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Arnold L. Rosenberg
Alan L. Selman (Eds.)

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Essays in Memory of Shimon Even

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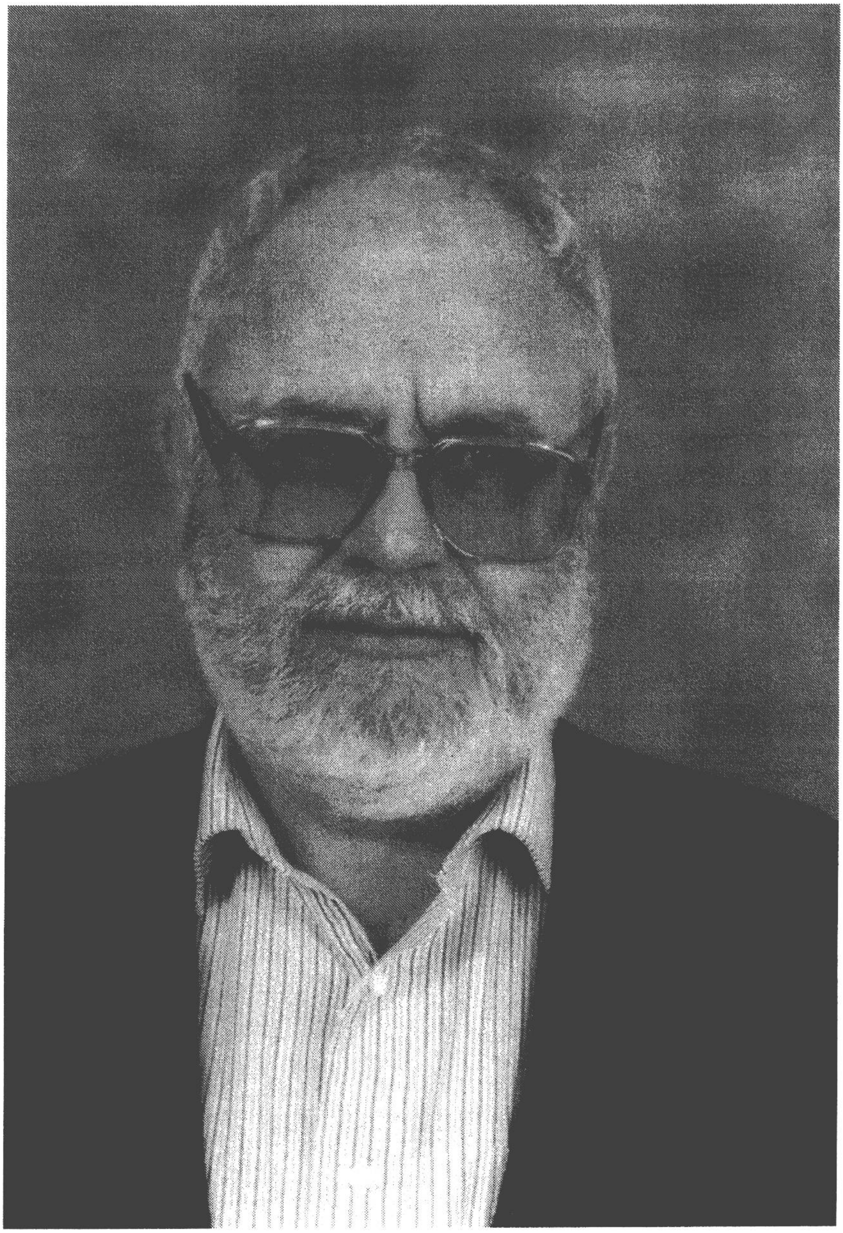

Shimon Even (1935–2004)

Preface

On May 1, 2004, the world of theoretical computer science suffered a stunning loss: Shimon Even passed away. Few computer scientists have had as long, sustained, and influential a career as Shimon.

Shimon Even was born in Tel-Aviv in 1935. He received a B.Sc. in Electrical Engineering from the Technion in 1959, an M.A. in Mathematics from the University of Northern Carolina in 1961, and a Ph.D. in Applied Mathematics from Harvard University in 1963. He held positions at the Technion (1964–67 and 1974–2003), Harvard University (1967–69), the Weizmann Institute (1969–74), and the Tel-Aviv Academic College (2003-04). He visited many universities and research institutes, including Bell Laboratories, Boston University, Cornell, Duke, Lucent Technologies, MIT, Paderborn, Stanford, UC-Berkeley, USC and UT-Dallas.

Shimon Even played a major role in establishing computer science education in Israel and led the development of academic programs in two major institutions: the Weizmann Institute and the Technion. In 1969 he established at the Weizmann the first computer science education program in Israel, and led this program for five years. In 1974 he joined the newly formed computer science department at the Technion and shaped its academic development for several decades. These two academic programs turned out to have a lasting impact on the evolution of computer science in Israel.

Shimon Even was a superb teacher, and his courses deeply influenced many of the students attending them. His lectures, at numerous international workshops and schools, inspired a great number of students and researchers. His books, especially his celebrated *Graph Algorithms*, carried his educational message also to computer scientists who were not fortunate enough to meet him in person. As a mentor to aspiring researchers, Shimon was almost without peer, nurturing numerous junior researchers and advising many graduate students, who went on to have their own successful research careers.

Shimon Even was a pioneer in the areas of graph algorithms and cryptography, and his research contributions to these areas influenced the course of their development. Shimon was famous for not confining his interests to a few topics, but choosing rather to work in such diverse areas as switching and automata theory, coding theory, combinatorial algorithms, complexity theory, distributed computing, and circuit layout. In each of these areas, he produced high-quality, innovative research for more than four decades.

Shimon was the purest of pure theoreticians, following his nose toward research problems that were "the right" ones at the moment, not the faddish ones. His standards were impeccable, to the point where he would balk at employing any result whose proof he had not mastered himself. His integrity was unimpeachable: he would go to great lengths to defend any principle he believed in.

Shimon had a great passion for computer science as well as a great passion for truth. He valued simplicity, commitment to science, natural questions and carefully prepared expositions. By merely following his own way, Shimon influenced numerous researchers to adopt his passions and values. We hope that this is reflected in the current volume.

This volume contains research contributions and surveys by former students and close collaborators of Shimon. We are very pleased that Reuven Bar-Yehuda, Yefim Dinitz, Guy Even, Richard Karp, Ami Litman, Yehoshua Perl, Sergio Rajsbaum, Adi Shamir, and Yacov Yacobi agreed to send contributions. In accordance with Shimon's style and principles, the focus of these contributions is on addressing natural problems and being accessible to most researchers in theoretical computer science. The contributions are of three different types, reflecting three main scientific activities of Shimon: original research, technical surveys, and educational essays.

The Contributions

The contributions were written by former students and close collaborators of Shimon. In some cases the contributions are co-authored by researchers who were not fortunate enough to be close to Shimon or even to have met him in person. Below we comment on particular aspects of each contribution that we believe Shimon would have appreciated.

Original Research

Needless to say, everybody likes original research, and Shimon was no exception. We believe that Shimon would have been happy with the attempt to make these research contributions accessible to a wide range of researchers (rather than merely to experts in the area). In order to promote this goal, these contributions were reviewed both by experts and by non-experts.

- P. Fraigniaud, D. Ilcinkas, S. Rajsbaum and S. Tixeuil: *The Reduced Automata Technique for Graph Exploration Space Lower Bounds.* Shimon liked connections between areas, and the areas of graph algorithms and of automata theory were among his favorites.
- O. Goldreich: *Concurrent Zero-Knowledge with Timing, Revisited.* Shimon would have joked at Oded's tendency to write long papers.
- R.M. Karp: *Fair Bandwidth Allocation Without Per-Flow State.* Shimon would have like the fact that the starting point of this work is a practical problem, and that it proceeds by distilling a clear computational problem and resolving it optimally.
- R.M. Karp, T. Nierhoff and T. Tantau: *Optimal Flow Distribution Among Multiple Channels with Unknown Capacities.* This paper has the same flavor as the previous one, and Shimon would have liked it for the very same reason.

- A. Litman: *Parceling the Butterfly and the Batcher Sorting Network.* Shimon would have liked the attempt to present a new complexity measure that better reflects the actual cost of implementations.
- X. Zhou, J. Geller, Y. Perl, and M. Halper: *An Application Intersection Marketing Ontology.* Shimon would have liked the fact that simple insights of graph theory are used for a problem that is very remote from graph theory.
- R.L. Rivest, A. Shamir and Y. Tauman: *How to Leak a Secret: Theory and Applications of Ring Signatures.* Shimon would have like the natural ("daily") problem addressed in this paper as well as the elegant solution provided to it.
- O. Yacobi with Y. Yacobi: *A New Related Message Attack on RSA.* Shimon would have enjoyed seeing a father and son work together.

Technical Surveys

Shimon valued the willingness to take a step back, look at what was done (from a wider perspective), and provide a better perspective on it. We thus believe that he would have been happy to be commemorated by a volume that contains a fair number of surveys.

- R. Bar-Yehuda and D. Rawitz: *A Tale of Two Methods.* Shimon liked stories, and he also liked the techniques surveyed here. Furthermore, he would have been excited to learn that these two techniques are in some sense two sides of the same coin.
- Y. Dinitz: *Dinitz' Algorithm: The Original Version and Even's Version.* Shimon is reported to have tremendously enjoyed Dinitz's lecture that served as a skeleton to this survey.
- C. Glaßer, A.L. Selman, and L. Zhang: *Survey of Disjoint NP-pairs and Relations to Propositional Proof Systems.* This survey focuses on one of the applications of promise problems, which was certainly unexpected in 1984 when Shimon Even, together with Alan Selman and Yacov Yacobi, introduced this notion.
- O. Goldreich: *On Promise Problems.* This survey traces the numerous and diverse applications that the notion of promise problems found in the two decades that have elapsed since the invention of the notion.
- G. Malewicz and A.L. Rosenberg: *A Pebble Game for Internet-Based Computing.* Shimon liked elegant models, and would have been interested to see pebble games used to model an Internet-age problem.

Educational Essays

Shimon liked opinionated discussions and valued independent opinions that challenge traditional conventions. So we are sure he would have enjoyed reading these essays, and we regret that we cannot have his reaction to them.

- G. Even: *On Teaching Fast Adder Designs: Revisiting Ladner & Fischer.* Shimon would have been very proud of this insightful and opinionated exposition of hardware implementations of the most basic computational task.
- O. Goldreich: *On Teaching the Basics of Complexity Theory.* Shimon would have appreciated the attempt to present the basics of complexity theory in a way that appeals to the naive student.
- A.L. Rosenberg: *State.* Shimon would have supported the campaign, launched in this essay, in favor of the Myhill-Nerode Theorem.

December 2005

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The Reduced Automata Technique for Graph Exploration Space Lower Bounds*

Pierre Fraigniaud[1] **, David Ilcinkas[2] **, Sergio Rajsbaum[3] ***, and
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Abstract. We consider the task of exploring graphs with anonymous nodes by a team of non-cooperative robots, modeled as finite automata. For exploration to be completed, each edge of the graph has to be traversed by at least one robot. In this paper, the robots have no a priori knowledge of the topology of the graph, nor of its size, and we are interested in the amount of memory the robots need to accomplish exploration, We introduce the so-called *reduced automata technique*, and we show how to use this technique for deriving several space lower bounds for exploration. Informally speaking, the reduced automata technique consists in reducing a robot to a simpler form that preserves its "core" behavior on some graphs. Using this technique, we first show that any set of $q \geq 1$ non-cooperative robots, requires $\Omega(\log(\frac{n}{q}))$ memory bits to explore all n-node graphs. The proof implies that, for any set of q K-state robots, there exists a graph of size $O(qK)$ that no robot of this set can explore, which improves the $O(K^{O(q)})$ bound by Rollik (1980). Our main result is an application of this latter result, concerning *terminating* graph exploration with one robot, i.e., in which the robot is requested to stop after completing exploration. For this task, the robot is provided with a pebble, that it can use to mark nodes (without such a marker, even terminating exploration of cycles cannot be achieved). We prove that terminating exploration requires $\Omega(\log n)$ bits of memory for a robot achieving this task in all n-node graphs.

* A preliminary version of this paper appears in the proceedings of the 12th International Colloquium on Structural Information and Communication Complexity (SIROCCO), Mont Saint-Michel, France, May 24-26, 2005, as part of [13].

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1 Introduction

The problem of exploring an unknown environment occurs in a variety of situations, like robot navigation, network maintenance, resource discovery, and WWW search. In these situations the entities performing exploration can be either a physical mobile device or a software agent. In this paper, we restrict our attention to the case where the environment in which the mobile entities are moving is modeled as a graph. At an abstract level, graph exploration is the task where one or more mobile entities, called *robots* in this paper, are trying to collectively traverse every edge of a graph. In addition to the aforementioned applications, graph exploration is important due to its strong relation to complexity theory, and in particular to the undirected *st*-connectivity (USTCON) problem (cf., e.g., [6]). Given an undirected graph G and two vertices s and t, the USTCON problem is to decide whether s and t are in the same connected component of G. The directed version of the problem is denoted STCON. It is known that STCON is complete for NL, the class of non-deterministic log-space solvable problems. Whether USTCON is complete for L, the class of problems solvable by deterministic log-space algorithms, has been a challenging open problem for quite a long time, and it is only very recently that Reingold proved that USTCON is indeed complete for L [15]. Note that the existence of a finite set of finite-state automata able to explore all graphs would have put USTCON in L, and proving or disproving this existence had therefore motivated quite a long sequence of studies. Cook and Rackoff [6] eventually proved that even a more powerful machine, called JAG, for "Jumping Automaton for Graphs", cannot explore all graphs (a JAG is a finite set of globally cooperative finite-state automata enhanced with the ability, for every automaton, to "jump" from its current position to any node occupied by another automaton). Since this latter result, the exploration graph problem is focussing on determining the space complexity of robots able to explore all graphs.

As far as upper bounds in concerned, Reingold showed in [15] that his log-space algorithm for USTCON implies the existence of log-space constructible *universal exploration sequences* (UXS) of polynomial length. Roughly speaking, a UXS [14] is a sequence of integers that (1) tell a robot how to move from node to node in a graph (the exit port at the kth step of the traversal is obtained by adding the kth integer of the UXS to the entry port), and (2) guarantee to explore every node of a graph of appropriate size (a UXS is defined for a given size, and a given degree). Rephrasing this latter result, there is a $O(\log n)$-space robot that explores all the graphs of size n. The extend to which this bound can be decreased by using a set of $q > 1$ cooperative robots remains open. Also, the question of the existence of log-space constructible *universal traversal sequences* (UTS) [1] remains open (a UTS is a sequence of port-numbers so that the output port at the kth step of the traversal is the kth element of the sequence).

As far as lower bounds are concerned, most papers are dealing with the design of small *traps* for arbitrary teams of robots, i.e., small graphs that no robot of the team can explore. (Formally, a trap consists of a graph and a node from where the robots start the exploration.) The first trap for a finite state robot is generally attributed to Budach [5] (the trap is actually a planar graph). The trap constructed by Budach is however of large size, and a much smaller trap was described in [12] which proved that, for any K-state robot, there exists a trap of at most $K + 1$ nodes. In [16], Rollik proved that no finite set of finite locally-cooperative automata, i.e., automata that exchange information only when they meet at a node, can explore all graphs. In the proof of this result, the author uses as a tool a trap for a set of q non-cooperative K-state robots (such robots may have different transition functions, hence they will follow different paths in the explored graph). This latter trap is of size $O(K^{O(q)})$ nodes. Rollik's trap for cooperative robots is even larger: $\tilde{O}(K^{K^{\cdot^{\cdot^{\cdot^{K}}}}})$ nodes, with $2q + 1$ levels of exponentials where the $\tilde{O}$ notation hides logarithmic factors. In this paper, we present a new lower bound technique for graph exploration, called *reduced automata technique*. Roughly, this technique consists in reducing a robot to a simpler form that preserves its "core" behavior on some graphs: except for some easily described closed paths, the reduced robot follows the path of the original robot, on any such graph.

The interested reader can find other pointers to the literature in, e.g., [3–5, 7, 8, 12]. To complete the picture, and before describing our results in more details, let us point out that Shimon Even, whom this book is dedicated to, was interested in graph exploration problems early on in his career. In particular, in his 1976 seminal paper with Tarjan [11], he presented a way of numbering nodes during a DFS traversal that proved to be useful in many algorithms. In collaboration with A. Litman and P. Winkler [10], he then studied traversal in directed networks. With G. Itkis and S. Rajsbaum [9], he described a traversal strategy for undirected graphs that constructs a subgraph with good connectivity but few edges. And recently, in collaboration with S. Bhatt, D. Greenberg, and R. Tayard [2], he studied the problem of using a robot as simple as possible (with access to some local memory stored in the vertices) to find an Eulerian cycle in mazes and graphs.

1.1 Problem Settings

As in [6, 16], we are interested in exploration of undirected graphs where nodes are not uniquely labeled. Note that, besides the theoretical interest of understanding when or at what cost such graphs can be explored, the unlabeled-node setting can occur in practice, due to, e.g., privacy concerns, limited capabilities of the robots, or simply anonymous edge intersections. The robots, modeled as a deterministic automata, can however identify the edges incident to a node through unique port labels, from 1 to the degree of the node. We consider two types of exploration:

- Perpetual exploration, in which the task of the robots is to, eventually, traverse all edges.
- Terminating exploration, in which the robots, after completing exploration, must eventually stop.

In acyclic graphs, terminating exploration is strictly more difficult than perpetual exploration. In particular, it is shown in [7] that terminating exploration in n-node bounded degree trees requires a robot with memory size $\Omega(\log\log\log n)$, whereas perpetual exploration is possible with $O(1)$ bits. In arbitrary graphs, terminating exploration cannot be achieved. Indeed, it is easy to see that a robot can traverse all edges of some graphs, say a cycle, but that it cannot recognize when it has visited a node twice, because nodes are not uniquely labeled. That is, there are graphs that a robot can explore perpetually, but it can never stops. Thus, as in previous work in this setting, e.g., [3,4,8], we assume that, for terminating exploration, robots can mark nodes: a robot can drop a pebble in a node and later identify it and pick it up.

Following the common conventions in the literature, the robots aiming at performing perpetual exploration are not given pebbles, whereas robots aiming at performing terminating exploration are given one or more pebbles. As a consequence, the two problems becomes incomparable. Indeed, terminating exploration is more demanding than perpetual exploration, but the "machines" designed for these two tasks do not have the same power.

A *team* of robots is a set of deterministic automata with possibly different transition functions, all starting from the same starting point. When sets or teams of robots are considered, the robots of a team can communicate in various manners. Four cases are considered in the literature:

- Non-cooperative robots: the robots are oblivious of each other, and each of them acts independently from the others.
- Locally cooperative robots: robots meeting at a node can exchange information, including their identities and their current states.
- Globally cooperative robots: the robots are perpetually aware of the states of the others, of whether they meet and who they meet, and of the degrees of the nodes occupied by the robots.
- Jumping Automaton: the robots are globally cooperative, and any robot is able to jump from the node it is currently occupying to a node currently occupied by any other robot.

In this paper, we restrict our attention to the two weakest models: non-cooperative robots, and locally cooperative robots.

1.2 Our Results

In this paper, we present a new lower bound technique for graph exploration, called *reduced automata technique*. Based on this technique, the lower bounds presented in this paper are obtained as follows. Assume a set of q robots is given. Then construct the smallest possible graph, called a *trap* for this set of robots, such that if the robots are placed in some specified nodes of the graphs, then there is at least one edge that is not traversed by any of the robots. If the q robots have K states each, and the trap has $f_q(K)$ nodes, then the space lower bound for a set of q robots exploring all n-node graphs is $\Omega(\log f_q^{-1}(n))$ bits.