegative orthant. It is the polyhedron that is naturally associated with the problem of finding a minimum T-Steiner cut in G w.r.t. nonnegative edge weights. While it is well understood for two terminals (s-t-cuts), for larger sets T no inequality descriptions have been known so far despite quite some efforts that have been spent into investigating this problem for T being the complete node set of G (global cuts). In this talk we derive such descriptions for all graphs and up to five terminals. Moreover, we prove that for each number k there is a finite list of inequalities from which one can derive by means of iterated applications of two simple operations inequality descriptions of the Steiner cut dominant for every graph and up to k terminals. We furthermore introduce the concept of the Steiner rank of a facet of a global cut dominant and classify the facets of Steiner rank at most five. Via blocking duality those results yield corresponding results for the vertices of the subtour elimination polytope that is most relevant in the context of the traveling salesman problem.

Analyzing the max entropy algorithm for TSP

Nathan Klein

In 2020, Karlin, Oveis Gharan and I showed that the so-called "max entropy" algorithm is a randomized better-than-3/2 approximation for metric TSP. After briefly reviewing this result, I will talk about two recent improvements we made to our analysis: first, that the integrality gap of the subtour polytope is bounded below 3/2, and second, that the algorithm can be made deterministic. Our arguments rely on properties of strong Rayleigh distributions, the structure of near minimum cuts, and the fact that the generating polynomial of our tree distribution can be efficiently evaluated.

Congruency-constrained optimization

Martin Nägele

A long-standing open question in Integer Programming is whether integer programs with constraint matrices with bounded subdeterminants are efficiently solvable. An important special case thereof are congruency-constrained integer programs of the form $\min\{c^\top x\colon Tx \leq b, \gamma^\top x \equiv r \pmod{m},\ x \in \mathbb{Z}^n\}$ with a totally unimodular constraint matrix T. Such problems have been shown to be polynomial-time solvable for $m = 2$, which led to an efficient algorithm for integer programs with bimodular constraint matrices, i.e., full-rank matrices whose $n \times n$ subdeterminants are bounded by two in absolute value.

In this talk, we delve into recent progress on congruency-constrained TU problems beyond the case of $m = 2$, and explore the challenges that come with generalizing parity constraints to arbitrary congruency constraints even in very simple combinatorial problems.

This talk is based on joint work with Christian Nöbel, Richard Santiago, and Rico Zenklusen.

The Limits of Local Search for Weighted k-Set Packing

Meike Neuwohner

We consider the weighted k-Set Packing problem, where, given a collection $\mathcal{S}$ of sets, each of cardinality at most k, and a positive weight function $w : \mathcal{S} \to \mathbb{R}_{>0}$, the task is to find a sub-collection of $\mathcal{S}$ consisting of pairwise disjoint sets of maximum total weight. As this problem does not permit a polynomial-time $o(\frac{k}{\log k})$-approximation unless $P = NP$, most previous approaches rely on local search. For twenty years, Berman's algorithm *SquareImp*, which yields a polynomial-time $\frac{k+1}{2} + \epsilon$-approximation for any fixed $\epsilon > 0$, has remained unchallenged. Only recently, it could be improved to $\frac{k+1}{2} - \frac{1}{63{,}700{,}992} + \epsilon$ by Neuwohner. In her paper, she showed that instances for which the analysis of SquareImp is almost tight are "close to unweighted" in a certain sense. But for the unit weight variant, the best known approximation guarantee is $\frac{k+1}{3} + \epsilon$. Using this observation as a starting point, we conduct a more in-depth analysis of close-to-tight instances of SquareImp. This finally allows us to generalize techniques used in the unweighted case to the weighted setting. In doing so, we obtain approximation guarantees of $\frac{k+\epsilon_k}{2}$, where $\lim_{k\to\infty} \epsilon_k = 0$. On the other hand, we prove that this is asymptotically best possible in that searching for local improvements of logarithmically bounded size cannot produce an approximation ratio below $\frac{k}{2}$.

Parametric min cut complexity

Thomas McCormick

Consider the Max Flow / Min Cut problem where the arc capacities depend on one or more parameters. Then the max flow value as a function of the parameter(s) is a piecewise linear concave function. The complexity of a class of problems is the worst-case number of pieces in this function.

It has been know since Carstensen (1983) that in general this function has exponential complexity. But Gallo, Grigoriadis, and Tarjan (1989) showed that when we restrict to Source-Sink Monotone (SSM) networks and a single parameter, the complexity is only linear, and this has been generalized by various authors.

SSM networks are a special case of a general theory of parametric optimization by Topkis, which applies equally to more than one parameter. Our main result is that even with just two parameters, the complexity of SSM Min Cut is exponential.

Quantum annealing versus digital computing: An experimental comparison

Petra Mutzel

Quantum annealing is getting increasing attention in combinatorial optimization. The quantum processing unit by D-Wave is constructed to approximately solve Ising models on so-called Chimera graphs. Ising models are equivalent to quadratic unconstrained binary optimization (QUBO) problems and maximum cut problems on the associated graphs. We have tailored branch-and-cut as well as semidefinite programming algorithms for solving Ising models for Chimera graphs to provable optimality and use the strength of these approaches for comparing our solution values to those obtained on the current quantum annealing machine, D-Wave 2000Q. This allows for the assessment of the quality of solutions produced by the D-Wave hardware. In addition, we also evaluate the performance of a heuristic by Selby. It has been a matter of discussion in the literature how well the D-Wave hardware performs at its native task, and our experiments shed some more light on this issue. In particular, we examine how reliably the D-Wave computer can deliver true optimum solutions and present some surprising results.

This is joint work with Michael Jünger, Elisabeth Lobe, Gerhard Reinelt, Franz Rendl, Giovanni Rinaldi, and Tobias Stollenwerk.

About traveling salesmen and unicorns

Ina Prinz

In this talk we will look at the close link between the development of computational tools and the solution of the traveling salesman problem. A historical excursion will show which calculating aids were specifically tailored for the traveling salesman and that the invention of the calculating machine 400 years ago brought a decisive turning point. The successors of this calculating machine still help solving traveling salesman problems today. On this tour d'horizon we will also learn why the traveling salesman would not exist without the unicorn and why, conversely, the traveling salesman is living proof of the existence of unicorns. Let's be surprised ...

The speed and bias of the Hamilton cycle maker-breaker game

Bruce Reed

In the biased Hamilton Cycle Maker-Breaker game, introduced by Chvátal and Erdős, two players alternate choosing edges from a complete graph. In the game with bias b, Maker chooses one previously unchosen edge in each turn and Breaker chooses b. The game is Maker-win for the given bias if Maker can ensure she chooses the edges of a Hamilton Cycle and Breaker-win otherwise. Letting n be the number of vertices, if the bias is 0 then Maker wins the game in n moves. On the other hand, if the bias $b = b(n)$ is $\binom{n}{2} - 1$ then Breaker wins. Furthermore, if Breaker wins for some bias b, then she also wins for bias $b + 1$. We discuss the threshold at which the game becomes Breaker win, and the number of moves maker needs to ensure she wins for b below this threshold, which is called the speed of the game.

Choose your witnesses wisely

Laura Sanità

This talk will focus on a graph optimization problem, called the Witness Tree problem, which seeks for a spanning tree of a graph minimizing a certain non-linear objective function. This problem is of interest because it plays a crucial role in the analysis of the best approximation algorithms for two fundamental network design problems: Steiner Tree and Node-Tree Augmentation. We will show how a wiser choice of witness trees leads to an improved approximation for Node-Tree Augmentation, and for Steiner Tree in special classes of graphs.

Packing cycles in planar and bounded-genus graphs

Niklas Schlomberg

We devise constant-factor approximation algorithms for finding as many disjoint cycles as possible from a certain family of cycles in a given planar or bounded-genus graph. Here disjoint can mean vertex-disjoint or edge-disjoint, and the graph can be undirected or directed. The family of cycles under consideration must be uncrossable and allow for a certain oracle access. Our setting generalizes many problems that were studied separately in the past. Among our corollaries are the first constant-factor approximation algorithm for vertex-disjoint paths in fully planar instances and approximate min-max theorems of the Erdős-Pósa type.

This is joint work with Hanjo Thiele and Jens Vygen.

On the Shannon capacity of sums and products of graphs

Alexander Schrijver

We discuss the behaviour of the Shannon capacity of graphs under taking sums and products, also in the light of recent results of Anna Blasiak, Boris Bukh, Chris Cox, and Jeroen Zuiddam.

Quickest minimum cost transshipments

Martin Skutella

While the minimum cost quickest flow problem is NP-hard, the quickest minimum cost flow problem can be solved efficiently via a straightforward reduction to the quickest flow problem without costs. More generally, we show how the quickest minimum cost transshipment problem can be reduced to the efficiently solvable quickest transshipment problem. Moreover, we present a novel algorithm for the quickest transshipment problem that uses a generalized discrete Newton method and improves the running times of previous algorithms by several orders of magnitude

This is joint work with Miriam Schlöter and Khai Van Tran.

Recent results on packing arborescences

Zoltán Szigeti

I will give a survey on the theory of packing arborescences. All the results generalize Edmonds' famous theorem on packing of k spanning s-arborescences. New results will also be presented. I will show among others how to find a packing of (not necessarily spanning) arborescences in a given digraph such that the number of arborescences containing v is a given number k for every vertex v, the number of arborescences of root v is lower and upper bounded for every vertex v, and the set of roots of the arborescences forms the basis of a given matroid.

Reducing Path TSP to TSP

Vera Traub

Path TSP is the generalization of the classical TSP where the start and the endpoint of the tour are prescribed and are possibly distinct. We present a black-box reduction from Path TSP to the classical tour version (TSP). More precisely, we show that given an α-approximation algorithm for TSP, there is an $(\alpha + \epsilon)$-approximation algorithm for the more general Path TSP for any $\epsilon > 0$. This reduction implies that the approximability of Path TSP is the same as for TSP, up to an arbitrarily small error and avoids future discrepancies between the best known approximation factors achievable for these two problems, as they existed for several decades. Recently, our reduction has been used by Karlin, Klein, and Oveis Gharan to derive approximation guarantees below $3/2$ for Path TSP. Moreover, our reduction also applies to Graph Path TSP, which asks for tours in unit-weight graphs. By combining it with the 1.4-approximation algorithm for Graph TSP by Sebő and Vygen, we obtain a polynomial-time $(1.4 + \epsilon)$-approximation algorithm for Graph Path TSP.

This is joint work with Jens Vygen and Rico Zenklusen.

On machine learning and discrete mathematics: A case study on error-correcting codes

Gyorgy Turan

Recent advances in machine learning often raise the problem of interpretability: going beyond successful prediction it may be desirable to "understand" the results obtained. For example, it may be useful to accompany the prediction of a molecular property with an "explanation", which could be a molecular substructure responsible for the property. While understanding and explanation are hard to define in general, in some contexts there may be natural definitions available. In particular, deep learning has recently been used to produce error-correcting codes, which previously have been constructed using combinatorial and algebraic methods. Are the new codes similar to classical codes or are they different from those? We present some preliminary results on this question using methods such as influence, discrete optimization, property testing and Fourier analysis of Boolean functions.

This is joint work with N. Devroye, N. Mohammadi, A. Mulgund, H. Naik, R. Shekhar, Y. Wei and M. Zefran.

Advances in exact algorithms for vehicle routing

Eduardo Uchoa

The Vehicle Routing Problem (VRP) is among the most widely studied problems in the fields of operations research and combinatorial optimization. The currently best exact VRP algorithms are based on the combination of column generation and cut separation, in the so-called Branch-Cut-and-Price (BCP) algorithms. This talk surveys significant recent contributions by several authors. In particular, it presents the concept of cuts with limited memory (Pecin et al. 2014), a technique that represented a breakthrough in some of the most classical VRP variants, allowing the optimal solution of instances with up to a few hundred points. It finishes by presenting VRPSolver, a generic exact VRP framework that obtains state-of-the-art performance in dozens of variants.

Approximating Nash social welfare for submodular valuations

László Végh

We give a 35-approximation algorithm for the Nash Social Welfare problem under submodular valuations. The previous best approximation factor was linear in the number of agents. We also consider the asymmetric variant of the problem where the objective is to maximize the weighted geometric mean of agents' valuations, and give a $35(\alpha + 1)$-approximation if the ratio between the smallest and largest weights is at most α.

This is joint work with Jugal Garg, Edin Husić, Wenzheng Li, and Jan Vondrák. It significantly improves and simplifies two previous papers (Garg, Husić, Végh, STOC 2021, and Li, Vondrák, FOCS 2021).

From TSP to vehicle routing — theory and practice

Jens Vygen

Over the past few years, our understanding of the approximability of the TSP and natural extensions has improved substantially. Our survey will also include recently discovered reductions, including the first improvement for capacitated vehicle routing since the 1980s, as well as open problems. Moreover, we outline our techniques for handling vehicle routing instances in industrial practice, with many constraints and time-dependent travel times.

The Cook et al. proximity question: Improvements and future directions

Robert Weismantel

Cook, Gerards, Schrijver and Tardos have shown in 1986 that optimal solutions of a linear integer optimization problem and its linear relaxation have distance of at most $n\Delta$ in each component, provided they exist. Here n denotes the dimension of the problem and Δ denotes the largest absolute value among all determinants associated with submatrices of the underlying constraint matrix. We improve this bound and establish further links to other fundamental problems in discrete optimization.

On path lengths of undirected binary trees

Laurence Wolsey

The Balanced Minimum Evolution Problem (BMEP) used to estimate the philogeny of a given set of molecular data can be viewed as the problem of optimizing a specific nonlinear function

$$\min \left\{ \sum_{i<j} \frac{w_{ij}}{2^{\tau_{ij}}} \right\}$$

over the set of path-length matrices (τ_{ij}) of unrooted binary trees. Here we study the polyhedral combinatorics of this set of matrices and develop a mixed integer linear programming formulation that is tested on a standard set of BMEP instances.

This is joint Work with Daniele Catanzaro (UCLouvain) and Raffaele Pesenti (Universita Ca'Foscari, Venezia).

Approximating weighted connectivity augmentation below factor 2

Rico Zenklusen

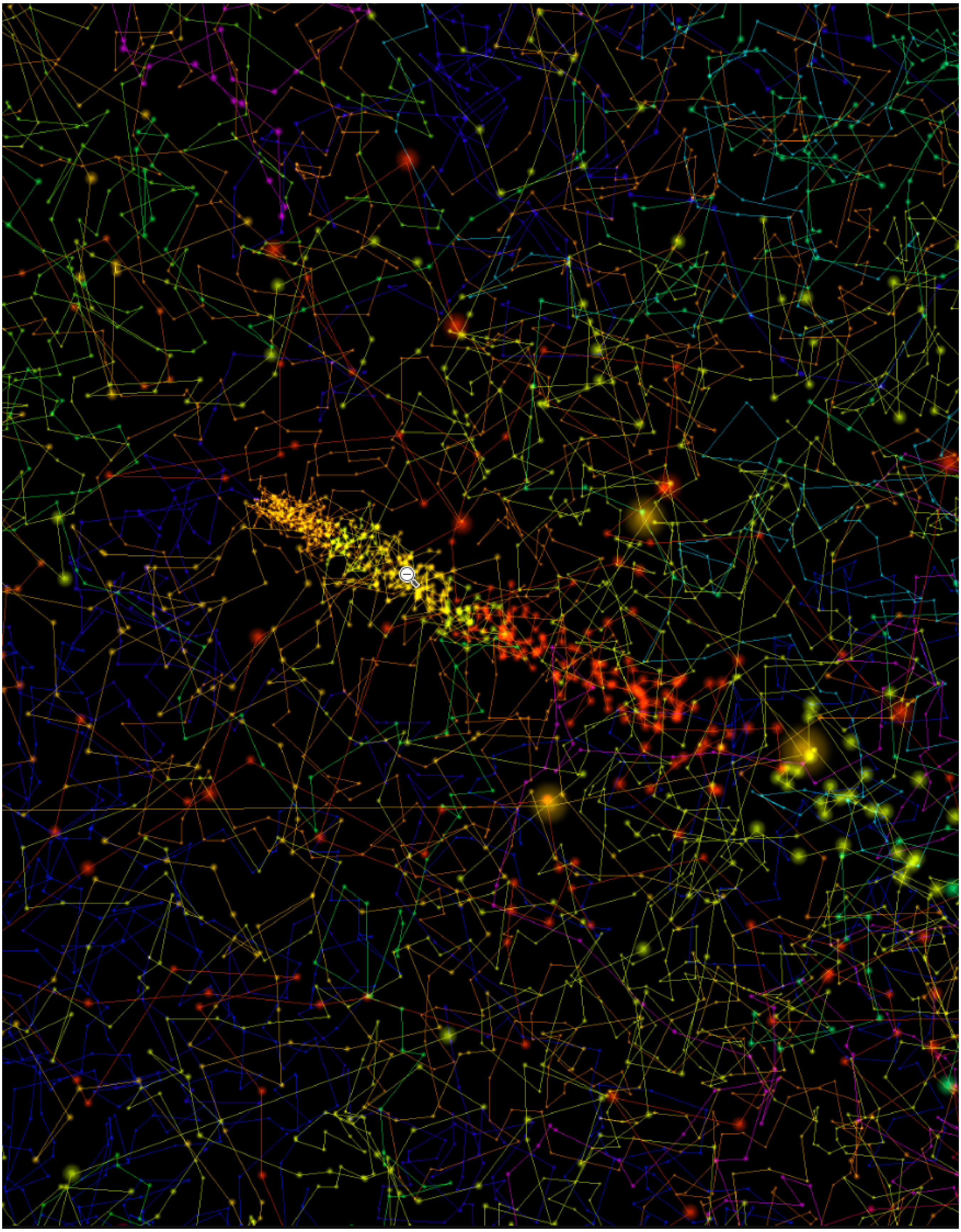
The Weighted Connectivity Augmentation Problem (WCAP) asks to augment the edge-connectivity of a graph by adding a min cost edge set among given candidate edges. It is among the most elementary network design problems for which no better-than-2 approximation has been known, whereas 2-approximations can easily be obtained through a variety of well-known techniques.

In this talk, I will discuss an approach showing that approximation factors below 2 are achievable for WCAP, ultimately leading to a $(1.5+\epsilon)$-approximation. Our approach is based on a highly structured directed simplification of WCAP with planar optimal solutions. We show how one can successively improve solutions of this directed simplification by moving to mixed-solutions, consisting of both directed and undirected edges. These insights can be leveraged in local search and relative greedy strategies, inspired by recent advances on the Weighted Tree Augmentation Problem, to obtain a $(1.5+\epsilon)$-approximation.
This is joint work with Vera Traub.

Capacitated vehicle routing

Hang Zhou

In the capacitated vehicle routing problem, we are given a metric space with a vertex called depot, a set of vertices called terminals, and a positive tour capacity. Each terminal has a demand. The goal is to find a minimum length collection of tours starting and ending at the depot such that the demand of each terminal is covered by some tour, and the total demand of the terminals in each tour does not exceed the tour capacity. In this talk, I will talk about recent progress in the capacitated vehicle routing on trees and in the Euclidean space.



Extract from a tour through 1,331,906,450 stars from the Gaia DR2.

(source: `https://www.math.uwaterloo.ca/tsp/star/gaia2_tour.html`)

4 List of participants

Aardal, Karen	TU Delft
Abdi, Ahmad	London School of Economics
Achterberg, Tobias	Gurobi Optimization
Ahrens, Markus	IBM
Applegate, David	Google Research
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Bienstock, Daniel	Columbia University
Bihler, Tilmann	University of Bonn
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Brenner, Ulrich	University of Bonn
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Conti, Lorenzo	University of Bonn
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Dadush, Daniel	CWI
Dash, Sanjeeb	IBM Research
Drees, Martin	University of Bonn
Ebert, Daniel	University of Bonn
Ellerbrock, Antonia	University of Bonn
Espinoza, Daniel	Google Research
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Fukasawa, Ricardo	University of Waterloo
Gehring, Lukas	University of Bonn
Gierschmann, Jakob	University of Bonn
Gleixner, Ambros	Zuse Institute and HTW Berlin

Glubrecht, Adrian	University of Bonn
Goemans, Michel	MIT
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Hougardy, Stefan	University of Bonn
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Müller, Dirk	University of Bonn
Mundt, Max	University of Bonn
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Reinelt, Gerd	Heidelberg University
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Rocca, Patrick	University of Bonn
Rohe, Andre	Meta
Saccardi, Pietro	University of Bonn
Sanità, Laura	Bocconi University
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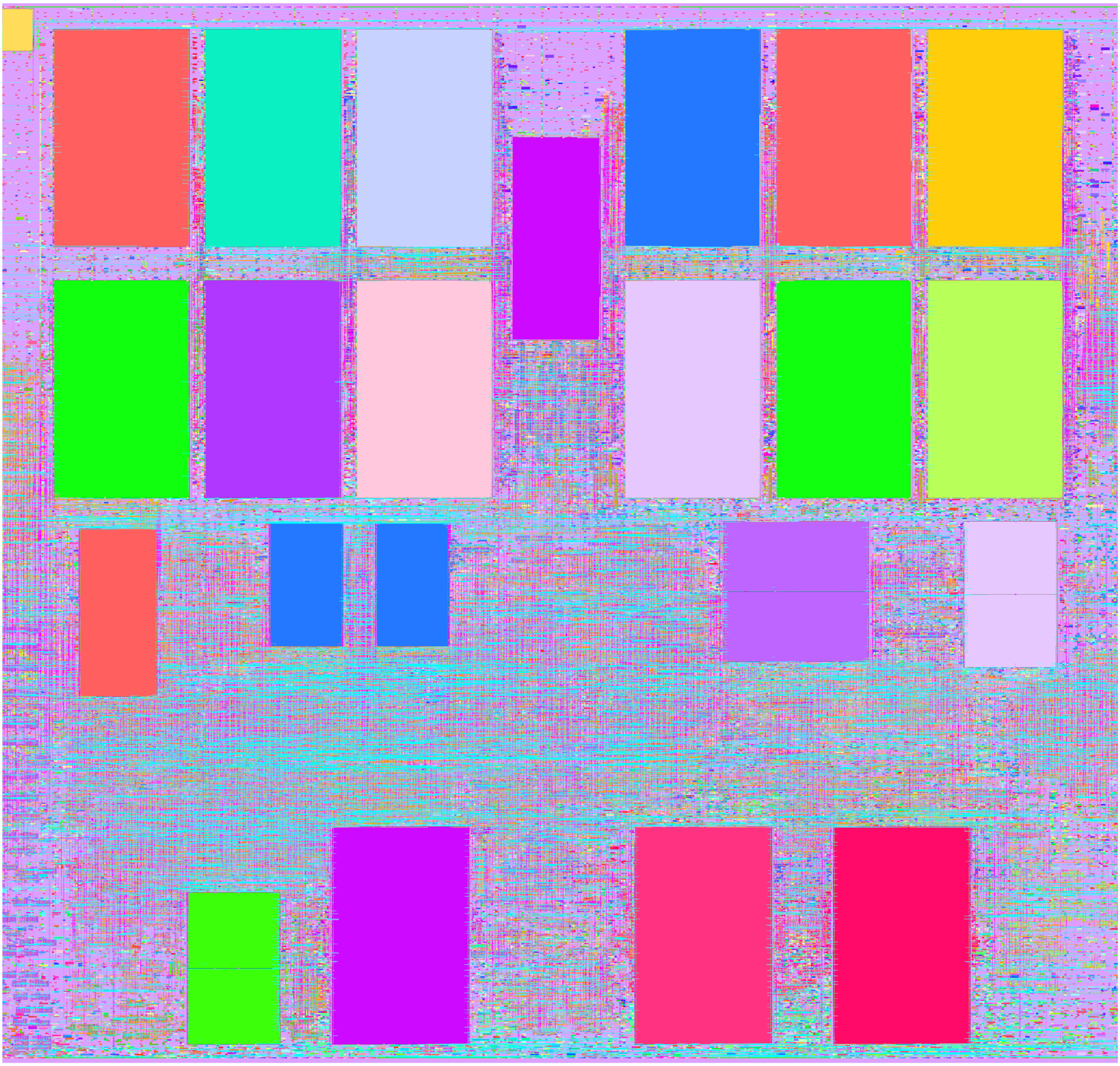
Szigeti, Zoltán	University Grenoble Alpes
Traub, Vera	University of Bonn
Turan, Gyorgy	Universites of Illinois and Szeged
Uchoa, Eduardo	UFF, Rio de Janeiro
Végh, László	London School of Economics
Vygen, Jens	University of Bonn
Weismantel, Robert	ETH Zürich
Wolsey, Laurence	UC Louvain
Zenklusen, Rico	ETH Zürich
Zhou, Hang	École Polytechnique Paris

5 Restaurant recommendations

Name	Style	Price Range	Address
KostBar	soups take-away	€	Riesstraße 2A
Il Punto	italian	€€€	Lennéstraße 6
Café Sahneweiß	vegetarian	€€	Kaiserstraße 1D
Ginger's	asian	€	Lennéstraße 61
Tuscolo	italian	€€	Gerhard-von-Are-str. 8
Oliveto	mediterranean	€€€	Adenauerallee 9
Zum Treppchen	german	€€	Weberstraße 42
Ichiban Sushibar	sushi	€€	Stockenstr. 14
Mandu	korean	€	Franziskanerstr. 5
Schumann's	mediterranean	€€	Weberstraße 43
Ruland	italian	€€	Bischofsplatz 1
Marktplatz	street food trucks	€	Markt
Supasalad	salads & Subs	€	Quantiusstraße 32
Midi	bistro	€€	Münsterplatz 11
Esskalation	vegan	€€	Bonner Talweg 26
Il Melo	italian	€€	Bonner Talweg 29
Casbah	mediterranean	€€	Bottlerplatz 10
Elefant	german	€€	Sternstraße 78

(Approximately ordered by their distance from the Arithmeum.)



Bill 65

IBM technology; Coordinates: X: 0..20889600, Y: -3279075..10744036; colored by t2-c3.ctrf

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