Algorithm Engineering Group

Site report 2004

The research activity of the group of Algorithm Engineering (AE) is concerned with the design, the engineering, the theoretical and experimental performance analysis of combinatorial algorithms for problems arising in modern Computer Systems and Networks, and in applications related to complex resource management problems. Our main research interests deal with the solution of optimization problems and the design of efficient data structures, with special emphasis on those applications involving large data sets. In particular we concentrate on:

1. algorithms that perform efficiently in a dynamically changing environment;
2. models and methodologies for the analysis and design of algorithms for information retrieval;
3. the efficient management of communication and information delivery and recovery in Wireless Networks and on the Internet;
4. the design and analysis of approximation algorithms for NP-hard optimization problems;
5. the design of on-line algorithms that work with incomplete information on the input instance;
6. the design and implementation of tools and platforms for the experimental analysis and visualization of the behavior of algorithms and data structures.

The achievements of the AE group are widely recognized. Giorgio Ausiello is Editor in Chief of Theoretical Computer Science, Series A, Algorithms and Complexity. He has also been awarded the title of 'Doctor Honoris Causa of Dauphine University'.

Members of the AE group are continuously involved in the Program and Steering Committees of prestigious International Conferences.

Giorgio Ausiello has been in the Selection Committee of the Goedel Prize during years 2003 - 2005. He is also involved in the Program Committee of the 32nd International Colloquium on Automata, Languages and Programming (ICALP'05).

Alberto Marchetti-Spaccamela has been member of the Steering Committee of the European Symposium on Algorithms and has been involved in the Program Committee of the 30th International Workshop on Graph-Theoretic Concepts in Computer Science (WG'04).

Stefano Leonardi has been involved in the Program Committees of the Workshop on Models and Algorithms for Planning and Scheduling Problems (MAPSP05), the 1st International Workshop on Algorithmic Aspects of Wireless Sensor Networks 2004, the 3rd International Conference on Fun with Algorithms (FUN04), the 21th International Symposium on Theoretical Aspects of Computer Science (STACS04), and the International Workshop on Self-* Properties in Complex Information Systems 2004. He is also Program Chair of the 13th Annual European Symposium on Algorithms (ESA'05) and has been Program Chair of the 3rd Workshop on Algorithms and Models for the Web-Graph (WAW 2004).

Camil Demetrescu has been involved in the Program Committees of the 12th European

Symposium on Algorithms 2004 (ESA'04) - Design and Analysis Track, the 9th Scandinavian Workshop on Algorithm Theory 2004 (SWAT'04), the 4th Workshop on Algorithmic Methods and Models for Optimization of Railways 2004 (ATMOS'04), and the 31st International Workshop on Graph-Theoretic Concepts in Computer Science (WG'05). He has also been invited to join the Steering Committee of the ACM-SIAM Workshop on Algorithm Engineering and Experiments (ALENEX) from 2005 to 2008 and has been Program Co-chair (with Roberto Tamassia) of the 7th Workshop on Algorithm Engineering and Experiments (ALENEX'05).

The AE group has recently organized several international scientific events. In particular, the group has organized the "45th Annual IEEE Symposium on Foundations of Computer Science" (FOCS'04) in Rome in October 2004. This is the first time in 44 years this prestigious symposium is held outside North America. In conjunction with FOCS, the group has also organized the "Workshop on Algorithms and Models for the Web" (WAW'04). Algorithmica devoted a special issue to papers presented during the ALGO 2002 event, held in Rome in September 2002, and organized by the Algorithmic group. This collection of papers on Approximation and On-line algorithms has been edited by Stefano Leonardi and appears in Algorithmica, volume 40, chapter "Approximation and On-line Algorithms".

A regular Seminar Program, the Interdepartmental Seminar on Algorithms (SIA), is also organized in cooperation with the Department of Computer Science of this University (see `http://www.dis.uniroma1.it/sia/`).

The AE group is currently cooperating with several prestigious research institutions: Max Planck für Informatik (Saarbrücken, Germany), CTI-Patras (Greece), ETH (Zurich, Switzerland), Université de Paris (Dauphine, France), Tel-Aviv University (Israel), AT&T - Research Labs (Florham Park, NJ, USA), ICSI-Berkeley (USA), Brown University (Providence, RI, USA), Microsoft Research (Mountain View, CA, USA).

The AE group is presently involved in the following research projects: EU IST "Approximation and On-line Algorithms (APPOL2)."; EU-RTN AMORE "Algorithmic Methods for Optimizing the Railways in Europe"; MIUR "Resource Allocation in Computer Networks"; MIUR National Project "Rete multimediale nell'evoluzione verso UTMS - Linea di ricerca Applicazione ai beni culturali"; EU-IST "Coevolution and self-organization in dynamical networks (COSIN)"; EU Contract 001907 "Dynamically Evolving Large Scale Information Sytems" (DELIS); MIUR National Project ALINWEB "Algorithmics for Internet and the Web"; FIRB National Projects - WEBMINDS and VICOM. A national committee of the MIUR has also approved a financial support of 1M-Euro in three years for the institution at the University of Rome "La Sapienza" of an *Excellence Centre* that aims at creating new scientific and technical synergies in the area of transportation and logistics. A major role in this project is played by the Algorithm Engineering group at DIS.

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Graphs and Combinatorial Algorithms. In [9] we present the first fully dynamic algorithm for maintaining all pairs shortest paths in directed graphs with real-valued edge weights. Given a dynamic directed graph G such that each edge can assume at most S different real values, we show how to support updates in $O(n^{2.5}\sqrt{S\log^3 n}\,)$ amortized time and queries in optimal worst-case time. This algorithm is deterministic: no previous fully dynamic algorithm was known before for this problem. In the special case where edge weights can only be increased, we give a randomized algorithm with one-sided error that supports updates faster in $O(S \cdot n \log^3 n)$ amortized time.

We also show how to obtain query/update trade-offs for this problem, by introducing two new families of randomized algorithms. Algorithms in the first family achieve an update bound of $\widetilde{O}(S \cdot k \cdot n^2)$ [1] and a query bound of $\widetilde{O}(n/k)$, and improve over the previous best known update bounds for k in the range $(n/S)^{1/3} \leq k < (n/S)^{1/2}$. Algorithms in the second family achieve an update bound of $\widetilde{O}\left(S \cdot k \cdot n^2\right)$ and a query bound of $\widetilde{O}(n^2/k^2)$, and are competitive with the previous best known update bounds (first family included) for k in the range $(n/S)^{1/6} \leq k < (n/S)^{1/3}$.

In [8] we study novel combinatorial properties of graphs that allow us to devise a completely new approach to dynamic all pairs shortest paths problems. Our approach yields a fully dynamic algorithm for general directed graphs with non-negative real-valued edge weights that supports any sequence of operations in $O(n^2 \log^3 n)$ amortized time per update and unit worst-case time per distance query, where n is the number of vertices. We can also report shortest paths in optimal worst-case time. These bounds improve substantially over previous results and solve a problem that has been open for over thirty years. Our algorithm is deterministic, uses simple data structures, and appears to be very fast in practice [17].

In [10] we present an algorithm for directed acyclic graphs that breaks through the $O(n^2)$ barrier on the single-operation complexity of fully dynamic transitive closure, where n is the number of edges in the graph. We can answer queries in $O(n^\epsilon)$ worst-case time and perform updates in $O(n^{\omega(1,\epsilon,1)-\epsilon} + n^{1+\epsilon})$ worst-case time, for any $\epsilon \in [0,1]$, where $\omega(1,\epsilon,1)$ is the exponent of the multiplication of an $n \times n^\epsilon$ matrix by an $n^\epsilon \times n$ matrix. The current best bounds on $\omega(1,\epsilon,1)$ imply an $O(n^{0.575})$ query time and an $O(n^{1.575})$ update time in the worst case. Our subquadratic algorithm is randomized, and has one-sided error. As an application of this result, we show how to solve single-source reachability in $O(n^{1.575})$ time per update and constant time per query.

In [29] we devise algorithms for maintaing dynamically graph spanners, i.e., sparse subgraphs that preserve the distances in the original graph within an approximation ratio. In

[1] Throughout this report, we use $\widetilde{O}(f(n))$ to denote $O(f(n)\mathrm{polylog}(n))$.

particular, we show how to maintain a spanner with $O(n^{3/2})$ edges in an unweighted undirected graph with n vertices in $O(n)$ time per edge insertion or edge deletion, amortized over a sequence of $\Omega(n)$ operations. Distances are maintained within a factor of 3 of the distances in the original graph (3-spanner). Recently [36], the work has been extended to maintain a 5-spanner with $O(n^{4/3})$ edges.

In [34] we propose a dynamic shortest path algorithm for an application on computing statistical properties of networks subject to path distance minimization. The graph under assumption is undirected, unweighted and has a dynamic topology, e.g., at any time arcs can be inserted to or removed from the current topology.

In [35] we address the issue of assigning OSPF weights and multiplicities to each arc, aiming to design efficient OSPF networks with minimum total cost needed to route the required demand and handle any single arc or router failure. We propose an evolutionary algorithm for this problem, and present results applying it to several real-world problem instances.

In [26, 27] we survey the main techniques developed in the literature for the maintenance of dynamic trees and dynamic graphs.

Algorithms for the Web. The main goal of this research line is to analyze the structure and to measure the properties of the directed graph induced by the Web hyperlinked structure comprised by the html pages and the links among them. Because of the rapid pace at which the real Webgraph is growing over the time, it is necessary to develop and use collection of routines that are able to deal with massive graphs stored in files in secondary memory. Our main contribution, in the first part of the last year, was the implementation of such a library of routines [31]. Our routines are able to generate graphs according to many of the random models presented in literature in order to reproduce properties of the real Webgraph. In order to measure such properties, we also provide programs that can measure these graphs (the ones generated according to known models) as well as real samples of the Webgraph. We present a "multifile" format to represent graphs in secondary memory; we include routines that convert some graph-file formats from/to our .ips multifile format. Binaries and source code of all the program of this library are freely downloaded from the European Research Project Cosin website; to compile them the gcc compiler version ≥ 2.9 and linux operating system are needed. The library has been tested with graphs up to 2 billion edges.

This library allows us to conduct an experimental study of the large scale properties of web graphs on a large crawl from 2001 of 200M pages and about 1.4 billion edges made available by the WebBase project at Stanford. We report our experimental findings on the topological properties of such a graph, such as the number of bipartite cores and the distribution of degrees, PageRank values, and strongly connected components in [11]. Moreover we were able to compare the features of many of the models that have been proposed so far in the literature and analyze the differences with the real WebBase sample [12]. Most of the results of our measurements, with a panoramic view of the stochastic graph models and the algorithmic challenges that such a huge structure poses, are summarized in [20].

We also observed that the *bow-tie* structure of the Web revealed by Broder et al. is a relatively clear abstraction of the macroscopic picture of the Web graph, but it is very uninformative with respect to the finer details of the Web graph. In order to mine the inner structure of the bow-tie, we introduce some other statics. These new measurements allowed us to understand better the structure of the single components of the *bow-tie*. The *daisy* picture for the Webgraph that emerges from this experimental study is presented in [30].

The last part of our work consists of a theoretical analysis of the Link Analysis Ranking Algorithm with emphasis on the properties of stability and similarity of well-designed ranking algorithm. These properties were first introduced and studied by Borodin et al. In [33], we prove that on a broad class of random graphs (a) the HITS algorithm is stable with high probability, and (b) the HITS algorithm is similar to the InDegree algorithm, the simple heuristic that assigns to each node weight proportional to the number of incoming links.

Our experimental studies confirm the presence of power laws with coefficients 2.1 in most of the properties we analyzed. The main problem we have to face is the lack of fresh samples of the Webgraph. For instance, we observed a different percentage composition of the WebBase bow-tie component if compared with previous measurements of Broder. However, due to the lack of newer crawls, we are not able to conjecture if the same measures won't be repeated on more recent and bigger samples.

Algorithms for Optimization and Games. In [5] we have introduced the notion of smoothed competitive analysis of online algorithms. Smoothed analysis has been proposed by Spielman and Teng to explain the behaviour of algorithms that work well in practice while performing very poorly from a worst case analysis point of view. We apply this notion to analyze the Multi-Level Feedback (MLF) algorithm to minimize the total flow time on a sequence of jobs released over time when the processing time of a job is only known at time of completion. The initial processing times are integers in the range $[1..2^K]$ and they are smoothened by changing the k least significant bits under a quite general class of probability distributions. We show that MLF admits a smoothed competitive ratio that exponentially decreases as the variance of the distribution increases. A direct consequence of our result is also the first average case analysis of MLF. We show a constant expected ratio of the total flow time of MLF to the optimum under several distributions including the uniform distribution.

In [3] we study a randomized version RMLF of the MLF algorithm described above. We prove that this randomized version of the Multi-level Feedback algorithm is competitive for single and parallel machine systems, in our opinion providing another theoretical validation of the goodness of an idea that has proven effective in practice along the last two decades.

In [6] we study the problem of scheduling parallel machines online, allowing preemptions while disallowing migration of jobs that have been scheduled on one machine to another. For a given job, we measure the quality of service provided by an algorithm by the *stretch* of the job, defined as the ratio between the amount of time spent by the job in the system (the *response time*) and its processing time. The scheduling goal is to minimize the average stretch.

We prove an $O(1)$ competitive ratio for this problem. Our result shows that migration is not necessary to be competitive for minimizing average stretch; in contrast, we prove that preemption is essential, even if randomization is allowed.

In [4] we explore the quality of service (QoS) that is achievable by *semi-clairvoyant* online scheduling algorithms, which are algorithms that only require approximate knowledge of the initial processing time of each job, on a single machine. We give a semi-clairvoyant algorithm that is $O(1)$-competitive with respect to average flow time on one single machine. We also show a semi-clairvoyant algorithm on parallel machines that achieves up to contant factors the best known competitive ratio.

It is known that the clairvoyant algorithm SRPT is optimal with respect to average flow time and is 2-competitive with respect to average stretch. Thus it is possible for a clairvoyant algorithm to be simultaneously competitive in both average flow time and average stretch. In contrast we show that no semi-clairvoyant algorithm can be simultaneously $O(1)$-competitive with respect to average stretch and $O(1)$-competitive with respect to average flow time. Thus in this sense one might conclude that the QoS achievable by semi-clairvoyant algorithms is not competitive with clairvoyant algorithms.

In [2] we consider downlink scheduling in next generation 3G/4G wireless data networks. These allow multiple codes (or channels) to be allocated to a single user, where each code can support multiple data rates. Providing fine-grained QoS to users in such networks poses the two dimensional challenge of assigning *both* power (rate) and codes to every user. We abstract general downlink scheduling problems suitable for proposed next generation wireless data systems. Our contribution includes a communication-theoretic model for multirate wireless channels. In addition, while conventional focus has been on throughput maximization, we attempt to optimize the maximum response time of jobs, which is more suitable for streams of user requests. We are able to provide very simple, online algorithms for approximating the optimal maximum response time. We also perform an experimental study with realistic data of channel conditions and user requests that strengthens our theoretical results.

In [15] we explore the effects of locality on the performance of paging algorithms. Traditional competitive analysis fails to explain important properties of paging assessed by practical experience. In particular, the competitive ratios of paging algorithms that are known to be efficient in practice (e.g. LRU) are as poor as those of naive heuristics (e.g. FWF). It has been recognized that the main reason for these discrepancies lies in an unsatisfactory modelling of locality of reference exhibited by real request sequences. We propose an adversarial model in which the probability of requesting a page is also a function of the page's age. In this way, our approach allows to capture the effect of locality of reference. We consider several families of distributions and we prove that the competitive ratio of LRU becomes constant as locality increases, as expected. We also prove that the performance of FWF rapidly degrades as locality increases, while the converse happens for LRU.

In [16] we consider the *multicommodity rent-or-buy* (MROB), in which we are given a network together with a set of k terminal pairs. The goal is to provision the network so that a given amount of flow can be shipped between all terminal pairs simultaneously.

In order to provision the network one can either *rent* capacity on edges at some cost per unit of flow, or *buy* them at some larger fixed cost. Bought edges have no incremental, flow-dependent cost. The overall objective is to minimize the total provisioning cost. In this paper we give a 5.5-approximation for the MROB problem by refining the algorithm of Gupta et al. and greatly simplifying their analysis. The improvement in our paper is based on a more careful adaptation and simplified analysis of the primal-dual algorithm for the Steiner forest problem due to Agrawal, Klein and Ravi. Our result significantly reduces the gap between the single-sink and multi-sink cases.

In [1] we consider the Quota Traveling Salesman Problem. This is a generalization of the well known Traveling Salesman Problem. The goal of the traveling salesman is, in this case, to reach a given *quota* of sales, minimizing the amount of time. In this paper we address the on-line version of the problem, where requests are given over time. We present algorithms for various metric spaces, and analyze their performance in the usual framework of competitive analysis. In particular we present a 2-competitive algorithm that matches the lower bound for general metric spaces. In the case of the halfline metric space, we show that it is helpful not to move at full speed, and this approach is also used to derive the best on-line polynomial time algorithm known so far for the On-Line TSP (in the homing version).

In [14] we present an overview of several on-line optimization problems which involve exploration or chasing, in the framework of metrical service systems.

Two chapters of the handbook "Optimization Combinatoire" have also been prepared, one concerning approximation preserving reductions [25] and one on on-line algorithms [24].

In [21] we design an approximately budget-balanced and group-strategyproof cost-sharing mechanism for the Steiner forest game. An instance of this game consists of an undirected graph $G = (V, E)$, non-negative costs c_e for all edges $e \in E$, and a set $R \subseteq V \times V$ of k terminal pairs. Each terminal pair $(s, t) \in R$ is associated with an agent that wishes to establish a connection between nodes s and t in the underlying network. A feasible solution is a forest F that contains an s, t-path for each connection request $(s, t) \in R$. Previously, Jain and Vazirani gave a 2-approximate budget-balanced and group-strategyproof cost-sharing mechanism for the Steiner tree game — a special case of the game considered here. Such a result for Steiner forest games has proved to be elusive so far, in stark contrast to the well known primal-dual $(2 - 1/k)$-approximate algorithms for the problem. The cost-sharing method presented in this paper is 2-approximate budget-balanced and this is tight with respect to the budget-balance factor.

In [13] we present cost sharing methods for connected facility location games that are cross-monotonic and competitive and that recover a constant fraction of the cost of the constructed solution. The novelty of this paper is that we use randomized algorithms and that we share the expected cost among the participating users. As a consequence, our cost sharing methods are simple and achieve attractive approximation ratios. We also provide a primal-dual cost sharing method for the connected facility location game with opening costs.

In [32] we consider the problem of Internet switching, where traffic is generated by selfish users. We study a packetized (TCP-like) traffic model, which is more realistic than the widely used fluid model. We assume that routers have First-In-First-Out (FIFO) buffers of bounded capacity managed by the drop-tail policy. The utility of each user depends on its transmission rate and the congestion level. Since selfish users try to maximize their own utility disregarding the system objectives, we study Nash equilibria that correspond to a steady state of the system. We quantify the degradation in the network performance called the price of anarchy resulting from such selfish behavior.

We show that for a single bottleneck buffer, the price of anarchy is proportional to the number of users. Then we propose a simple modification of the Random Early Detection (RED) drop policy, which reduces the price of anarchy to a constant. We demonstrate that a Nash equilibrium can be reached if all users deploy TCP Vegas as their transport protocol. We also consider some natural extensions of our model including the case of multiple Quality of Service (QoS) requirements, routing on parallel links and general networks with multiple bottlenecks.

Using idle times of the processors is a well-known approach to run coarse grained parallel algorithms for extremely complex problems. In [22] we present on-line algorithms for scheduling the processes of a parallel application that is known off-line on a dynamic network in which the idle times of the processors are dictated by an adversary. We also take communication and synchronization costs into account.

Our first contribution consists of a formal model to restrict the adversary in a reasonable way. We then show a constant factor approximation for the off-line scheduling problem. As this problem has to take communication cost into account, it can be seen as a generalization of many NP-hard parallel machine scheduling problems. Finally, we present on-line algorithms for different models with constant or with "nearly constant" competitive ratio.

Experimentation, visualization and applications. Directors are reactive systems that monitor the run-time environment and react to the emitted events. Typical examples of directors are debuggers and tools for program analysis and software visualization. In [18] we describe a cross-platform virtual machine that provides advanced facilities for implementing directors with low effort.

In [7], we describe Leonardo Web, a collection of tools for building animated presentations that can be useful for teaching, disseminating, and e-learning. Presentations can be created via the combined use of a visual editor and a Java library. The library allows it to generate animations in a batch fashion directly from Java code according to an imperative specification style. Batch-generated animations can then be refined and customized using the editor. Presentations can be finally viewed with a simple Java player, which ships both as a stand-alone application for off-line deployment and as a Java applet embedded in a Web page. The player supports step-by-step and continuous execution, reversibility, speed selection, and smooth animation.

In [17], we present the results of an extensive computational study on dynamic algorithms for all pairs shortest path problems. We describe our implementations of the recent dynamic algorithms of King and of Demetrescu and Italiano, and compare them to the dynamic algorithm of Ramalingam and Reps and to static algorithms on random, real-world and hard instances. Our experimental data suggest that some of the dynamic algorithms and their algorithmic techniques can be really of practical value in many situations.

In [19], we report on our own experience in studying a fundamental problem on graphs: all pairs shortest paths. In particular, we discuss the interplay between theory and practice in engineering a simple variant of Dijkstra's shortest path algorithm. In this context, we show that studying heuristics that are efficient in practice can yield interesting clues to the combinatorial properties of the problem, and eventually lead to new theoretically efficient algorithms.

In [23] we describe the status of an on-going research on Architectural and Building Collaborative Design - a joint effort of experts of various disciplines. The resulting framework concerns mainly the architectural and building design, but the main ideas apply also to other contexts where heterogeneous project teams are involved in a cooperative design effort. Among the main issues, a special attention devoted to: *(i)* an integrated model of the structure of the networked architectural design process (operators, activities, phases and resources), *(ii)* the required knowledge and constraints (distributed and functional to the operators and the process phases), and *(iii)* the algorithms for the maintenance of the consistency of the project which is going to be built within the provided constraints.

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