Helmut Alt, Bernard Chazelle,
Raimund Seidel (editors):

Computational Geometry

Dagstuhl-Seminar-Report; 109
13.03.-17.03.95 (9511)

ISSN 0940-1121

Tel.: +49 - 6871 - 2458
Fax: +49 - 6871 - 5942

Das Internationale Begegnungs- und Forschungszentrum für Informatik (IBFI) ist eine gemeinnützige GmbH. Sie veranstaltet regelmäßig wissenschaftliche Seminare, welche nach Antrag der Tagungsleiter und Begutachtung durch das wissenschaftliche Direktorium mit persönlich eingeladenen Gästen durchgeführt werden.

Bezugsadresse: Geschäftsstelle Schloss Dagstuhl
Universität des Saarlandes
Postfach 15 11 50
D-66041 Saarbrücken, Germany
Tel.: +49 -681 - 302 - 4396
Fax: +49 -681 - 302 - 4397
e-mail: office@dag.uni-sb.de
www: http://www.dag.uni-sb.de/dagstuhl.html

Report

on the Fourth Dagstuhl Seminar on

Computational Geometry

March 13 - 17, 1995

The Fourth Dagstuhl Seminar on Computational Geometry was organized by Helmut Alt (Freie Universität Berlin), Bernard Chazelle (Princeton University) and Raimund Seidel (Universität des Saarlandes).

35 talks were given by 37 participants from 11 countries. 11 participants came from the US, 9 from Germany, 4 from Canada, 3 from the Netherlands, 2 from Austria, France and Israel, and 1 from Hungary, the UK, Singapore and Japan.

This report contains the abstract of all the 35 talks, in the order as they were given at the meeting, as well as a report on the open problem session.

Compilation done by Bernd Gärtner (open problems report by Raimund Seidel).

List of Participants.

Pankaj Agarwal, Duke University
Helmut Alt, Freie Universität Berlin
Annamaria Amenta, Geometry Center
Boris Aronov, Polytechnic University
Tetsuo Asano, Osaka Electro-Communication University
Franz Aurenhammer, TU Graz
Marshall Bern, Xerox PARC
Vasilis Capoyleas, Max-Planck-Institut f. Informatik Saarbrücken
Timothy M. Chan, University of British Columbia
Bernard Chazelle, Princeton University
Olivier Devillers, INRIA - Sophia-Antipolis
Katrin Dobrindt, Utrecht University
Scot Drysdale, Dartmouth College
Martin Dyer, University of Leeds
Bernd Gärtner, Freie Universität Berlin
Leonidas Guibas, Stanford University
Dan Halperin, Stanford University
Klara Kedem, Ben-Gurion University
David G. Kirkpatrick, University of British Columbia
Rolf Klein, FernUniversität Hagen
Heinrich Müller, Universität Dortmund
János Pach, Hungarian Academy of Sciences
Richard Pollack, Courant Institute / NYU
Günter Rote, TU Graz
Marie-Francoise Roy, Université de Rennes 1
Carlo Séquin, University of California at Berkeley
Jörg-Rüdiger Sack, Carleton University
Otfried Schwarzkopf, Utrecht University
Raimund Seidel, Universität des Saarlandes
Micha Sharir, Tel Aviv University
Michiel Smid, Max-Planck-Institut f. Informatik Saarbrücken
Jack Snoeyink, University of British Columbia
Subhash Suri, Washington University
Tiow-Seng Tan, National University of Singapore
Emo Welzl, Freie Universität Berlin
Günter M. Ziegler, TU Berlin
Marc van Kreveld, Utrecht University

List of Speakers.

Monday.

M. Sharir, R. Klein, M. Smid, R. Pollack, M.-F. Roy, S. Suri, J. Snoeyink, M. Dyer, B. Gärtner

Tuesday.

M. van Kreveld, K. Dobrindt, N. Amenta, C. Séquin, M. Bern, D. Kirkpatrick, F. Aurenhammer, G. Rote, S. Drysdale

Wednesday.

J. Pach, J.-R. Sack, E. Welzl, G. M. Ziegler, O. Schwarzkopf

Thursday.

H. Alt, T. Chan, L. Guibas, O. Devillers, D. Halperin, B. Aronov, R. Seidel, T. Asano

Friday.

T.-S. Tan, K. Kedem, P. Agarwal, B. Chazelle, J. Snoeyink

List of Abstracts.

Voronoi Diagrams in Higher Dimensions

by MICHA SHARIR (joint work with B. Aronov, P. Chew, K. Kedem, J.D. Boissonnat, M. Yvinec, B. Tagansky and E. Welzl)

We wish to estimate the combinatorial complexity of the Voronoi diagram of n convex polyhedral sites in $\mathbb{R}^d$ (points, lines, etc.) induced by a polyhedral convex distance function (where the defining polytope has a constant number of facets). An 'equivalent' formulation is: Let P be a convex polytope in $\mathbb{R}^d$, and let $A_1, \dots, A_n$ be the sites. We want to bound the number of *free, rigid homothetic* placements of P. (Here *free* means that P's interior meets no site, *rigid* means that P's boundary makes the maximum possible number of contacts with sites (which is $d+1$ in $\mathbb{R}^d$, assuming general position), and *homothetic* means that P is only allowed to translate and scale.) These placements correspond to the vertices of the Voronoi diagram.
If P is a ball (Euclidean distance) and the sites are points, then it is well known that the maximal diagram complexity is $\Theta(n^{\lceil d/2 \rceil})$. We have conjectured that roughly the same bound holds in fairly general situations, and were not aware of any example with significantly larger complexity. However, after the talk, Boris Aronov came up with a simple construction where the diagram has $\Omega(n^{d-1})$ complexity. The conjecture is still open when the sites are singleton points.
We substantiate the conjecture in several special cases:
(1) Sites are lines in $\mathbb{R}^3$, P is a polytope with $O(1)$ faces: maximum complexity is $O(n^2 \alpha(n) \log n)$ and $\Omega(n^2 \alpha(n))$.
(2) Sites are line segments in $\mathbb{R}^3$, P as above: upper bound is open, and lower bound is $\Omega(n^2 \alpha^2(n))$.
(3) Sites are points in $\mathbb{R}^3$ and P is a regular octahedron (the L^1-distance): maximum complexity is $\Theta(n^2)$.
(4) Sites are points in $\mathbb{R}^d$ and P is a cube (the L^∞-distance): maximum complexity is $\Theta(n^{\lceil d/2 \rceil})$ (just like the Euclidean case). The same bound holds if P is a simplex.
Hiding in (4) is a new bound on the maximum complexity of the union of n axis-parallel hypercubes in $\mathbb{R}^d$: it is $\Theta(n^{\lfloor d/2 \rfloor})$ if all cubes have equal sizes, and is $\Theta(n^{\lceil d/2 \rceil})$ otherwise.
All the upper bounds are proved using a new probabilistic analysis technique due to Tagansky. This technique applies (so far) only when the problem can be described in terms of *piecewise-linear* constraints, and fails in more general situations (e.g. it fails when P is a ball).
Many related problems are still open: for example, problems (1) and (2) are open for the Euclidean metric; problems (3) and (4) are open for more general P, etc.

How to find the Kernel of a Polygon

by ROLF KLEIN (joint work with C. Icking)

We assume that a mobile robot wakes up in an unknown starshaped polygon. Its task is to walk to the closest point of the kernel. Each invisible 'cave' of the polygon defines a halfplane into which the robot should move in order to gain insight into the cave. The strategy we propose requires the robot to compute the intersection of these halfplanes, and to follow the angular bisector of the resulting wedge.
The path created by this strategy is 'self-approaching' in the following sense: if a, b, c are consecutive points (in start-to-goal orientation) then $|b-c| \leq |a-c|$ holds.

We then show that the length of a self-approaching curve is bounded from above by the perimeter of its convex hull. This can be used for proving that the curve length does not exceed a constant (e.g. 5.52) times the distance between its endpoints. We have an example where this ratio equals 5.331...
Consequently, our strategy for finding the closest kernel point is competetive with a factor of 5.52. No factor less than $\sqrt{2}$ can be achieved.
It remains to close the gap (5.3331 ... 5.52) for self-approaching curves, and to improve on the performance of the strategy.

Euclidean Spanners: Short, Thin, and Lanky

by MICHIEL SMID (joint work with S. Arya, G. Das, D. Mount and J. Salowe)

Euclidean spanners are important data structures in geometric algorithm design, because they provide a means of approximating the complete Euclidean graph with only $O(n)$ edges, so that the shortest path length between each pair of points is not more than a constant factor longer than the Euclidean distance between the points.
However, in many applications of spanners, it is important that the spanner possess a number of additional properties: low total edge weight, bounded degree, and low diameter. Existing research on spanners has considered one property or the other. We show that it is possible to build spanners in optimal $O(n \log n)$ time and $O(n)$ space that achieve optimal or nearly optimal tradeoffs between all combinations of these properties. We achieve these results in large part because of a new structure, called the dumbbell tree which provides a method of decomposing a spanner into a constant number of trees, so that each of the $O(n^2)$ spanner paths is mapped entirely to a path in one of the trees.

Road Map Algorithms

by RICKY POLLACK (joint work with S. Basu and M.-F. Roy)

A roadmap $R(S,M)$ for a semialgebraic set $S \subseteq R^k$ which passes through the points of the finite set M is a one dimensional semi-algebraic set satisfying
(1) $M \subseteq R(S,M) \subseteq S$
(2)
(a) if C is a connected component of S then $C \cap R(S,M)$ is non-empty and connected,
(b) for every connected component C' of $S \cap \pi^{-1}(x)$, $C' \cap R(S,M) \neq \emptyset$
where π is the projection from $\mathbb{R}^k$ onto the first coordinate.
We suppose that the semialgebraic set is defined by s polynomials $P_1 \dots P_s \subseteq D[x_1, \dots x_k]$ where D is subring of R and the polynomials P_i have degrees bounded by d.
We outline a correct roadmap algorithm for S whose complexity (measured by the number of arithmetic operations in D) is $s^{k+2}d^{O(k^2)}$.
The techniques used are based on ideas presented in our recent paper on quantifier elimation (FOCS'94). It also follows previous developments due to Schwartz-Sharir, Canny, Grigor'ev-Vorobjov, Heintz-Roy-Solerno and Gournay-Risler.

A new approach to systems of inequalities

by MARIE-FRANCOISE ROY (joint work with Nicolaj Mnëv and Henri Lombardi)

We associate to a system of polynomial inequalities a net of small equations and inequalities. They are given by $x = 0$, $x = 1$, $x \geq 0$, $x + y = a$, $xy = a$.
Any polynomial can be described by such a net, adding more variables. We define two equivalence relations on systems of polynomials:

- logical equivalence
- algebraic equivalence

and prove they coincide.
Two sets are logically equivalent when they can be extended to the same net, using algebraic rules (associativity, $x > 0, y \geq 0 \Rightarrow x + y \geq 0$ and similar rules) and simplification rules (for example $a^3 \geq 0 \Rightarrow a \geq 0$, $ab > 0, a > 0 \Rightarrow b > 0$, $a(a^2 + b) \geq 0, b \geq 0 \Rightarrow a \geq 0$).
Two nets are algebraically equivalent if their rings of quadratic functions are isomorphic. Quadratic functions are obtained by inverting $\neq 0$ elements, taking positive square roots of positive functions and algebraic operations, from the variables.
Our hope is to be able to associate invariants to nets, respecting their equivalence. It would provide new ways of deciding if a semialgebraic set is empty or not.

Approximating Shortest Paths on a Convex Polytope in $\mathbb{R}^3$

by SUBHASH SURI (joint work with J. Hershberger)

We give a simple linear-time algorithm that computes a path of length at most $2D(p, q)$ for any two points p, q on the surface of a convex polytope P in $\mathbb{R}^3$. By extending the algorithms, we can also approximate distances from a fixed source point p to all vertices of P in time $O(n \log n)$. The approximation factor is $2.38(1 + \varepsilon)$ for any $\varepsilon > 0$. A weak approximation result for shortest paths among k disjoint convex polytopes is this: an $O(n)$ algorithm for computing an obstacle-avoiding path of length $2kD(p, q)$.

Approximative Nearest Neighbor Queries

by JACK SNOEYINK (joint work with T. Chan)

We survey recent approaches to the problem of approximate nearest neighbor queries: given a set of n points $\{p_1, \ldots p_n\}$ in $\mathbb{E}^d$, form a data structure that, for a query point q and $\varepsilon > 0$ finds a p_i where $d(q, p_i) \leq (1 + \varepsilon) \min_j d(q, p_j)$. We focus on the dependence on dimension d and tolerance ε of known approaches and also give some new results (especially in low dimensions) with better ε-dependence.

On the Minkowski Sum of Simple Polygons

by JACK SNOEYINK (proved the night before with B. Aronov, T. Chan and D. Halperin)

We prove that the complexity of the outer face of the boundary of the Minkowski sum of two simple polygons P and Q with n and k edges, $n > k$ is $\Theta(nk\alpha(k))$. The upper bound is by analyzing Davenport-Schinzel sequences of families; the lower bound is a construction based on lower envelopes of line segments. Micha Sharir reports that the upper bound can be derived from S. Har-Peled's results on combining k arrangements.

A Parallel Algorithm for fixed-dimensional Linear Programming

by MARTIN DYER

We discuss the complexity of linear programming in fixed dimension in the sequential and parallel case. We describe a new parallel algorithm, based on Megiddo's sequential algorithm, which improves the complexity of the problem on an n-processor EREW PRAM.

Randomized Simplex Algorithms on Klee-Minty Cubes

by BERND GÄRTNER (joint work with G. Ziegler)

We consider the behavior of the simplex algorithm on combinatorial cubes. Particularly interesting is the RANDOM_EDGE pivot rule which at any nonoptimal vertex traverses any of the improving edges with equal probability. We prove an $\Omega(n^2/\log n)$ lower bound for the number of pivot steps on the Klee-Minty cube, a well known worst case example for exponential behavior of a deterministic simplex variant. This improves on the previously known $\Omega(n)$ bound and leaves only a $\log n$ gap to the upper bound of $O(n^2)$.
We discuss an abstract framework in which it might more easily be possible to obtain superquadratic lower bounds for the RANDOM_EDGE rule.

A new Approach to Subdivison Simplification

by MARC VAN KREVELD (joint work with M. de Berg and S. Schirra)

Given a polygonal planar subdivision S and a set P of points in the faces of the subdivision, we study the problem of computing a new subdivision with fewer vertices but such that the points of P remain in the same face. A subdivision can be viewed as a collection of polygonal chains, and we will reduce the complexity of these in turn. Let C be a polygonal chain with n vertices and let P be a set of m extra points. The simplification C' of C uses a subset of the vertices of C and has the following properties:

- all points on C should be within distance ε from the corresponding part of C', where $\varepsilon > 0$ is a pre-specified error tolerance,
- C' may not have self-intersections,
- C' may not intersect any other chains of S,
- the points of P should be to the same side of C' as of C.

The algorithm runs in $O(n(n+m)\log n)$ time and the reduction in size is optimal for x-monotone chains (and somewhat more general chains as well). The algorithm is simple; the most difficult steps are a standard plane sweep and shortest paths in an unweighted DAG. It extends the line simplification algorithm previously described by Imai & Iri.

On levels of detail in Terrains

by KATRIN DOBRINDT (joint work with M. de Berg)

In many applications it is important that one can view a scene at different levels of detail. A prime example is flight simulation: a high level of detail is needed when flying low, whereas a low level of detail suffices when flying high. More precisely, one would like to visualize the part of the scene that is close at a high level of detail, and the part that is far away at a low level of detail. We propose a hierarchy of detail levels for a polyhedral terrain (or, triangulated irregular network) that allows this: given a view point, it is possible to select the appropriate level of detail for each part of the terrain in such a way that the parts still fit together continuously. The main advantage of our structure is that it uses the Delaunay triangulation at each level, so that triangles with very small angles are avoided. This is the first method that uses the Delaunay triangulation and still allows to combine different levels into a single representation.

Projections of 4D Polytopes

by NINA AMENTA (joint work with G. Ziegler and B. Gärtner)

We show an example of a four dimensional polytope whose projection to the plane has $O(n^2)$ vertices. This question has applications to non-linear optimization; if the projection to 2D had asymptotically fewer vertices, then it would be possible to maximize a convex function over a 4D polytope with n facets in less than $O(n^2)$ time. Unfortunately our example shows that this is not possible in all cases.
The example is a polytope essentially described by Klee and Minty in their classic paper "How good is the simplex algorithm?". It is combinatorially equivalent to a product polytope, but geometrically warped. We checked the projection by making a computer graphics model of the polytope and interactively controlling the projection to the screen. We showed a rough-cut of a video.

Practical Collision Detection for Interactive Walkthroughs

by CARLO H. SEQUIN

The existence of the fast closest-feature tracking algorithm developed by Lin and Canny was a strong invitation to try to add collision detection to the interactive version of our Soda hall walkthrough program. The algorithm existed as a well-written program module with good documentation of the required interface, and it was not too hard to make the program work. However, to provide actual collision detection in the framework of our interactive walkthrough model was a substantially more involved task.
First, the Lin-Canny algorithm deals only with convex polyhedra. To make it useful for the artifacts found in a typical building, those objects had to be decomposed into unions of convex polyhedra and a significant amount of book-keeping had to be added to track the closest feature pairs on all n*m combinations of convex sub-parts.
Furthermore, the closest-feature algorithm ends up in an infinite loop if the two objects are already intersecting. Thus care has to be taken to avoid that situation by putting thin safety zones around every object and by taking rather conservative bounds on the time steps with which one tries to approach a possible intersection event.
Another difficulty resulted from the fact that we tried to combine two quite different environments: The Walkthru program uses object descriptions in the form of polygon lists, where each facet carries its own vertex coordinates, while the closest-feature algorithm needs a fully developed winged-edge data structure of simple convex elements. We did not want to reprogram either one of the two environments. We created some additional data structures which are loaded on demand whenever two objects have a chance to interact in the near future.
Overall, the amount of code devoted to these "engineering issues" far outweighs the code for the closest-feature algorithm.

Averaging Point Sets with Approximate Weights

by MARSHALL BERN (joint work with D. Eppstein, L. Guibas, J. Hershberger, S. Suri and J. Wolter)

Let S be a set of n points in $\mathbb{R}^d$, each with an unknown weight drawn from a known range. What is the locus of possible centroids of S? We show that this locus is a convex polytope, a perspective projection of a zonotope in $\mathbb{R}^{d+1}$; its worst-case complexity is $\Theta(n^{d-1})$. We give an optimal $O(n \log n)$ algorithm for computing the locus in the case $d = 2$. We also consider a generalization in which there are explicit bounds on the total weight of S. In this case, the locus is a projection of a section of a zonotope, and the complexity increases to $O(n^d)$.

Optimal Motions of a Rod amidst Polygonal Obstacles

by DAVID KIRKPATRICK (joint work with T. Asano and C. Yap)

We consider the problem of moving a rod (line segment, ladder) from one placement in the plane to another so as to avoid proper intersections with any of a collection of specified polygonal obstacles. The question of existence of such a motion has been well studied. We address the problem of finding an optimal motion. Our optimality criterion is based on minimizing the length of the orbit of a fixed but arbitrary point in the interior of the rod (the so-called "d_1-distance").
We first present a characterization Theorem that describes all locally optimal motions in terms of critical curves (including circles, ellipses and ???) determined by pairs of obstacle features and so-called reflection curves (formed by displaced obstacle features). This characterization would suffice to construct a polynomial time algorithm if it could be shown that motions include only a constant number of successive reflections between stopovers at object vertices or critical curves. Unfortunately this is not the case in general. In fact, the problem of determining if a motion exists whose d_1-length is less than a specified value, is NP-hard. This construction paralleles the proof of Canny and Reif that the shortest path problem for a point in a three-dimensional polygonal scene is NP-hard.

A Matching Lemma for Planar Triangulations

by FRANZ AURENHAMMER, GÜNTER ROTE (joint work with O. Aichholzer, M. Taschwer)

We prove that two different triangulations of the same planar point set always intersect in a systematic manner, concerning both their edges and their triangles. In particular, there exists a perfect matching between their edge sets such that matched edges either cross or coincide. Based on this general property, improved lower bounds on the total edge length (weight) of a triangulation are obtained by solving an assignment problem. The new bounds cover all previously known bounds and can be computed in polynomial time. As a byproduct, an easy-to-recognize class of point sets is exhibited where the minimum weight triangulation coincides with the greedy triangulation. While the complexity status of the former triangulation is unknown for general point sets, the latter can be computed in an efficient way by various known algorithms.

A Simple Linear-Time Algorithm to Compute the Greedy Triangulations of Uniformly Distributed Points

by SCOT DRYSDALE (joint work with G. Rote, O. Aichholzer)

The greedy triangulation of a set of points in the plane is the triangulation obtained by starting with an empty set of edges and at each step adding the shortest compatible edge between two of the points, where an edge is defined to be compatible if it crosses none of the previously added edges. We present a simple, practical algorithm that computes the greedy triangulation in expected $O(n)$ time and space, for n point's chosen from a uniform distribution over some fixed convex shape C.
This algorithm is an improvement of the $O(n \log n)$ algorithm by Dickerson, Drysdale, McElfresh and Welzl. It is similar in approach, but generates only $O(n)$ plausible edges to test.instead of $O(n \log n)$.

Geometric Ramsey Theorems

by JÁNOS PACH (joint work with G. Toth and G. Karolyi)

Theorem 1. Let $f(n)$ denote the largest number such that any family of n convex sets in the plane contains either $f(n)$ pairwise disjoint members or $f(n)$ pairwise intersecting members. Then

$$n^{1/5} \leq f(n) \leq n^{\log 4/\log 27}.$$

The set of $\binom{n}{2}$ segments connecting n points in general position in the plane is said to form a complete geometric graph.

Theorem 2. Any complete geometric graph whose edges are colored with two colors contains a non-selfintersecting spanning tree, all of whose edges are of the same color.

Theorem 3. Any complete geometric graph of $3n-1$ points, whose edges are colored with two colors, contains n pairwise disjoint edges of the same color.

Killing two Birds with one Stone

by JÖRG-RÜDIGER SACK (joint work with F. Bauernöppel, E. Kranakis, D. Krizanc, A. Maheshwari, M. Noy, J. Urrutia)

Suppose that an archer is hunting birds flying over hunting grounds described as a bounded region, possibly with holes formed by obstacles such as mountains and lakes. In an attempt to minimize the number of arrows used, the archer tries to indentify pairs of birds that can be pierced by a single arrow (birds line up).
Let $X = \{p_1, \ldots, p_n\}$ be a collection of points (general position) in ($\mathbb{R}^2$ or) $\mathbb{R}^3$ such that the z-coordinate of each element of X is > 0. Let S be a compact plane set of $\mathbb{R}^3$, called stage contained in $H_0 = \{p \in \mathbb{R}^3 \mid z - \text{coordinate of } p = 0\}$. Given X and S, construct a graph $G(X,S)$; p_i, p_j are adjacent if the line through p_i and p_j intersects S. $G(X,S)$ is called stage graph. In the planar case, S is a line segment.

- We show that the family of stage graphs generated is exactly the set of permutation graphs.
- This yields an $O(|V|^2)$ algorithm for recognizing stage graphs.
- The characterization implies a linear space representation.
- The archer's problem can be solved via matching in $O(\sqrt{|V|}|E|)$ time. Using 2-processor scheduling, an $O(|V|+|E|)$ algorithm is obtained. Through vector dominance and using computational geometry we establish an $O(n \log^3 n)$ solution, $n = |V|$.
- This implies an improved matching algorithm for permutation graphs and for some 2-processor scheduling tasks.
- We also obtain simple, new and improved algorithms for vector dominance and rectangle query problems. E.g., we obtain a new simple EREW PRAM algorithm for reporting all dominance pairs (previously CREW).
- Generalizations to multiple stages and 3D have also been studied. E.g., we give upper and lower bounds on the number of stages required to represent all graphs and particular classes.

At most k-sets

by Emo Welzl

Given a set of n points in 3-space, a subset $S \subset P$ is called a $\leq k$-set, if $0 < |S| \leq k$ and S can be separated from $P - S$ by a hyperplane. For $k < n/4$, we show a tight upper bound of $k^2n - (k-1)(2k+5)k/3$ for the number of $\leq k$-sets of P.

Shelling balls and spheres and an application

by Günter M. Ziegler

Shellability is a powerful concept that originated in polytope theory (Bruggesşer & Mani's 1971 proof that polytopes are shellable) but found widespread applications in combinatorics and (computational) geometry.
There is a long history of constructions of non-shellable triangulations of 3-dimensional (topological) balls, among them Newman's 1929 example that may have been the first, R H Bing's 1962 construction using knotted curves, and M. E. Rudin's 1958 nonshellable triangulation of a tetrahedron with only 14 vertices (all on the boundary) and 41 facets. Contrasting this, we present an example of a z-convex non-shellable simplicial ball with only 12 vertices and 25 facets. [Added in proof: one can even achieve 10 vertices and 21 facets.]
Also we show that shellings of 3-balls and 4-polytopes can "get stuck": 4-polytopes are not "extendably shellable." Our constructions imply that the Delaunay triangulation algorithm of Beichl & Sullivan 1990, which proceeds along an arbitrary shelling of a Delaunay triangulation, can get stuck in the $3D$ version: for example this may happen if the shelling follows a knotted curve.

Ipe – an extensible drawing editor

by Otfried Schwarzkopf

Many of us spend a considerable amount of time preparing figures for our papers. **Ipe** is a system that's meant to make this easier, and is particularly useful for the kind of drawing typical for a computational geometry paper. The main properties of **Ipe** are

- LaTeXsupport: All text is entered as LaTeXsource. **Ipe** shows a bounding box of the right size on the screen, and can show a second window with the resulting output.
- Snapping: Objects on the canvas can be made 'magnetic', so it becomes easy to align new objects with already existing ones.
- Extensibility: There is a very simple interface that allows you to add your own functions to **Ipe**.
- Multi-page mode for making slides or transparencies

More information about **Ipe** is available at

http://www.cs.ruu.nl/people/otfried/html/ipe/html.

The Voronoi Diagram of Curved Objects

by HELMUT ALT (joint work with O. Schwarzkopf)

Voronoi diagrams of curved objects can show certain phenomena that make their computation difficult: nonconnectedness, bisectors that are not simple curves, 'self-Voronoi-edges', i.e. Voronoi-edges between different parts of the same site.; these self-Voronoi-edges may end at seemingly arbitrary points.
We give a systematic study of these phenomena characterizing their differential geometric and topological properties. We show that a given set of curves can be refined such that the resulting curves define a 'well-behaved' Voronoi diagram. We give a randomized incremental algorithm to compute this diagram. Its expected runtime is $O(n \log n)$, where n is the number of pieces the original curves have been decomposed into. For algebraic curves of constant degree, for example, this number is proportional to the original number of curves.

Output-sensitive Results on Convex Hulls, Extreme Points and Related Problems

by TIMOTHY M. CHAN

We use known data structures for ray shooting and linear programming queries to derive new output-sensitive results on convex hulls, extreme points, and related problems. We show that the f-face convex hull of an n-point set P in fixed dimension d can be constructed in $O(n \log f + (nf)^{1-1/(\lfloor d/2 \rfloor+1)} \log^{O(1)} n)$ time. In particular, this yields new optimal output-sensitive convex hull algorithms in two and three dimensions. We also show that the h extreme points of P can be computed in $O(n \log^{d+2} h + (nh)^{1-1/(\lfloor d/2 \rfloor+1)} \log^{O(1)} n)$ time. Our techniques are then applied to obtain improved time bounds for other problems including convex layers, levels in arrangements, and linear programming with few violated constraints.

The Union of Moving Polygonal Pseudodisks

by LEONIDAS GUIBAS (joint work with M. de Berg, H. Everett)

Let P be a set of polygonal pseudodisks in the plane with n edges total translating with fixed velocities. We show that the maximum number of combinatorial changes in the union of the pseudodisks is $\Theta(n^2\alpha(n))$. For more general motions we get a bound of the form $O(n\lambda_{s+2}(n))$ where s is the maximum number of times any three edges become concurrent. We apply this result to rederive more simply certain results in motion planning: the complexity of the free space for a convex polygon that is (a) translating and rotating in $\mathbb{E}^2$ amidst convex obstacles, or (b) translating in $\mathbb{E}^3$ amidst convex polyhedra is $O(n^2\alpha(n))$. We also show that the space of all lines missing n convex homothets in $\mathbb{E}^3$ of constant complexity each is $O(n^3\alpha(n))$.
All the above bounds are tight or nearly tight in the worst case.

Exact Sign Computation of 2×2 and 3×3 Determinants

by OLIVIER DEVILLERS (joint work with F. Avnaim, J.-D. Boissonnat, F. Preparata, M. Yvinec)

We propose a method for computing exactly the sign of determinants with b-bit integer entries using only a b-bit arithmetic in 2D and $b+1$-bit arithmetic in 3D. For computing 3×3 determinant $D = |U_1 U_2 U_3|$ the idea is that either you can realize that the vector U_3

is far above or below the plane spanned by U_1 and U_2 and you can find the sign of D, or U_3 is close to this plane and you can subtract from U_3 an integer combination of U_1 and U_2 to get a vector $R = U_3 - k_1U_1 - k_2U_2$ such that the z-coordinate of R is less than half of the one of U_3. Then you can iterate on $D = |U_1U_2R|$. By choosing U_3 to be the vector with largest z-coordinate you ensure that $3b$ iterations are certainly enough to conclude. The algorithm has been implemented and compares favorably with an exact computation of the determinant. Report, test data and code for SparcStation and DEC Station are available at URL

http://www.inria.fr:/prisme/personnel/devillers/anglais/determinant.html

Two Efficient Algorithms for Arrangements

by DAN HALPERIN (joint work with M. de Berg and L. Guibas, resp. L. Guibas, H. Hirukawa, J.-C. Latombe and R. Wilson)

(1) We present a deterministic output-sensitive algorithm for computing the vertical decomposition of an arrangement of n triangles in three-dimensional space that runs in $O(n^2 \log n + V \log n)$ time, where V is the complexity of the decomposition. The algorithm is reasonably simple and in particular, it tries to perform as much of the computation in two-dimensional spaces as possible.
The algorithm is extended to compute the vertical decomposition of arrangements of n algebraic surface patches of constant maximum degree in three-dimensional space in time $O(n\lambda_q(n) \log n + V \log n)$, where V is the combinatorial complexity of the vertical decomposition, $\lambda_q(n)$ is a near-linear function related to Davenport-Schinzel sequences, and q is a constant that depends on the degree of the surface patches and their boundaries. We also present an algorithm with improved running time for the case of triangles which is, however, more complicated than the first algorithm. The running time of the faster algorithm is $O(\min(n^{4/5+\varepsilon}V^{4/5}, n^2 \log n) + V \log n)$.

(2) We then present an algorithm for sampling a special substructure in arrangements of convex polytopes, and its application to assembly planning. Our result is motivated by the problem of partitioning a polyhedral assembly with infinitesimal translation and rotation. This problem can be transformed into that of traversing an arrangement of convex polytopes in the space of directions of rigid motions. We identify a special type of cells in that arrangement, so-called *maximally covered cells*, and we show that it suffices for the problem at hand to consider a representative point in each of these special cells rather than to compute the entire arrangement. Using this observation we devise an algorithm that improves considerably over the best previously known solutions. The algorithm has been implemented, and several experimental results will be presented and discussed.

Stabbing Triangulations by Lines in 3D

by BORIS ARONOV (joint work with P.K. Agarwal, S. Suri)

Let S be a set of (possible degenerate) triangles in $\mathbb{R}^3$ whose interiors are disjoint. A triangulation of $\mathbb{R}^3$ with respect to S, denoted by $T(S)$, is a simplicial complex in which each face of $T(S)$ is either disjoint from S or contained in a face of S of equal or higher dimension. The *line stabbing number* of $T(S)$ is the maximum number of tetrahedra of $T(S)$ intersected by a segment that does not intersect any triangle of S. We investigate the line stabbing number of triangulations in several cases – when S is a set of points, when triangles of S form the boundary of a convex or non-convex polyhedron, or when the triangles of S form the boundaries of k disjoint convex polyhedra. We prove almost tight worst-case upper bounds and lower bounds on line stabbing numbers for these cases. We also estimate the number of tetrahedra necessary to guarantee low stabbing number.

Short Proofs for Random Sampling and Randomized Incremental Construction

by RAIMUND SEIDEL

We give short proofs for two of the central results in the theory of configuration spaces. These spaces were introduced by Clarkson and Shor and have been a unifying tool in the application of randomization to computational geometry. In the formulation of Mulmuley, a configuration space consists of a set S of n 'objects' and a finite set C of 'configurations', where each $c \in C$ has associated with it a set $tr(c)$ of 'triggers' and a set $st(c)$ of 'stoppers'. A configuration c is called active for $R \subseteq S$ if $tr(c) \subseteq R$ and $st(c) \subseteq S - R$; c is said to become active during an enumeration $s_1, s_2, \ldots, s_n$ of S if it is active for some prefix set $\{s_1, \ldots, s_j\}$. Of special interest are the following quantities, where $R \subseteq S$ and $i \in \mathbb{N}$:

$$\begin{aligned} f_0(R) &= |\{c \in C \mid c \text{ active for } R\}| \\ X_i(\pi) &= \sum_{c \in C,\ c \text{ becomes active during } \pi} (|tr(c)| + |st(c)|)^{\underline{i}} \\ B_i(R) &= \sum_{c \in C,\ \text{active for } R} |st(c)|^{\underline{i}}, \end{aligned}$$

along with their expectations $f_0(r) = E[f_0(R)], A_i = E[X_i(\pi)], B_i(r) = E[B_i(R)]$, where R is drawn uniformly from $\binom{S}{r}$ and π is drawn uniformly from all permutations of S. Typically A_0 and A_1 describe the expected space and time requirements of randomized irncremental construction. $B_i(r)$ often arises in the analysis of randomized divide-and-conquer. We prove the following bounds:

$$\begin{aligned} A_i &\leq n^{\underline{i}} d^{\underline{i+1}} \sum_{0 \leq r \leq n} \frac{f_0(r)}{r^{\underline{i+1}}} \qquad \text{for } 0 \leq i < \delta \\ B_i(r) &\leq (n-r)^{\underline{i}} \frac{(d+1)^{\overline{i+1}}}{(r+1)^{\overline{i+1}}} \sum_{0 \leq j \leq r} f_0(j). \end{aligned}$$

Here $\delta = \min\{|tr(c)| \mid c \in C\}$ and $d = \max\{|tr(c)| \mid c \in C\}$.

Applications of Computational Geometry in Computer Vision

by TETSUO ASANO

Computational Geometry can contribute to Computer Vision in various manners. A direct way of contribution is to develop (asymptotically) faster algorithms or improve the computational complexities of existing algorithms. Another way of contribution is to define a notion mathematically to formulate it as an optimization problem. As one such example I talked about curve detection algorithms. Although a number of algorithms have been presented for this purpose under the name of Hough Transform, the desired output was sometimes very vaguely defined. Our approach starts with a strict definition of digital curve components and formulate it as a problem of visiting every cell in the arrangement of corresponding dual lines. The proposed algorithm runs in $O(n^d)$ time and $O(n)$ space where d is the complexity of the family of curves. The third way of contribution is to develop an efficient algorithm for a problem for which no polynomial-time algorithm has been knwon or analyze the computational complexity. Along this line I explained two approaches. One is related to Image Segmentation, which requires to partition a given image into several regions corresponding to meaningful regions in the image. We gave polynomial-time algorithms in some restricted cases and showed some NP-hardness results. I also showed that Contour representation opf an image which is a totally geometric expression helps us to design efficient algorithms for several problems which were not solved by any other methods. Flaw repairing and interpolation of gray levels are included. Finally, I showed the effectiveness of our approach by experimental results.

Shelling 3D-triangulations

by Tiow-Seng Tan

A sequence $(\tau_1, \tau_2, \ldots, \tau_n)$ of j tetrahedra of a 3D triangulation $\mathcal{T}$ is a partial shelling of $\mathcal{T}$ if $\bigcup_{i=1}^{k} \tau_i$ is a topological 3-ball for every $k \leq j$. A shelling of $\mathcal{T}$ is a partial shelling for which j is the number of tetrahedra in $\mathcal{T}$, and $\mathcal{T}$ is shellable if it admits a shelling. We study the open question on the time complexity of computing a shelling (if it exists) for a given triangulation $\mathcal{T}$. It is known that not all partial shellings can be extended to a shelling. We show that an extendable partial shelling $\mathcal{P}$ (i.e. one that can be extended to a shelling) union with a tetrahedron in $\mathcal{T} - \mathcal{P}$ that shares 2 or 3 facets with $\mathcal{P}$ produces yet another extendable partial shelling. This simple observation may be useful in designing an efficient algorithm for the problem studied.

Geometric Selection and Optimization via Sorted Matrices

by Klara Kedem

We show that in some selection and optimization problems in computational geometry, the optimization scheme of Frederickson and Johnson, using implicitly sorted matrices, yields better runtimes than the Megiddo parametric optimization scheme.
The main idea is to detect an ordering in the space of candidate solutions of the problem, then represent them in an implicitly sorted matrix and apply the [FJ] optimization scheme. The [FJ] scheme will generally multiply the decision algorithm runtime by a $\log n$-factor, and the [Me] scheme will multiply by a factor of $\log^2 n$.
The problems with which we exemplify the technique are
(1) Find two strips whose union covers a given point set, such that the width of the wider strip is minimized. Here we construct implicitly a matrix sorted by columns.
(2) Given a point set in the plane and two directions l_1 and l_2, find two squares, one parallel to l_1 and and the other to l_2, that together cover the point set and whose maximum size is minimized. Here we use a sorted matrix.
(3) Find two axis-parallel rectangles R_1, R_2 whose union covers a planar point set so as to minimize $\max(\mu(R_1), \mu(R_2))$ where μ is a monotone, nondecreasing function in the width and the height of the rectangles. Here we use a constant number of implicitly sorted matrices.
Moral: look into ordering in the space of candidate solutions.

Randomized Algorithms for some Geometric Optimization Problems

by Pankaj Agarwal (joint work with M. Sharir)

We present randomized algorithms for a number of geometric optimization problems, including the following:

(i) Compute the width of a set of n points in $\mathbb{R}^3$.
(ii) Compute the minimum width annulus containing a set of points in the plane.
(iii) Compute a longest segment lying inside a simple polygon.
All the three problems can be solved in $O(n^{3/2+\varepsilon})$ expected time, for any $\varepsilon > 0$.

Spectral Techniques in Range Searching

by Bernard Chazelle

Given N weighted points in the plane and N boxes (or triangles), compute the sum of the weights of the points in each box (triangle).
The model allows real weights with addition and subtraction (*no* multiplication). We prove an $\Omega(N \log\log N)$ lower bound for boxes and $\Omega(N \log N)$ for triangles. The proof relies on estimates of the spectrum of $A^T A$, where A is the incidence matrix of the underlying set system.

On the Minkowski Sum of Simple Polygons

by Jack Snoeyink (proved the night before with B. Aronov, T. Chan and D. Halperin)

We prove that the complexity of the outer face of the boundary of the Minkowski sum of two simple polygons P and Q with n and k edges, $n > k$ is $\Theta(nk\alpha(k))$. The upper bound is by analyzing Davenport-Schinzel sequences of families; the lower bound is a construction based on lower envelopes of line segments. Micha Sharir reports that the upper bound can be derived from S. Har-Peled's results on combining k arrangements.

List of Open Problems.

Ricky Pollack: (Originally posed by Dennis Shasha) **Voronoi Game:**

Given a rectangular grid (or square if you wish) n by m. Two or more players are going to play a game of k moves where $k \ll \min(m, n)$.

We'll look at the two player game first assuming the players are called White and Black, each having k stones.

Players alternate placing stones on the board. At the end, a Voronoi diagram is formed. A polygon is owned by White if it contains a white stone in it and black otherwise. Frontiers between black and white polygons may be neutral. The winner is the player with the largest area.

Symmetry issue: The second player can always play symmetrically. So, we can break symmetry in three ways.

1. Have a definite center.
2. Require that the second player place two stones immediately after the first player's first move. So, the first player will also be the last one to play.
3. Require that a player always play in the same column or the same row as some other piece on the board.

Snipe Variant: Let $j < k$: White and Black place their k stones as in the Voronoi game, but after they finish they alternate turns removing j stones (either their own or their opponent's).

Shuffle variant: Let $j < k$: White and Black place their k stones as in the Voronoi game, but after they finish they alternate turns moving stones (either their own or their opponent's).

(Apparently a PC implementation of a version of this game is available from shasha@shasha.cs.nyu.edu.)

Marc van Krefeld:

1. Given a set of n lines in the plane and two points s, t that lie on the skeleton of the arrangement of the lines. Can one compute a shortest path from s to t on the skeleton of the arrangement faster than quadratic time?
2. Given a polyhedral terrain with n vertices and two points s, t on the terrain. Can one decide if there exists a path from s to t that has monotonously decreasing height faster than in $O(n \log n)$ time (without preprocessing)?
3. Given a simple polygon with k disjoint holes and n vertices in total, and also two points s and t in the polygon. Can one compute a path from s to t faster than in $O(n + k \log k)$ time (it need not be the shortest path)?

Raimund Seidel:

Let p and q be two distinct points in the plane and let γ be a curve directed from p to q. For a point x on γ let v_x be a tangent line of γ at x in the forward direction, and let $C_x(\alpha)$ be the cone with apex at x with symmetry axis v_x and with angle of aperture 2α. Now call γ an α-selfapproaching curve iff for every x on γ the part of γ between x and q is contained in $C_x(\alpha)$.

Rolf Klein showed in his talk, that for the special case of $\alpha = \pi/2$ the length of an α-selfapproaching curve is at most 5.44 times the distance $d(p,q)$.

Is it true, that for every $0 < \alpha < \pi$ there is a constant $b(\alpha)$ so that the length of every α-selfapproaching curve is at most $b(\alpha)$ times the distance between its endpoints? If not, for what α's is this true? How small can one prove $b(\alpha)$ to be?

Günter Rote:

A curve has no angles sharper than α if, for any three points x, y, and z appearing on the curve in this order, the angle xyz is at least $\pi - \alpha$. Prove that the longest such curve between two given endpoints p and q in the plane is a circular arc for whose points y the angle pyq is equal to $\pi - \alpha$.

János Pach:

There are two different ways how to define the crossing number of a graph G:

A) The minimum number of crossing pairs of edges in a drawing of G in the plane (where the edges can be represented by arbitrary Jordan curves connecting two vertices but not passing through a third vertex).

B) The minimum number of points where two edges cross each other in a drawing of G in the plane (no three edges are allowed to cross at the same point).

Clearly, the latter minimum is at least as large as the first one. Are they exactly (or roughly) equal?

Bernard Chazelle:

1. A classical result in discrepancy theory says that no matter how one bicolors the vertices of an N-by-N grid there exists a halfplane within which one color outnumbers the other one by at least $c\sqrt{N}$, for some constant $c > 0$. Is it possible to find $p = O(N^2)$ halfplanes such that given any coloring one of them has large discrepancy? This is clearly true for large enough p. But how small can p be so that the maximum discrepancy remains on the order of root N.
2. k-nearest neighbor searching in $\{0,1\}^N$: Store M points (M = a few thousands) in $\{0,1\}^N$ ($N \approx 1000$) so that given a query point in $\{0,1\}^N$, the k nearest neighbors (Hamming distance) ($k \leq 20$) can be found quickly. What is desired is a method that leads to an efficient, simple working program.

Emo Welzl:

Let P be a set of $n \geq d+1$ points in d-space in general position (i.e., no $d+1$ points lie on a common hyperplane). We define its *nonconvexity* by

$$\mathrm{nc}(P) = \mathrm{card}\{A \in \tbinom{P}{d+2} \mid A \text{ is not in convex position}\}$$

Clearly, P is in convex position if and only if $\mathrm{nc}(P) = 0$.

PROBLEM. Is it always possible to continously move a set P of $n \geq 4$ in 3-space into convex position so that the nonconvexity never increases? (During the whole motion the set P has to be in general position, except for a finite number of time steps, when exactly one coplanarity occurs.)

REMARKS. An affirmative answer to the problem implies that, for each $k < n/2$, the number of $\leq k$-sets of an n-point set in 3-space is maximized in convex position, where this number is known to be

$$k^2 n - \frac{k(k-1)(2k+5)}{3} .$$

Marshall Bern: (Problems from Eppstein)

Let S be a finite set of points in the Euclidean plane. Let S' be a finite superset of S, and let $MWT(S')$ represent the length of the shortest triangulation of S'. Let $MWST(S)$ be the infimum over all S' of $MWT(S')$. Is there always an S' such that $MWT(S') = MWST(S)$?

Now assume that S is in convex position. Is there always an S' with $MWT(S') = MWST(S)$, such that each point of S' lies on an edge of the convex hull of S?

Subhash Suri:

Let P be a convex polytope in 3-space. For two points p, q on the surface of P, let $D(p, q)$ denote the length of a shortest path (geodesic) joining p, q on P. Let $A(p, q)$ denote the length of a "planar" shortest path between p and q on P—a planar path is constrained to lie on a plane passing through p, q.

Let α denote the worst-case ratio $A(p, q)/D(p, q)$ over all convex polytopes and all pairs of points p, q.

Prove lower and upper bounds for the ratio α.

Günter Rote:

A *lattice packing* of the plane by a polygon P is determined by two vectors u and v such that the set $\{P + \lambda u + \mu v \mid \lambda, \mu \text{ integer}\}$ covers the plane. The *density* of the packing is the ratio between the total area used and the area covered. Find an efficient algorithm that, for a given polygon P, finds the lattice covering with minimum density.

Remark: For lattice coverings by centrally symmetric polygons, as well as for lattice packings, linear-time algorithms were given by SilverMount (J. Algorithms, 1990).

Jack Snoeyink: (Due to Chris Gold)

Suppose that you want to traverse the edges of a Voronoi diagram. Because the Voronoi is a planar graph, if you remove edges that form a spanning tree of the faces, then the edges that remain form a spanning tree of the vertices and you can traverse this tree starting from any vertex by leaving a vertex by the edge just ccw of the one you used to enter the vertex. This takes a constant amount of memory.

One simple way to do this for the Voronoi diagram of points is to imagine that the edge just left of the lowest vertex of each cell (i.e., the of each vertex) is deleted. That is, ignore the uppermost left-going edge of the current vertex when deciding which edge to exit and, if you find that you entered a vertex along its uppermost left-going edge, then return to where you came from.

The question is, is there a similar simple rule that can apply to the Voronoi diagram of line segments? The fact that segments could be replaced by many points indicates that there is a similar rule; is it possible that there is one requiring no changes to the graph and no memory?

Dagstuhl-Seminar 9511: List of Participants

Pankaj K. **Agarwal**
Duke University
Computer Science Dept.
LSRC Bldg.
Box 90129
Durham NC 27708-0129
USA
pankaj@cs.duke.edu
tel.: +1-919-660-6540

Helmut **Alt**
Freie Universität Berlin
Fachbereich Mathematik und Informatik
Institut für Informatik
Takustr. 9
D-14195 Berlin
Germany
alt@inf.fu-berlin.de
tel.: +49-30-838-75160

Annamaria **Amenta**
The Geometry Center
1300 South Second Street
Minneapolis MN 55454
USA
nina@geom.umn.edu

Boris **Aronov**
Polytechnic University
Computer Science Dept.
333 Jay Street
Brooklyn NY 11201
USA
aronov@ziggy.poly.edu

Tetsuo **Asano**
Osaka Electro-Communication University
Dept. of Applied Electronics
Faculty of Engineering
18-8 Hatsu-cho / Neyagawa
Osaka 572
Japan
asano@amlab.osakac.ac.jp
tel.: +81-720-24-1131 -2450

Franz **Aurenhammer**
TU Graz
Institut für Grundlagen der
Informationsverarbeitung (IGI)
Schiesstattgasse 4
A-8010 Graz
Austria
auren@igi.tu-graz.ac.at

Marshall **Bern**
Xerox PARC
3333 Coyote Hill Road
Palo Alto CA 94304
USA
bern@parc.xerox.com
tel.: +1-415-812-4443

Vasilis **Capoyleas**
Max-Planck-Institut
für Informatik
Im Stadtwald
66123 Saabrücken
Germany
capoyleas@mpi-sb.mpg.de
tel.: +49-681-302-54 24

Timothy M. **Chan**
University of British Columbia
Department of Computer Science
201-2366 Main Mall
Vancouver BC V6T 1Z4
Canada
tchan@cs.ubc.ca

Bernard **Chazelle**
Princeton University
Department of Computer Science
35 Olden Street
Princeton NJ 08544
USA
chazelle@cs.princeton.edu

Olivier **Devillers**
INRIA - Sophia-Antipolis
B.P. 93
F-06902 Sophia Antipolis Cedex
France
olivier.devillers@sophia.inria.fr
tel.: +33-9365-7763

Katrin **Dobrindt**
Universiteit Utrecht
Vakgroep Informatica
Padualaan 14 Postbus 80.089
NL-3508 TB Utrecht
The Netherlands
katrin@cs.ruu.nl
tel.: +31-30-534031

Scot **Drysdale**
Dartmouth College
6211 Sudikoff Laboratory
Hanover NH 03755-3510
USA
scot.drysdale@dartmouth.edu
tel.: +1-603-646-2101

Martin **Dyer**
University of Leeds
School of Computer Studies
Leeds LS2 9JT
Great Britain
dyer@scs.leeds.ac.uk
tel.: +44-532-335442

Bernd **Gärtner**
Freie Universität Berlin
Fachbereich Mathematik und Informatik
Institut für Informatik (WE 03)
Takustr. 9
D-14195 Berlin
Germany
gaertner@tcs.fu-berlin.de
tel.: +49-30-838-75166

Leonidas **Guibas**
Stanford University
Computer Science Department
Stanford CA 94305
USA
guibas@cs.stanford.edu
tel.: +1-415-723-0304

Dan **Halperin**
Stanford University
Robotics Lab
Dept. of Computer Science
Stanford CA 94305
USA
halperin@cs.stanford.edu
tel.: +1-415-723-3994

Klara **Kedem**
Ben-Gurion University
Department of Mathematics
and Computer Science
Ber-Sheva 84105
Israel
kedem@ivory.bgu.ac.il
tel.: +972-7-461-628

David G. **Kirkpatrick**
University of British Columbia
Department of Computer Science
201-2366 Main Mall
Vancouver BC V6T 1Z4
Canada
kirk@cs.ubc.ca
tel.: +1-604-822-4777

Rolf **Klein**
FernUniversität Hagen
Praktische Informatik VI
Elberfelder Straße 95
D-58084 Hagen
Germany
rolf.klein@fernuni-hagen.de
tel.: +49-2331-987-327

Marc **van Kreveld**
Utrecht University
Vakgroep informatica
Padualaan 14
NL-3508 TB Utrecht
The Netherlands
marc@cs.ruu.nl
tel.: +31-30-534-119

Heinrich **Müller**
Universität Dortmund
Informatik VII
Graphische Systeme
Otto-Hahn-Str. 16
D-44221 Dortmund
Germany
mueller@ls7.informatik.uni-dortmund.de
tel.: +49-231-755-63 24

Janos **Pach**
Hungarian Academy of Sciences
Mathematical Institute Pf. 127
H-1364 Budapest
Hungary
pach@math-inst.hu

Richard **Pollack**
Courant Institute / NYU
Dept. of Mathematics
251 Mercer St.
New York NY
USA
pollack@geometry.nyu.edu
tel.: 1-212-998-3167

Günter **Rote**
TU Graz
Institut für Mathematik
Steyrergasse 30
A-8010 Graz
Austria
rote@ftug.dnet.tu-graz.ac.at
tel.: +43-316-873-7127

Marie-Françoise **Roy**
Universit'e de Rennes 1
Institut Math'ematique de Rennes
Campus de Beaulieu
F-35042 Rennes Cedex
France
costeroy@univ-rennes1.fr

Carlo **Séquin**
University of California at Berkeley
Computer Science Division EECS
Soda Hall
Berkeley CA 94720-1776
USA
sequin@cs.berkeley.edu
tel.: +1-510-642-5103

Jörg-R. **Sack**
Carleton University
School of Computer Science
Herzberg Building
Colonel by Drive
Ottawa K1S 5B6
Canada
sack@scs.carleton.ca
tel.: +1-613-788-4361 /-4333

Otfried **Schwarzkopf**
Utrecht University
Vakgroep informatica
Padualaan 14
NL-3508 TB Utrecht
The Netherlands
otfried@cs.ruu.nl
tel.: +31-30-533977

Raimund **Seidel**
Universität des Saarlandes
Fachbereich 14 - Informatik
Postfach 15 11 50
D-66041 Saarbrücken
seidel@cs.uni-sb.de
tel.: +49-681-302-4513

Micha **Sharir**
Tel Aviv University
School of Mathematics
Tel Aviv 69978
Israel
sharir@math.tau.ac.il
tel.: +972-3-640-8804

Michiel **Smid**
Max-Planck-Institut für Informatik
Im Stadtwald
D-66123 Saarbrücken
Germany
michiel@mpi-sb.mpg.de

Jack **Snoeyink**
University of British Columbia
Department of Computer Science
201-2366 Main Mall
Vancouver BC V6T 1Z4
Canada
snoeyink@cs.ubc.ca
tel.: +1-604-822-8169

Subhash **Suri**
Washington University
Dept. of Computer Science
1 Brookings Drive
St. Louis MO 63130-4899
USA
suri@cs.wustl.edu
tel.: +1-314-935-75 46

Tiow-Seng **Tan**
National Univ. of Singapore
Department of Information Systems
& Computer Science
Lower Kent Ridge Rd.
Singapore 0511
Republic of Singapore
tants@iscs.nus.sg
tel.: +65-772-6764

Emo **Welzl**
Freie Universität Berlin
Fachbereich Mathematik und Informatik
Institut für Informatik (WE 03)
Takustr. 9
D-14195 Berlin
Germany
emo@inf.fu-berlin.de
tel.: +49-30-838 -75150 / -75103 (Sek.)

Günter M. **Ziegler**
TU Berlin
Fachbereich Mathematik
Str. des 17. Juni 136
D-10623 Berlin
Germany
ziegler@math.tu-berlin.de
tel.: +49-30-314-25730

Zuletzt erschienene und geplante Titel:

F. Meyer a.d. Heide, H.J. Prömel, E. Upfal (editors):
Expander Graphs, Random Graphs and Their Application in Computer Science, Dagstuhl-Seminar-Report; 87; 11.04.-15.04.94 (9415)

J. van Leeuwen, K. Mehlhorn, T. Reps (editors):
Incremental Computation and Dynamic Algorithms, Dagstuhl-Seminar-Report; 88; 02.05.-06.05.94 (9418)

R. Giegerich, J. Hughes (editors):
Functional Programming in the Real World, Dagstuhl-Seminar-Report; 89; 16.05.-20.05.94 (9420)

H. Hagen, H. Müller, G.M. Nielson (editors):
Scientific Visualization , Dagstuhl-Seminar-Report; 90; 23.05.-27.05.94 (9421)

T. Dietterich, W. Maass, H.U. Simon, M. Warmuth (editors):
Theory and Praxis of Machine Learning, Dagstuhl-Seminar-Report; 91; 27.06.-01.07.94 (9426)

J. Encarnação, J. Foley, R.G. Herrtwich (editors):
Fundamentals and Perspectives of Multimedia Systems, Dagstuhl-Seminar-Report; 92; 04.07.-08.07.94 (9427)

W. Hoeppner, H. Horacek, J. Moore (editors):
Principles of Natural Language Generation, Dagstuhl-Seminar-Report; 93; 25.07.-29.07.94 (9430)

A. Lesgold, F. Schmalhofer (editors):
Expert- and Tutoring-Systems as Media for Embodying and Sharing Knowledge, Dagstuhl-Seminar-Report; 94; 01.08.-05.08.94 (9431)

H.-D. Ehrich, G. Engels, J. Paredaens, P. Wegner (editors):
Fundamentals of Object-Oriented Languages, Systems, and Methods, Dagstuhl-Seminar-Report; 95; 22.08.-26.08.94 (9434)

K. Birman, F. Cristian, F. Mattern, A. Schiper (editors):
Unifying Theory and Practice in Distributed Systems, Dagstuhl-Seminar-Report; 96; 05.09.-09.09.94 (9436)

R. Keil-Slawik, I. Wagner (editors):
Interdisciplinary Foundations of Systems Design and Evaluation, Dagstuhl-Seminar-Report; 97; 19.09.-23.09.94 (9438)

M. Broy, L. Lamport (editors):
Specification and Refinement of Reactive Systems - A Case Study, Dagstuhl-Seminar-Report; 98; 26.09.-30.09.94 (9439)

M. Jarke, P. Loucopoulos, J. Mylopoulos, A. Sutcliffe (editors):
System Requirements: Analysis, Management, and Exploitation, Dagstuhl-Seminar-Report; 99; 04.10.-07.10.94 (9440)

J. Buchmann, H. Niederreiter, A.M. Odlyzko, H.G. Zimmer (editors):
Algorithms and Number Theory, Dagstuhl-Seminar-Report; 100; 10.10.-14.10.94 (9441)

S. Heinrich, J. Traub, H. Wozniakowski (editors):
Algorithms and Complexity for Continuous Problems, Dagstuhl-Seminar-Report; 101; 17.10.-21.10.94 (9442)

H. Bunke, T. Kanade, H. Noltemeier (editors):
Environment Modelling and Motion Planning for Autonomous Robots, Dagstuhl-Seminar-Report; 102; 24.10.-28.10.94 (9443)

W. Maass, Ch. v.d. Malsburg, E. Sontag, I. Wegener (editors):
Neural Computing, Dagstuhl-Seminar-Report; 103; 07.11.-11.11.94 (9445)

G. Berry, W.P. de Roever, A. Poigné, A. Pnueli (editors):
Syncronous Languages, Dagstuhl-Seminar-Report; 104; 28.11.-02.12.94 (9448)

B. Becker, R. Bryant, O. Coudert, Ch. Meinel (editors):
Computer Aided Design and Test, Dagstuhl-Seminar-Report; 105; 13.02.-17.02.95 (9507)

D. Garlan, F. Paulisch, W. Tichy (editors):
Software Architectures, Dagstuhl-Seminar-Report; 106; 20.02.-24.02.95 (9508)

W.J. Cullyer, W.A. Halang, B. Krämer (editors):
High Integrity Programmable Electronic Systems, Dagstuhl-Seminar-Report; 107; 27.02.-03.03.95 (9509)

J. Gruska, T. Toffoli, H. Umeo, R. Vollmar (editors):
Cellular Automata, Dagstuhl-Seminar-Report; 108; 06.03.-10.03.95 (9510)

H. Alt, B. Chazelle, R. Seidel (editors):
Computational Geometry, Dagstuhl-Seminar-Report; 109; 13.03.-17.03.95 (9511)

W. Bibel, K. Furukawa, M. Stickel (editors):
Deduction, Dagstuhl-Seminar-Report; 110; 20.03.-24.03.95 (9512)

B. Freitag, C.B. Jones, Ch. Lengauer, H.-J. Scheck (editors):
Object-Orientation with Parallelism and Persistence, Dagstuhl-Seminar-Report; 111; 03.04.-07.04.95 (9514)

J. Doran, N. Gilbert, U. Mueller, K. Troitzsch (editors):
Social Science Microsimulation: A Challenge for Computer Science, Dagstuhl-Seminar-Report; 112; 01.05.-05.05.95 (9518)

R. Studer, M. Musen (editors):
Shareable and Reusable Problem Solving Methods, Dagstuhl-Seminar-Report; 113; 08.05.-12.05.95 (9519)

J. Blazewicz, K. Ecker, L. Welch (editors):
Scheduling in Computer & Manufacturing Systems, Dagstuhl-Seminar-Report; 114; 15.05.-19.05.95 (9520)

H. Beilner, G. Ciardo, C. Lindemann, K. Trivedi (editors):
Performance and Dependability Modeling with Stochastic Petri Nets, Dagstuhl-Seminar-Report; 115; 22.05.-26.05.95 (9521)

M. Aigner, J. Spencer, E. Triesch (editors):
Computing with Faulty Inputs, Dagstuhl-Seminar-Report; 116; 29.05.-02.06.95 (9522)

J.-R. Abrial, E. Börger, H. Langmaack (editors):
Methods for Semantics and Specification, Dagstuhl-Seminar-Report; 117; 05.06.-09.06.95 (9523)

W. Effelsberg, D. Ferrari, O. Spaniol, A. Danthine (editors):
Architecture and Protocols for High Performance Networks, Dagstuhl-Seminar-Report; 118; 19.06.-23.06.95 (9525)

Ph. Flajolet, R. Kemp, H. Prodinger, R. Sedgewick (editors):
`Average-Case'-Analysis of Algorithms, Dagstuhl-Seminar-Report; 119; 03.07.-07.07.95 (9527)

D. Gustfield, T. Lengauer, C. Sander (editors):
Molecular Bioinformatics, Dagstuhl-Seminar-Report; 120; 10.07.-14.07.95 (9528)

J. Chomicki, G. Saake, C. Sernadas (editors):
Role of Logics in Information Systems, Dagstuhl-Seminar-Report; 121; 17.07.-21.07.95 (9529)

R.S. Boyer,A. Bundy, D.Kapur, Ch. Walther (editors):
Automation of Proof by Mathematical Induction, Dagstuhl-Seminar-Report; 122; 24.07.-28.07.95 (9530)