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“Average-Case”-Analysis of Algorithms

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Seminar Report 9328

Average Case Analysis of Algorithms

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Overview

Analysis of algorithms aims at characterizing precisely the performances of major data structures and algorithms of computer science. The emphasis of the meeting was on average–case analysis. The domain was founded by Knuth some 31 years ago. He first showed —amongst many other things!— that most basic sorting and searching methods can be precisely analyzed and organized into a complexity scale with respect to expected performance.

This meeting was the first one ever to be dedicated exclusively to analysis of algorithms. The number of invited participants was 37, of which 30 gave presentations of recent results summarized below. The talks could be grouped roughly as dealing with *Methods* or *Applications*, both aspects being often closely intertwined.

Methods concern combinatorial models of random structures that are relevant to major algorithms and data structures. Recent years have seen important developments in this area where key parameters of trees, permutations, strings, and so on, are beginning to be organized into coherent theoretical frameworks. Current approaches largely revolve around generating functions as the basic object both for combinatorial enumerations and for asymptotic analysis.

Presentations related to *Methods* started with the talk of Don Knuth who showed how generating function techniques permit to quantify the evolution of random graphs. Flajolet surveyed the use of Mellin transforms for asymptotics with applications in digital trees, protocols, sorting networks, etc.; Kirschenhofer revealed deep connections between some of Ramanujan's modular identities and digital trees; Sprugnoli presented a coherent framewok for asymptotics of classes of generating functions; Kemp and Trier developed generating function methods for multidimensional tree models while Bergeron showed how to systematically analyze increasing trees in this way. Another facet was the connection between average–case analysis and probabilistic methods, examples being presented by Louchard (stochastic processes), Gutjahr (random trees and branching processes), and Drmota (limit distributions and complex multivariate asymptotics).

Applications by now extend far beyond sorting and searching, although the classical problems still contribute a considerable source of inspiration and problems. For instance, it is unknown to this day whether the asymptotic distribution of costs of Quicksort is expressible in terms of standard special functions, though many characteristics of the distribution became recently available (tails, higher moments, etc). A 20 years old problem was solved by Sedgewick who finally settled the question of the average–case complexity of heapsort. Compton showed how the Ramanujan–Knuth function is essential in understanding deadlock effects in computer systems; Salvy used classic hypergeometric theory and integral representations to analyze quadtrees of all dimensions; Vallée demonstrated how the lattice reduction algorithm of Gauß can be subjected to precise average–case analysis; finally Panny showed that even a simple algorithm like Mergesort has a hidden fractal behaviour.

Analysis also makes tangible progress when confronted with new classes of problems. So, the behaviour of data compression algorithms is by now better understood (Jacquet, Szpankowski, Vitter); it becomes possible to precisely quantify the complexity of string matching algorithms (Régnier) with possible implications for DNA sequencing (Gonnet). Skip lists are a provably efficient alternative to balanced trees (Prodinger), and methods originally directed towards random tree models turn out to be also useful in understanding real-time systems (Schmid). Actually, efficient simulation algorithms may well result from rather theoretical frameworks (Zimmermann). Exotic applications are even to be found in fault tolerance (Sipala) and numerical integration (Tichy).

At the same time, we are witnessing progress in probabilistic analysis whose scope goes beyond average-case estimates. Direct probabilistic methods in the style of the Hungarian school (Erdős *et al.*) apply well to random graph and combinatorial optimization problems. Some clear cases are the knapsack problem (Marchetti), merging algorithms (De La Vega), interconnection networks (Spirakis), or hypergraph algorithms (Althöfer). Perhaps even more cross-fertilization is to be expected in future years. The already mentioned conferences of Knuth, Drmota, Louchard, and Gutjahr, as well as Mahmoud's work (see his recent book on random search trees) point towards interesting convergences with classical analytic frameworks.

Across the diversity of applications, we find more and more visible the emergence of general methods that permit to analyze what one could call complex algorithmic systems. We can only hope that this small booklet of abstracts will convey some of the participants' enthusiasm with a maturing 31 years old subject.

The Organizers,
PHILIPPE FLAJOLET
RAINER KEMP
HELMUT PRODINGER

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Uwe Trier, Frankfurt am Main
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Wenceslas Fernandez de la Vega, Orsay
Jeffrey Vitter, Durham
Paul Zimmermann, Villers-les-Nancy

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PHILIPPE JACQUET

Travel Inside a Funny Complex Differential Equation

I. ALTHÖFER, G. GONNET, PH. FLAJOLET, D. KNUTH, H. MAHMOUD, P. SPIRAKIS, R. TICHY

Open Problem Session

Abstracts

The Birth of the Giant Component

by DONALD KNUTH

The first few minutes of this talk considered "the birth of analysis of algorithms" - my personal experiences from 31 years ago when I first noticed how pleasant it is to find quantitative formulas that explain the performance characteristics of an important algorithm. Those experiences profoundly changed my life! I also mentioned why it became necessary to invent a name for such activities.

The rest of the time was devoted to an overview of a long paper just published in *Random Structures and Algorithms*, 4 (1993), 233-358 (joint work with Svante Janson, Tomasz Luczak and Boris Pittel). I emphasized philosophical issues and things that seemed most significant in retrospect after the paper was completed. (The paper is about the way a giant component evolves in a random graph or multigraph).

I also mentioned a few things that were not included in the paper because they didn't work as expected, since they might prove interesting in future investigation. For example, I noted that the generating function $G(w,z)$ for random multigraphs satisfies

$$G(w,z) = e^z + \frac{1}{2}\int_0^w \vartheta^2 G(w,z)\,dw,$$

where ϑ is the operator $z\frac{\partial}{\partial z}$. Therefore $G(w,z) = \lim_{k\to\infty} G_k(w,z)$, where

$$G_0(w,z) = e^z \text{ and } G_{k+1}(w,z) = e^z + \frac{1}{2}\int_0^w \vartheta^2 G_k(w,z)\,dw.$$

These generating functions G_k enumerate multigraphs with somewhat peculiar weights. I didn't have time to pursue this line further.

The principle result of the paper is that an evolving graph or multigraph on n vertices has at most one component throughout its evolution with probability $\to \frac{5\pi}{18}$ as $n \to \infty$.

An analysis of bivariate generating functions classifies the evolution when the graph has $\frac{1}{2}n + \mu$ edges for $|\mu| \leq n^{\frac{3}{4}}$, and we also obtain precise results for larger values of $|\mu|$.

Ramanujan's Q-function and Asymptotics

by KEVIN COMPTON

Ramanujan first studied the function

$$Q(m) = 1 + \frac{m(m-1)}{m^2} + \frac{m(m-1)(m-2)}{m^3} + \cdots + \frac{m!}{m^m}$$

in 1911. (This function had been studied earlier by Cauchy). It was first denoted by the letter Q by Knuth, who used it in his first analysis of an algorithm in 1962. Since that time it has found numerous applications in computer science. We describe here how the Q-function arises in the analysis of statistics relating to deadlock in multiprocessing systems. We use this example to show how to obtain asymptotics of coefficients of functions related to the Q-function.

We consider multiprocessing systems where processes make independent Poisson distributed resource requests with mean arrival time 1 and assume resources are not released. For m, the total number of resources in a system and i and j, the number of free resources and active processes when the system begins, we denote by T_{ij}, P_{ij} and R_{ij} the expected deadlock time, expected total processing time, and expected number of components allocated in the system. We show that $T_{m1} = 1 + Q(m)$ and derive other expressions related to the Q-function for general T_{ij}, P_{ij} and R_{ij}. We use the tree function $T(x)$ $(= -W(-x)$, where W is Lambert's W-function from Maple) to derive asymptotics for these quantities.

We conclude with general remarks about the family of functions related to the Q-function and speculate on automatic methods to obtain asymptotics for these functions.

The Mellin Transform Technology

by PHILIPPE FLAJOLET

The Mellin transform

$$f(z) \quad \mapsto \quad f^*(s) = \int_0^\infty f(x)x^{s-1}\,dx$$

has proved to be a powerful tool in the asymptotic evaluation of combinatorial sums arising in counting and the analysis of algorithms. The talk reviews the major categories of usage of Mellin transforms for univariate asymptotics: 1) harmonic sums; 2) harmonic sums and singularity analysis; 3) functional equations.

Applications are to be found in the area of height of trees, sorting networks, carry propagation, digital search trees and tries.

Average Case Analysis of Multidimensional Numerical Integration
by ROBERT TICHY

We report on a recent approach of analyzing the average case behaviour of Quasi-Monte Carlo integration. The space C_d of all continuous functions on $[0,1]^d$ is equipped with the Wiener measure ω and for the average case complexity of the approximation of a d-dimensional integral $\int f$ by $\frac{1}{N}\sum_{n\leq N} f(p_n)$ with error $\leq \varepsilon$ the estimate $\mathcal{O}(\varepsilon^{-1}(\log \varepsilon^{-1})^{\frac{d-1}{2}})$ is established (Woszniakowski). This result is strongly connected with various notions from the theory of point distributions, such as discrepancy, L^p-discrepancy etc.. Several estimates for these discrepancies are presented as well as some constructions of low-discrepancy sequences.

Bottom Up Mergesort - A Detailed Analysis
by WOLFGANG PANNY

Although the behaviour of mergesort algorithms is basically known, the periodicity phenomena encountered in their analysis are not easy to deal with. In this talk, closed form expressions for the necessary number of comparisons are derived for the bottom up algorithm, which adequately describe its periodic behaviour. This allows, among other things, to reasonably compare the top down and the bottom up mergesort algorithms.

Stochastic On-Line Knapsack Problems
by ALBERTO MARCHETTI-SPACCAMELA (joint work with C. VERCELLIS)

Different classes of on-line algorithms are developed and analyzed, for the solutions of $\{0,1\}$ and selected stochastic knapsack problems, in which both, profit and size coefficients, are random variables. A linear time on-line algorithm is proposed for which the expected difference between the optimum and the approximate solution value is $\mathcal{O}(\log^{\frac{3}{2}} n)$. An $\Omega(1)$ lower bound on the expected difference between the optimum and the solution found by any on-line algorithm is shown to hold.

Ramanujan and the Average Case Analysis of Trie Parameters
by PETER KIRSCHENHOFER (joint work with H. PRODINGER and W. SZPANKOWSKI)

In this talk we present a nice application of several series transformation results from Ramanujan's Notebooks to the asymptotic analysis of the variance of different parameters of Tries, Patricia Tries and Digital Search Trees such as size, path length or depth of insertion (the material of this talk is taken from joint work with H. Prodinger and W. Szpankowski).

Adopting a method for the asymptotic evaluation of finite differences due to S.O. Rice we achieve rather involved expressions for the asymptotic expansions of the parameters in question. By the usage of well-suited formulæ from the Notebooks it can be shown that the formal main terms of these expansions cancel and the correct main terms can be identified. In the easiest case the transformation formulæ in question are closely related to the functional equation of the Dedekind η-function.

Faults in Linear Arrays with Multiple Bypass Links

by PAOLO SIPALA (joint work with IRINA A. SEMIBRATSKAYA)

As a model for some kinds of computing systems, we consider a linear array of identical *processing elements* $(\ldots, p_{-2}, p_{-1}, p_0, p_1, p_2, \ldots)$.

Each element p_i is connected to the next one, p_{i+1}, by a *regular* link; we may also have additional *bypass* links of some type t, connecting each element p_i to its successor p_{i+t} at distance t. Links may be unidirectional or bidirectional. A finite number of elements may be faulty, thus breaking all links incident to them. A configuration of faulty elements is termed *catastrophic*, when processing elements preceeding the faulty area cannot be connected to any one of those following it, by any chain of unbroken links.

Pagli et al. have fully characterized catastrophic fault patterns in linear arrays containing bypass links of a single type t. Here we extend their results to the case of several types $t_1, \ldots, t_k$ of bypass links, giving a method to enumerate the corresponding configurations of catastrophic faults.

Differential Equations and Increasing Trees

by FRANÇOIS BERGERON (joint work with B. SALVY and PH. FLAJOLET)

Using the language of species of structures, one can specify rooted f-trees with the equation $T = x\, f(T)$, where f stands for some species of structures such as "set", "list", ... The specification of rooted f-trees, with the condition that labels are increasing on any path from the root to a leaf, takes the form of a differential equation, integral equation:

$$T = \int_0^x f(T)dx.$$

Using this characterization, we can easily set differential equations for the study of the average value of recursive parameters of f-trees. These equations take the general form

$$R' = G + \frac{T''}{T'} R, \qquad (*)$$

where R stands for the generating function allowing the study of a parameter whose choice corresponds to a choice of G. Equation $(*)$ is easy to solve in the form

$$R = T'(x) \int_0^x \frac{G(u)}{T'(u)} du.$$

Hence we can study the asymptotic behaviour.

Analytic Methods and Asymptotic Distributions
by Michael Drmota (joint work with M. Soria)

The main purpose of this lecture is to show how to apply saddle point techniques combined with singularity analysis in order to obtain multivariate asymptotic expansions for coefficients of power series in more than one variable.

In particular, the asymptotic distribution properties of special parameters of simply generated families of trees (i.e. branching processes) and random mappings are analyzed by these techniques.

After discussing implicit functions it is shown by using a multivariate singularity analysis that the normalized contour of trees converges to Brownian excursion.

Furthermore, by a combination of saddle point techniques and singularity analysis the asymptotic distribution of points in random mappings with a fixed number of total predecessors is identified to be the convolution of a Gaussian and a Rayleigh distribution.

Probabilistic Analysis of Algorithms
by Guy Louchard

A methodology is presented to analyze the *stochastic* asymptotic behaviour of some algorithms and to derive the *dynamic* properties of some data structures, on which we perform operations such as insertions, deletions and queries.

Using probabilistic tools such as Brownian Motion and Random Walks, we derive the random properties of our structures.

A Language Approach to String Searching Performance

by MIREILLE RÉGNIER

We propose a general framework to derive the average performance of string searching algorithms. It relies mainly on languages and combinatorics on words, joined to some probabilistic tools. The approach is quite powerful: although we concentrate here on Morris-Pratt-like algorithms, it applies to a large class of algorithms that preprocess the pattern, notably to Boyer-Moore algorithms. The average searching time when the text character distribution is stationary is proven to be asymptotically kn. When the character distributions in text *and* pattern are Markovian - a suitable model for natural languages or biological applications - the linearity constant is computable by a closed formula. This formula provides an exact cost for small patterns, and a tight approximation for others.

Branching Processes and Recognizable Families of Trees

by WALTER GUTJAHR

Size-conditioned Galton-Watson branching processes are suitable models for the origin of certain discrete structures as they are processed by different types of algorithms. It is shown how to derive information on the average values e_n of a given parameter in the family tree of a branching process conditioned on the total progeny n, if its average values $e(w)$ in a class of corresponding *unconditional* branching processes are known.

Especially, it turns out that the asymptotic behaviour of e_n, as $n \to \infty$, is determined by the transition behaviour of $e(w)$ at the step from subcritical processes to the critical process.

Results are presented for the case of single type branching processes (corresponding to the so-called *simply generated families of trees*); a generalization to the multitype case (corresponding to *recognizable families of trees*) is outlined.

The Cost Structure of Quad Trees

by BRUNO SALVY (joint work with PH. FLAJOLET, G. LABELLE and L. LAFOREST)

Several characteristic parameters of randomly grown quad trees of any dimension are analyzed. Additive parameters have expectations whose generating functions are expressible in terms of generalized hypergeometric functions.

A complex asymptotic process based on integral representations and singularity analysis, when applied to the hypergeometric forms, leads to explicit values for various structure constants related to path length, retrieval costs, and storage occupation.

Looking for a Needle in a Haystack or Protein Identification from the Molecular Weight of its Fragments

by GASTON GONNET

Proteins are broken down by enzymes according to predefined patterns. While it is not possible to determine the amino acid composition from a molecular weight, it is possible to match the weights of a digested protein against the theoretical digestion of all proteins in a database. This application is motivated strongly on the diagnosis of illnesses and disfunction from 2D gels. The proposed method of protein identification allows us to identify proteins from very small samples.

The main issue computationally is to define a distance function between the weights of the sample and an arbitrary vector of weights. Once this distance is defined we can compute the probability that the distance is less than a certain ε. By computing this ε for every protein in the database and computing the corresponding probability, we can isolate the proteins which have the lowest probability (most rare coincidence by chance) which are good candidates to answer our search.

This is currently implemented and working as an automatic e-mail server and in use by a wide community.

Average Case Analysis of the Algorithm of Hwang and Li

by WENCESLAS FERNANDEZ DE LA VEGA (joint work with M. SANTHA)

We derive an asymptotic equivalent to the average running time (number of comparisons) of the merging algorithm of Hwang and Lin applied on two linearly ordered lists of numbers $a_1 < a_2 \ldots < a_m$ and $b_1 < b_2 \ldots < b_n$ when m and n tend to infinity with the ratio $p = \frac{m}{n}$ kept constant. We show that the distribution of the running time concentrates around its expectation except when p is a power of 2. In this latter case, we obtain the expectation in closed form.

On Random Trees Arising in the Analysis of Scheduling Algorithms for Real-Time Systems

by ULRICH SCHMID

We surveyed some of our research on scheduling algorithms for real-time systems, when we investigated some deadline meeting properties of different scheduling algorithms employed with servicing probabilistically arriving tasks. Avoiding equilibrium assumptions the distribution of the duration S_T of the period where the system operates without violating any task's (fixed) service time deadline T is determined.

It turns out that S_T is always approximately exponentially distributed with a parameter $\lambda_T = \frac{1}{\mu_T}$ which depends on the particular scheduling algorithms. The mathematical treatment reveals a somewhat surprising relevance of certain random trees in that context. In fact, μ_T is determined by means of a combinatorial and asymptotic analysis of the underlying tree structure.

Average Case Analysis of Prediction

by JEFFREY VITTER (joint work with P. KRISHAN)

Prefetching of pages is an important mechanism for speeding up access time to data on secondary storage. In this talk we introduce universal prefetchers that are optimal in terms of page fault rate. Our novel approach is to use data compression techniques that are both theoretically optimal and good in practice. The motivating intuition is that in order to compress data effectively, you have to be able to predict future data well, and thus good data compressors should be able to predict well for purposes of prefetching. We show for powerful models such as Markov sources and mth-order Markov sources that the page fault rates incurred by our prefetching algorithms are optimal in the limit for almost all sequences of page accesses. Practical simulations using data bases and CAD traces show that moderate prefetching can reduce the page fault rate from around 80 – 100 percent to around 25 – 50 percent, better than currently used prefetchers.

We strengthen the result to the worst case and derive a randomized algorithm that we prove analytically converges almost surely to the optimal page fault rate in the worst case for every sequence, with respect to the class of finite state prefetchers. In particular we make no assumptions at all about how the sequence of page requests is generated. We also achieve the important computational goal of implementing our prefetcher in optimal constant expected time per prefetched page, using a novel application of the optimal and practical dynamic discrete random variate generator of Matias, Vitter and Ni.

Multivariate Analysis of Random Trees

by HOSAM MAHMOUD

We discuss the role of joint probability distributions of several random variables in the analysis of algorithms. Uniform binary trees, binary search trees, recursive trees, plane-oriented recursive trees and bucket multiway search trees growing under different memory management systems will serve as illustrating examples.

On the Analysis of the Skiplist

by HELMUT PRODINGER (joint work with P. KIRSCHENHOFER)

The skiplist was recently introduced by Pugh as an alternative data structure to search trees. We define the path length to be the sum over all search costs of all the elements in the skiplist. There are horizontal and vertical costs. The second ones are simple; the first ones require the study of

$$P^{=m}(z,y) = p(1-p)^{m-1} zy P^{<m}(z,y) P^{\leq m}(z,y)$$

and

$$P(z,y) := \lim_{m\to\infty} P^{\leq m}(z,y).$$

From this recurrence, we can derive asymptotic equivalents for the average and the variance. The variance of the path length is of order n^2, thus being worse than the variances for tries, Patricia tries and digital search trees.

On the Inner Structure of Multidimensional Binary Trees

by RAINER KEMP

Multidimensional binary trees represent a symbiosis of trees and tries, and they essentially arise in the construction of binary search trees for multidimensional keys. In this talk we first present a detailed average case analysis of d-dimensional binary trees including the number of such trees of given size, the size of certain substructures and the number of special nodes. Specializing these general results, we define two models: In "Model I", the total number of nodes (=number of all prefixes of the keys stored in the tree) is equal to n; in "Model II", the number of nodes corresponding to the d-th components of the keys (=number of the district keys stored in the tree) is equal to n.

In the first model, the average search time for the *last* component of a key is of order $\mathcal{O}(\sqrt{n})$, and for all other components only $o(1)$. In "Model II", the situation is quite different. In this alternative model, the average search time for the *first* component of a key is of order $\mathcal{O}(\sqrt{n})$ and for all other components only $\mathcal{O}(1)$. The reason for this fact is the result that a tree under "Model II" tends to a structure consisting of a collection of linear chains, on the average.

In the last part of this talk we generalize the classical one-to-one correspondence between (unlabelled) ordered trees with n nodes and (unlabelled) extended binary trees with $(2n-1)$ nodes to monotonically labelled ordered trees and d-dimendional (extended) binary trees.

Compact Random Multidimensional Binary Trees

by UWE TRIER

Multidimensional binary search trees, which have been considered by R. Kemp, can be represented in a compact form as directed acyclic graphs, in which - layer by layer - common subtrees are shared, being represented only once. We show that a random d-dimensional binary tree with n nodes in the last layer has a compacted form of expected size asymptotically $C_{d,1}\frac{n}{\sqrt{\log n}}$ in its first layer, where $C_{d,1}$ depends on the dimension d. The expected size of another layer $r > 1$ is at most a constant $C_{d,r}$, where $C_{d,r}$ depends on the dimension d and the layer index r.

Average Case Analysis of some "Arithmetical" Algorithms

by BRIGITTE VALLÉE (joint work with H. DAUDÉ)

We study "reduction" algorithms, which find minimal bases for $\mathcal{H}$-modules. In the two-dimensional case, this is Gauss' algorithm. Its average case complexity is asymptotically constant, equal to (together with Flajolet)

$$\beta = \frac{\pi}{4\zeta(4)}\sum_m \frac{1}{m^2}\sum_n \frac{1}{n^2},$$

where the second sum extends to all n with

$$\frac{1}{\Phi^2} \leq \frac{n}{m} \leq \frac{1}{\Phi},$$

and Φ is the golden ratio.

Moreover, it admits an exponential tail, and there exists a natural conjecture about this precise behaviour.

The Analysis of Heapsort

by ROBERT SEDGEWICK (joint work with R. SCHAFFER)

The running time of Heapsort for a random permutation is shown to be $\sim \frac{1}{2}N\log N$ in the best case and $\sim N\log N$ on the average. The best case result is shown by an explicit construction, and the average case by a short argument that establishes the fact that only an exponentially small number of cases can lead to more than $N\log N - N\log\log N - 4N$ steps.

Reliable Networks for Parallel Computing and Regular Graphs with Failures

by PAUL SPIRAKIS (joint work with M. YUNG, K. KALEM and Z. KEDEM)

We analyze the *expected* overhead needed to compute any given parallel algorithm in networks whose edges or nodes may fail. Especially, we consider the possible existence of many short vertex disjoint paths among all node pairs in the resulting networks after the failures have happened.

For the $G_{n,p}$-model of random graphs, we give the threshold (for p) which with high probability guarantees the existence of at most a logarithmic number of $\log(n)$-length paths for all node pairs. We also give the thresholds for the existence of many paths of length 3, or length 2, among all vertex pairs.

We furthermore consider the case where our network (before failures) is a random regular graph of degree r. We show that:

1) for *constant* edge failure probability $1-p$:
   a) if $r \geq a\log(n)$ (for some $a > 0$) then the "faulty" regular graph behaves as a $G_{n,p'}$, with $p' = \frac{rp}{n}$;
   b) if $r \leq \frac{1}{2}\sqrt{\log(n)}$ then the unreliable regular graph is almost surely disconnected.
2) for edge failure probability $\Theta(\frac{1}{n})$ the unreliable regular graph preserves the properties of random regular graphs, as far as connectivity is concerned.

Our analysis for regular random graphs is based on a new structure (random configurations) that we introduce.

For unreliable networks which with high probability guarantee the existence of $\Theta(\log(n))$ vertex-disjoint path of $\log(n)$-length among any vertex pair, we show that $\mathcal{O}(\log(n))$-size buffers in the nodes guarantee no overflow with high probability for the simulations of any EREW PRAM computation.

We also show how the treat node failures as well.

Experimental Combinatorics

by PAUL ZIMMERMANN (joint work with PH. FLAJOLET and B. VAN CUTSEM)

A systematic approach to the random generation of labelled combinatorial objects is presented. It applies to structures that are decomposable, i.e., formally specifiable by grammars involving set, sequence, and cycle constructions. A general strategy is developed for solving the random generation problem with two closely related types of methods: for structures of size n, the boustrophedonic algorithms exhibit a worst-case behaviour of the form $\mathcal{O}(n \log n)$; the sequential algorithms have worst case $\mathcal{O}(n^2)$, while offering good potential for optimizations in the average case. Both methods appeal to precomputed numerical tables of linear size.

Asymptotics for Lagrange Inversion

by RENZO SPRUGNOLI (joint work with C. VENI)

Let $\{c_n\}_{n\in\mathbb{N}}$ be a sequence defined by $c_n = [t^n]F(t)\Phi(t)^n$, where $F(t)$ and $\Phi(t)$ are analytic functions with $\Phi(0) \neq 0$. By the Lagrange Inversion Theorem we know that the generating function of the sequence is $\mathcal{G}\{c_n\} = C(t) = F(W)(1 - t\Phi'(W))^{-1}$, where $W = W(t)$ is the unique solution of the basic relation $W = t\Phi(W)$, such that $W(0) = 0$.

When $C(t)$ only has a finite number of poles or of algebraico-logarithmic singularities on the circle of convergence and $\Phi(t)$ and $F(t)$ behave well, we can find an asymptotic development for $C(t)$, and consequently for c_n, also if an explicit formula for $C(t)$ does not exist or is difficult to find.

The method consists in applying the theory of implicit functions to find the singularities of $W = W(t)$ and then to relate them to the singularities of $C(t)$. In principle, the method allows us to obtain an arbitrary number of terms of the asymptotic expansion of $C(t)$ around the dominating singularity.

Several examples are shown, ranging from elementary cases, to the Ramanujan Q-function and to functions related to the tree-function $T(t)$.

Edge Search in Hypergraphs of Bounded Rank

by INGO ALTHÖFER

Given a finite hypergraph H with vertex set X and (hyper)edge set E it is our task to find an unknown edge $e^* \in E$ by "yes/no"-questions of the following type: for each vertex set $Y \subset X$ we may ask "$e^* \subset Y$?"

For a given question scheme let $l(e)$ be the number of questions in case of $e^* = e$. Assume that the unknown edge e^* has been selected according to a known probability distribution P on E.

Theorem. There is a question scheme with $l(e) \leq \log_2 \frac{1}{p(e)} + c_r$ for all $e \in E$. The constant $c_r > 0$ depends only on the maximal size r of a hyperedge in H. □

As a corollary we get the following bounds for the average number $\overline{L}(H,P)$ of questions:

$$H(P) \leq \overline{L}(H,P) \leq H(P) + c_r.$$

Here

$$H(p_1,\ldots,p_m) = \sum_{i=1}^{m} p_i \log_2 \frac{1}{\pi}$$

is the information theoretic entropy function ($c_1 = 1$ is the statement of Shannon's Noiseless Coding Theorem).

Data Compression and Digital Trees

by WOJCIECH SZPANKOWSKI (joint work with PH. JACQUET)

The Lempel-Ziv parsing scheme is a fundamental construction on strings that finds a wide range of applications, most notably in data compression, algorithms on strings, statistical inference, complexity theory (cf. test of randomness), and so forth. It partitions a sequence of length n into variable phrases (blocks) such that a new block is the shortest substring not seen in the past as a phrase.

A natural question arises that is of fundamental importance: how many phrases M_n do we obtain from a sequence of length n? It is easy to see that $\Theta(\sqrt{n}) \le M_n \le \mathcal{O}(\frac{n}{\log n})$. It is further known that almost surely $M_n \sim \frac{nh}{\log n}$ (for large n), where h is the entropy of the alphabet. But, in many applications one needs more refined information about the deviation of M_n around its mean, that is, one requires second-order behaviour of M_n. Ideally, we would like to know the limiting distribution and the large deviation behaviour.

In this talk, we derive such characteristics for the memoryless source with *unequal* probabilities of symbol generation (the so-called asymmetric *Bernoulli model*). Thus, we extend and refine the analysis of Aldous and Shields who obtained the limiting distribution only for the *symmetric* Bernoulli model, that is, when symbols are generated with the same probability. More precisely, among others we prove that, appropriately normalized, the number of phrases M_n converges to a standard normal distribution. We also asymptotically enumerate the number of parsings of length n built from a given number of phrases, thus providing an answer to the problem of Gilbert and Kadota.

Travel Inside a Funny Complex Differential Equation

by PHILIPPE JACQUET (joint work with W. SZPANKOWSKI)

We introduce a nonlinear, differential, complex multivariate equation with differences, which arises in several problems such as digital trees and data compression analysis. We courageously bring to evidence asymptotic estimates about this equation: in short, the logarithm of the function exists and has polynomial behaviour in so-called polynomial cones. Consequence of these results is the limiting normal distribution of the external path length in digital trees. This talk is in continuation of Wojciech Szpankowski's talk.

Addendum: the equation is

$$\frac{\partial}{\partial z}h(z,u) = h(puz,u)h(quz,u), \;\; p,q > 0, \;\; p+q=1.$$

Problem Session

Problem 1:
by DONALD KNUTH

Is there a doubly infinite sequence of real numbers a_n, not all zero, such that

$$\sum_{k=0}^{\infty} \frac{a_{n-k}}{k!} = 0$$

for all integers n?

NOTE. *This problem was solved by Jacquet and Flajolet (August 1993).*

Problem 2:
by DONALD KNUTH

Explore the following "game-theoretic" approach to hypothesis testing:
A certain random process has n possible outcomes, and we have m hypotheses about its underlying distribution. Under hypothesis H_j, outcome k occurs with probability p_{jk}; thus we are given mn probabilites, with

$$p_{j1} + p_{j2} + \cdots + p_{jn} = 1, \quad 1 \le j \le m.$$

If an experiment is performed and has outcome k, we will guess that correct hypothesis is H_j, with probability P_{jk}. We want to maximize the greatest lower bound on the expectation that our guess is correct. This means we want to determine $mn+1$ nonnegative values P_{jk} and λ such that

$$\begin{aligned} P_{1k} + P_{2k} + \cdots + P_{mk} &= 1, \quad 1 \le k \le n, \\ p_{j1}P_{j1} + p_{j2}P_{j2} + \cdots + p_{jn}P_{jn} &\ge \lambda, \quad 1 \le j \le m, \end{aligned}$$

where λ is as large as possible (a special kind of linear programming problem).

Simple example with $m = 2$: H_1 says that a coin comes up heads with probability $\frac{1}{2}$, and H_2 says that it comes up heads with probability $\frac{2}{3}$. We flip the coin 5 times, so the probability of $0, 1, \ldots, 5$ heads is respectively

$$\tfrac{1}{32}, \tfrac{5}{32}, \tfrac{10}{32}, \tfrac{10}{32}, \tfrac{5}{32}, \tfrac{1}{32} \quad \text{under } H_1;$$

$$\tfrac{1}{243}, \tfrac{10}{243}, \tfrac{40}{243}, \tfrac{80}{243}, \tfrac{80}{243}, \tfrac{32}{243} \quad \text{under } H_2.$$

The unique optimum strategy is to guess H_1, if there are 0, 1, or 2 heads, H_2 if there are 4 or 5 heads, and H_1 with probability $\frac{1128}{2495}$ if there are 3 heads. Our guess is correct with probability $\lambda = \frac{320}{499}$.

If the same coin is flipped 500 times, the optimum strategy guesses H_1 when there are $k < 293$ heads, H_2 when $k > 293$, and H_1 with probability $\approx .0096$ when $k = 293$. This is correct with probability .9993 under both hypothesss.

Continuous generalizations of this approach might also be interesting.

Problem 3:
by HOSAM MAHMOUD

Solve the differential equation

$$\frac{\partial^b}{\partial z^b} A(z) = e^{A(z)}$$

subject to the initial conditions:

$$\frac{\partial^i}{\partial z^i} A(0) = 1, \ i = 1, \ldots, b.$$

The problem arises in enumerating bucket recursive trees, a generalization of recursive trees. The symbol b is a fixed parameter.

Problem 4:
by HOSAM MAHMOUD

A binary pyramid grows as follows:

A person founds a chain-letter. He then sells his letter to other participants. At each stage, all letter holders compete to sell their letters to the next enterant in the chain letter scheme, subject to the rule that a participant can sell at most two letters (thus the nodes of the underlying tree get saturated). All participants who are in a position to sell (i.e. all unsaturated nodes) have equal chance of selling the next letter. Find the average depth of a node in a random binary pyramid.

Problem 5:

by ROBERT TICHY

Let (F_k) be the sequence of Fibonacci numbers defined by $F_{k+2} = F_{k+1} + F_k$ with $F_0 = 1$ and $F_1 = 2$. Then any positive integer n can be represented in Zeckendorf representation $n = \sum_{k\geq 0} \varepsilon_k F_k$ with $\varepsilon_k \in \{0, 1\}$ and $\varepsilon_k\, \varepsilon_{k+1} = 0$.

D. Knuth has considered the "circle product" $\circ$ defined by

$$m \circ n := \sum_{k\geq 0} \sum_{j\geq 0} \varepsilon_k \delta_j F_{k+j+2},$$

where ε_k and δ_j are the Zeckendorf digits of n and m, respectively. He proved that $\circ$ is associative. The circle product can be generalized to higher order linear recurring sequences such as $F_{k+d}^{(d)} = F_{k+d-1}^{(d)} + \cdots + F_k^{(d)}$ ("Multinacci" numbers of order d).

Is it possible to find some constant c such that the corresponding circle product (for Multinacci numbers)

$$m \circ n = \sum_{k\geq 0} \sum_{j\geq 0} \varepsilon_k \delta_j F_{k+j+c}$$

remains associative?

Problem 6:

by GASTON GONNET

We propose a database, based on readable text, publicly available, that will contain descriptions and citations of algorithms. This database will be maintained by a group of editors. The editors have the copyright of the data (although it is distributed for free) to insure that any changes are properly incorporated. To become an editor, you should contribute 50 entries to the database.

Each entry contains: name, purpose, class/type, input, operations and their complexity, data structures used, implementability index, code (?), citations and comments.

The database is human readable as well as computer readable (a CFL parser is available). Typical distribution of this database will be through anonymous ftp.

Problem 7:
by PHILPPE FLAJOLET

Luc Devroye has used probabilistic arguments to show that the expected height of a random binary search tree over n nodes is asymptotic to $c \log n$, where c is Robson's constant ($c \approx 4.3$). The problem can be recast in analytic terms as follows. Let

$$y_{h+1}(z) \;:=\; 1 + \int_0^z y_h^2(t)dt, \quad y_0(z) = 0, \tag{1}$$

(so that $y_\infty(z) = \dfrac{1}{1-z}$). Then the generating function of average heights

$$H(z) \;:=\; \sum_{n=0}^{\infty} [y_\infty(z) - y_h(z)] \tag{2}$$

satisfies

$$H(z) \;\sim\; \frac{c}{1-z} \log \frac{1}{1-z}, \quad z \to 1^-. \tag{3}$$

The problem is to show this estimate in an extended area of the complex plane. Devroye's result follows from (3). A consequence of an analytic proof of (3) should be to derive estimates on the variance (the exact order is yet unknown) of height, and most probably also a limiting distribution result.

Problem 8:
by PAUL SPIRAKIS

Let $G(V,E)$ be a graph. For each linear ordering $L = \{1, 2, \ldots, n\}$ of its vertices we define the quantity $m(L) = \sum_{\{i,j\} \in E} |i - j|$.

Let $m = \min_L\{m(L)\}$ (minimum linear arrangement). Let L^* be the ordering achieving m. Furthermore, assume $G \in G_{n,p}$:

1) provide expected poly time algorithms to find such an L^* and m;

2) provide expected poly time algorithms to find L: $m(L) \leq (1 + \varepsilon)m$;

3) find the distribution of m (for various values of p).

Problem 9:
by INGO ALTHÖFER

Consider a finite undirected graph $G = (V, E)$. Let $U_1, \ldots, U_k$ be k arbitrary subsets of V. Let $E_i = \{e \in E | e \subset U_i\}$. For every $e \in E$ we define

$$g_i(e) = \begin{cases} |E_i|, & \text{if } e \in E_i \\ |E| - |E_i|, & \text{else} \end{cases}$$

and $\overline{g}(e) = \frac{1}{k} \sum_{i=1}^{k} g_i(e)$.

Questions are:

- is there a universal constant $c > 0$ such that $\overline{g}(e) \leq \frac{1}{2}|E| + c$ for every $e \in E$?
- if yes, what is the optimal value for c and how small can $k := k(G)$ be chosen?

Problem 10:
by INGO ALTHÖFER

Consider a binary rooted tree in which each node x has two labels $m(x) \in \mathbb{N}_{\neq 0}$ and $r(x) \geq 1$ (rational). Labels of neighbouring nodes obey the following conditions:

- if $m(x) = 1$, then x is a leaf
- if $m(x) > 1$, then x has two successors y_1, y_2 such that
  a) $m(y_1) + m(y_2) = m(x)$,
  b) $m(y_i) \leq \frac{1}{2}m(x) + m(x)^{1-\frac{1}{3r(x)}}$, for $i = 1, 2$,
  c) $\frac{m(y_1)}{m(x)} r(y_1) + \frac{m(y_2)}{m(x)} r(y_2) = r(x)$.

The tree has exactly $m := m(\text{root})$ leaves $l_1, \ldots, l_m$. Let $d(l_i) =$ be the distance of l_i from the root and $\overline{d} = \frac{1}{m} \sum_{i=1} m d(l_i)$.

Questions are:

- is there a function c such that $\overline{d} \leq \log_2 m + c(r)$ in every such tree with $m = m(\text{root})$?
- if yes, how fast has $c(.)$ to grow?

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