Dedicated to

Boris (Boaz) Trakhtenbrot

in honor of his eighty-fifth birthday,
with deep admiration and affection.

A mighty man of valor . . . his name was Boaz
איש מבור חל ... חש מש
(Book of Ruth, 2:1)

Wishing him many,
many happy returns.
Boris Abramovich Trakhtenbrot
(b. 1921)
Preface

The Person

Boris Abramovich Trakhtenbrot1 (Борис Абрамович Трахтенброт) – his Hebrew given name is Boaz (בעז) – is universally admired as a founding father and long-standing pillar of the discipline of computer science. He is the field’s preeminent distinguished researcher and a most illustrious trailblazer and disseminator. He is unmatched in combining farsighted vision, unfaftering commitment, masterful command of the field, technical virtuosity, æsthetic expression, eloquent clarity, and creative vigor with humility and devotion to students and colleagues.

For over half a century, Trakhtenbrot has been making seminal contributions to virtually all of the central aspects of theoretical computer science, inaugurating numerous new areas of investigation. He has displayed an almost prophetic ability to foresee directions that are destined to take center stage, a decade or more before anyone else takes notice. He has never been tempted to slow down or limit his research to areas of endeavor in which he has already earned recognition and honor. Rather, he continues to probe the limits and position himself at the vanguard of a rapidly developing field, while remaining, as always, unassuming and open-minded.

Trakhtenbrot is a grand visionary who pioneered many fascinating directions and innovative concepts. Even when working on his doctoral dissertation (in the late 1940s), while every logician was thinking about infinite structures, he proved that the set of first-order formulæ valid on finite structures is not recursively enumerable. This result, which bears his name, precludes the possibility of any completeness theorem for first-order predicate calculus on finite structures. As such, it was the first important result in “finite model theory”, and heralded a field that rose dramatically in popularity over the subsequent decades, as more and more researchers realized its centrality and multitudinous applications.

This was just an early instance of very many ideas of genius that Trakhtenbrot brought to the field. He was the first to introduce the use of monadic second-order logic as a specification formalism for the infinite behavior of finite automata. This logic turned out to be very fundamental; various temporal logics are just “sugared” fragments of the monadic logic. The classic theorem that finite automata and weak monadic second-order logic are expressively equivalent was established by Trakhtenbrot, and independently by Büchi and Elgot, in 1958. Trakhtenbrot also initiated the study of topological aspects of ω-languages

---

1 Boris/Boaz Abramovich/Avramovich/Avraamovich Trakhtenbrot/Trahtenbrot/Trachtenbrot/Trajtenbrot.
and operators and provided a characterization of operators computable by finite automata. Furthermore, he provided solutions to special cases of the Church synthesis problem, which was later solved by Büchi and Landweber. The equivalence between the monadic logic and automata and the solvability of the Church problem have provided the necessary underlying mathematical framework for the development of formalisms for the description of interactive systems and their desired properties, for the algorithmic verification and the automatic synthesis of correct implementations given logical specifications, and for the advanced algorithmic techniques that are now embodied in industrial tools for verification and validation.

Trakhtenbrot was among the very first to consider time and space efficiency of algorithms (using what he called “signalizing functions”) and speak about abstract complexity measures, at a time when most others cast doubt on the very notion. His justly famous and truly elegant “Gap Theorem” and his development – with his student, Janis Barzdins – of the “crossing sequence” method were groundbreaking in this regard. His paper on “auto-reducibility” provided a turning point in abstract complexity. In the USSR, these works quickly became very influential, and, in the US, complexity took over as the central preoccupation of theoretical computer scientists.

Early on, Trakhtenbrot recognized that the classic conceptual view of computation as a sequential process does not suffice to capture the operation of modern computers. Computer networks, reactive systems, and concurrent computation are all not describable in traditional terms. Accordingly, many of his more recent works deal with various aspects of concurrency, including data flow networks, Petri nets, partial-order versus branching-time equivalence, bi-simulation, real-time automata, and hybrid systems. His operative style remains classic Trakhtenbrot: patient in-depth survey of existing literature, uncompromising evaluation and critical comparison of existing approaches, followed by his own extraordinary and prescient contributions.

The list of topics upon which Trakhtenbrot has made a lasting impression is breathtaking in its scope: decidability problems in logic, finite automata theory, the connection between automata and monadic second-order logic, complexity of algorithms, abstract complexity, algorithmic logic, probabilistic computation, program verification, the lambda calculus and foundations of programming languages, programming semantics, semantics and methodology for concurrency, networks, hybrid systems, and much more. Despite this prolificacy of subjects, the entire body of his work demonstrates the same unique melding of supreme mathematical prowess, with profound depth and thoroughness.

A roll call of Trakhtenbrot’s students reads like the “Who’s Who” of computer science in the USSR. (See his academic genealogy in the first chapter of this volume.) Trakhtenbrot was instrumental in the building of the computer science department in Novosibirsk, he collaborated with computer designers in the Soviet Union, and he helped in the establishment of a department of theoretical
informatics in Jena.\textsuperscript{2} The Latvian school of computer science flourished under the tutelage of his students, Brazdins and Rūsiņš Freivalds. In 1980, he emigrated from the Soviet Union and joined Tel Aviv University’s School of Mathematical Sciences. There he was instrumental in the growth phase of its computer science department, now a School of Computer Science in its own right, a leading academic center in the Mideast. Though nominally long-retired, he remains vitally active.

Trakhtenbrot is a master pedagogue and expositor. He consistently sets aside time and effort for writing surveys and textbooks. His book, *Algorithms and Automatic Computing Machines*, first written in Russian in 1957, was translated into English and a dozen other languages, and is universally recognized as the first important text in the field. Two major contributions to computer-science education were his 1965 book, *Introduction to the Theory of Finite Automata*, and his 1973 book on *Finite Automata (Behavior and Synthesis)*, both widely translated. A whole generation of computer scientists was shaped by his books. Moreover, he played the key rôle in the dissemination of Soviet computer science research in the West, writing surveys on such topics as Soviet approaches to brute force search (*perebor*). (See his publication list in the first chapter of this volume.)

On several occasions, Trakhtenbrot has treated his readers to glimpses of his life under totalitarian rule. (See Chapter 2 of this volume for a detailed scientific autobiography.) While in the USSR, he was barred from attending most of the international congresses to which he had been invited. He suffered under the last stages of the Stalin era, plagued as it was with persecution and victimization of “idealists”, “cosmopolitans”, etc. Philosophers and logicians of the like of Russel, Carnap, and Tarski (= Tajtelbaum) were taboo, and anyone who respected their ideas was suspect, especially Jews like Trakhtenbrot.\textsuperscript{3} His contributions are astounding under any measure; how much more so when consideration is given to the fact that he worked under the most adverse conditions: persecution, lack of support, almost no access to foreign meetings, and so on. His undaunted spirit should serve as an inspiration to the rest of the world.

**Celebrating his Birthdays**

**Zeroeth Birthday**

Boris Abramovich Trakhtenbrot was born on 20 February 1921 (Gregorian), according to official records, in Brichevo, a small North Bessarabian shtetl (presently in Moldova).

---

\textsuperscript{2} The Friedrich Schiller University in Jena bestowed a degree of doctor *honoris causa* on Trakhtenbrot in October 1997.

\textsuperscript{3} Boaz and other “idealists” did receive the support and encouragement of enlightened people like Andrei Kolmogorov, Alexey Lyapunov, Piotr Novikov (his advisor), Andrey Markov, and Sophia Yanovskaya, all great scientists whom Trakhenbrot always mentions with deep affection and gratitude.
Sixtieth Birthday

In the summer of 1979, Zdzislaw Pawlak proposed “to publish a collection of contributions by outstanding scientists in the field of theoretical computer science and foundations of mathematics in order to honor the 60th anniversary of Professor B. A. Trachtenbrot from Novosibirsk.” He, along with Calvin Elgot, Erwin Engeler, Maurice Nivat, and Dana Scott were to edit the festschrift. However, with the untimely death of Cal Elgot, and Boaz’s impending immigration to Israel with his family, the project had to be abandoned. Boaz arrived in Israel on 26 December 1980.

Seventieth Birthday

In June 1991, Zvi Galil, Albert Meyer, Amir Pnueli, and Amiram Yehudai organized “An International Symposium on Theoretical Computer Science in honor of Boris A. Trakhtenbrot on the occasion of his Retirement and Seventieth Birthday”. The event took place in Tel Aviv and brought together many of the world’s foremost scientists, including: Samson Abramsky, Georgy Adelson-Velsky, Arnon Avron, Val Breazu-Tannen, Manfred Broy, Bob Constable, Nachum Dershowitz, Zvi Galil, Rob van Glabbeek, Yuri Gurevich, Leonid Levin, Jean-Jacques Lévy, Gordon Plotkin, Amir Pnueli, Vaughan Pratt, Alex Rabinovich, Wolfgang Reisig, Vladimir Sazanov, Eli Shamir, Michael Taitslin, and Klaus Wagner. At that time, Albert Meyer eloquently highlighted his enormous debt to Trakhtenbrot, the scientist, and appreciation of Trakhtenbrot, the person, a debt and appreciation that countless other scientists share.

On this occasion, very many well-wishers who could not attend sent their blessings by other means:

- Bob McNaughton wrote, “We were colleagues in research... since our work in logic and automata theory in the 1960’s was so close. Since very early in my own career (dating back to 1950) and continuing to the present I have always had reason to admire your contributions.”
- Vitali Milman: “The name of Trakhtenbrot I heard first time in the 60s when I was still a student in Kharkov. We studied his book on “Automata” and considered him to be a “father” of Russian computer science. I was very proud when in ’80 it was said he will join our department, and was very happy that he spent the last decade working with us.”
- Robin Milner said, “You are one of the founders of our subject. Every time a new decade of computer scientists come along, they re-invent the subject. I hope you stay with us a long time, to make sure that we re-invent it properly.”

4 We would be remiss if we did not take this opportunity to acknowledge the crucial rôle of Berta Isakovna (née Rabinovich), Boaz’s wife of many years, who has lovingly, selflessly, and steadfastly supported Boaz “through fire and water”. Berta was also a motherly figure for his many students, whom she always welcomed warmly and for whom she invariably prepared the most delicious meals.
– John Shepherdson wrote to Albert Meyer, saying, “Please tell Boris that, for over 40 years I have enjoyed reading his highly significant and beautifully written papers. I would like to thank him for the help he has given me in correspondence. . . . I regard him not only as one of the most significant and elegant logicians of the generation after Goedel, Church and Kleene, but also as a very warm, friendly and helpful human being.”

– Dana Scott: “My heartfelt thanks for all the scientific contributions you have made over your career. . . . Your discoveries and insights, and your encouragement and stimulation of others have been exceptional and invaluable. You have lots of admirers.”

– Jerzy Tiuryn: “You are one of the unquestionable fathers of theoretical computer science in the USSR.”

For details of that event, see the report by Val Breazu-Tannen in SIGACT News (vol. 22, no. 4, Fall 1991, pp. 27–32). The hope was that the talks at this meeting would lead to a festschrift, but – despite concerted efforts at the time – that hope never materialized. Still, Trakhtenbrot’s colleagues and former students from Latvia did publish a volume, “Dedicated to Professor B. A. Trakhtenbrot, father of Baltic Computer Science, on the occasion of his 70th birthday,” entitled, Baltic Computer Science, in this same series (Lecture Notes in Computer Science, vol. 502, Springer-Verlag, May 1991).

Eightieth Birthday
In July 2001, in honor of his eightieth birthday and his “very important contribution to Formal Languages and Automata”, Trakhtenbrot was invited to give a keynote address on “Automata, Circuits, and Hybrids: Facets of Continuous Time” at the joint session of the International EATCS Colloquium on Automata, Languages and Programming (ICALP) and of the ACM Symposium on Theory of Computing (SIGACT), held on the island of Crete.

Eighty-Fifth Birthday
On Friday, 28 April 2006, the School of Computer Science at Tel Aviv University held a “Computation Day Celebrating Boaz (Boris) Trakhtenbrot’s Eighty-Fifth Birthday”. At a gala birthday party in Jaffa, some of the messages we received were read, including those from Samson Abramsky, Leonid Levin (“Allow me, from afar, to express my great admiration of deep insight and technical power that was always so characteristic of your work, and that have been combined with human decency and fairness that was not always easy to find in the environment in which you spent a big part of your life.”), Maurice Nivat, Robin Milner, Grisha Mints (“Your name is known to every [even beginning] logician.”), Gordon Plotkin, Dana Scott, Wolfgang Thomas (“I would like to express my feelings of deep thanks for your guidance of our research community, and also of amazement about your unfailing energy which pushed us over many decades.”), and Igor Zaslavsky together with his Armenian colleagues (“We, the Armenian
mathematical logicians and computer scientists, congratulate you with profound reverence on your 85th anniversary... Your human nobleness and total devotion to science always served as an inspiring example for us.

The scientific program included the following lectures:

1. “Introductory Remarks”, Dany Levia (Rector, Tel Aviv University).
5. “Models of Bounded Complexity in Describing Decidable Classes in Predicate Logics with Time”, Anatol Slissenko (Université de Paris 12).
6. “Linear Recurrences for Graph Polynomials”, Janos Makowsky (Technion).
8. “The Church Synthesis Problem with Parameters”, Alex Rabinovich (Tel Aviv University).
9. “Concluding Remarks”, Boaz Trakhtenbrot (Tel Aviv University).

This Volume

As a follow-up to that 85th birthday event, we asked Boaz’s students and colleagues (those who did not attend, as well as those who did) to contribute to a volume in his honor. This book is the result of that effort. More precisely, it is the culmination of an effort that has been brewing for almost thirty years, sometimes on a high flame, other times on low.

The collection of articles in this book begins with historical overviews by Trakhtenbrot and Albert Meyer. These are followed by 34 technical contributions (each of which was reviewed by one or two readers), which cover a broad range of topics:

- **Foundations**: Papers by Arnon Avron; by Andreas Blass and Yuri Gurevich; and by Udi Boker and Nachum Dershowitz.
- **Mathematical logic**: Papers by Sergei Artemov; by Matthias Baaz and Richard Zach; by Moti Gitik and Menachem Magidor; and by Grigori Mints.
- **Logics for computer science**: Papers by Johan van Benthem and Daisuke Ikegami; by Dov Gabbay; by Daniel Lehmann; by Alexander Rabinovich (student of Boaz) and Amit Shomrat; and by Moshe Vardi.
- **Mathematics for computer science**: Papers by Jan Bergstra, Yoram Hirshfeld, and John Tucker; by Leonid Levin; by Johann Makowsky and Eldar Fischer; and by Boris Plotkin and Tatjana Plotkin.

---

5 Our assignment of authors to categories is of necessity somewhat haphazard, because many of the contributions themselves span more than one topic.
– **Automata, formal languages, and logic:** Papers by Michael Dekhtyar (student) and Alexander Dikovsky; by Rūsiņš Freivalds (student); by Michael Kaminski and Tony Tan; and by Wolfgang Thomas.

– **Asynchronous computation:** Papers by Irina Lomazova (student); by Antoni Mazurkiewicz; and by Wolfgang Reisig.

– **Semantics of programming languages:** Papers by David Harel, Shahar Maoz, and Itai Segall; by Masahito Hasegawa, Martin Hofmann, and Gordon Plotkin; and by Vladimir Sazonov (student).

– **Verification:** Papers by Michael Dekhtyar (student), Alexander Dikovsky, and Mars Valiev (student); by Daniel Leivant; by Oded Maler, Dejan Nickovic, and Amir Pnueli; by César Sánchez, Matteo Slanina, Henny Sipma, and Zohar Manna; and by Valery Nepomniaschy (student).

– **Software engineering:** Papers by Mikhail Auguston (“grand-student” of Boaz) and Mark Trakhtenbrot (son of Boaz); and by Janis Barzdins (student), Audris Kalnins (grand-student), Edgars Rencis, and Sergejs Rikacovs.

*We offer this modest volume to Boaz in honor of his birthday and in recognition of his grand contributions to the field.*

5 December 2007
25 Kislev 5768

Tel Aviv
Organization

Reviewers

The editors were aided by the following individuals, to whom they are most grateful:

Gul Agha          Rajesh Karmani
Matthias Baaz     Menachem Kojman
Johan van Benthem Sumit Nein
Andreas Blass     Wojciech Penczek
Stan Burris       Wolfgang Reisig
Bruno Courcelle   Shmuel Tyshberowitz
Yuri Gurevich     Moshe Vardi
Yoram Hirshfeld   Greta Yorsh
Tirza Hirst       Anna Zamansky

About the Cover

The cover illustration is from *Architectura civil, recta y obliqua, considerada y dibuxada en el Templo de Jerusalem* (Vigevani [= Vigevano], 1678) by Juan Caramuel y Lobkowitz (b. Madrid, 1606). It is a rendition of the Jachin (right) and Boaz (left) ornamental bronze columns of King Solomon’s Temple in Jerusalem, cast by Hiram of Tyre (I Kings 7:13–22), and is reproduced courtesy of Antiquariat Turszynski, Herzogstr. 66, 80803 München, Germany.
# Table of Contents

From Logic to Theoretical Computer Science – An Update .......................... 1  
* Boris A. Trakhtenbrot

Reminiscences ....................................................................................... 39  
* Albert R. Meyer

Boris A. Trakhtenbrot: Academic Genealogy and Publications .............. 46  
* Arnon Avron, Nachum Dershowitz, and Alexander Rabinovich

Symmetric Logic of Proofs ..................................................................... 58  
* Sergei Artemov

Synthesis of Monitors for Real-Time Analysis of Reactive Systems ...... 72  
* Mikhail Auguston and Mark Trakhtenbrot

A Framework for Formalizing Set Theories Based on the Use of Static  
Set Terms ............................................................................................. 87  
* Arnon Avron

Effective Finite-Valued Approximations of General Propositional  
Logics .................................................................................................. 107  
* Matthias Baaz and Richard Zach

Model Transformation Languages and Their Implementation by  
Bootstrapping Method ......................................................................... 130  
* Janis Barzdiņs, Audris Kalnins, Edgars Rencis, and Sergejs Rikacovs

Modal Fixed-Point Logic and Changing Models .................................. 146  
* Johan van Benthem and Daisuke Ikegami

Fields, Meadows and Abstract Data Types .......................................... 166  
* Jan Bergstra, Yoram Hirshfeld, and John Tucker

Why Sets? ............................................................................................ 179  
* Andreas Blass and Yuri Gurevich

The Church-Turing Thesis over Arbitrary Domains ............................. 199  
* Udi Boker and Nachum Dershowitz

Generalized Categorial Dependency Grammars .................................. 230  
* Michael Dekhtyar and Alexander Dikovsky

Temporal Verification of Probabilistic Multi-Agent Systems ................ 256  
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Recurrence Relations for Graph Polynomials</td>
<td>266</td>
</tr>
<tr>
<td>Eldar Fischer and Johann A. Makowsky</td>
<td></td>
</tr>
<tr>
<td>Artin’s Conjecture and Size of Finite Probabilistic Automata</td>
<td>280</td>
</tr>
<tr>
<td>Rūsiņš Freivalds</td>
<td></td>
</tr>
<tr>
<td>Introducing Reactive Kripke Semantics and Arc Accessibility</td>
<td>292</td>
</tr>
<tr>
<td>Dov M. Gabbay</td>
<td></td>
</tr>
<tr>
<td>On Partially Wellfounded Generic Ultrapowers</td>
<td>342</td>
</tr>
<tr>
<td>Moti Gitik and Menachem Magidor</td>
<td></td>
</tr>
<tr>
<td>Some Results on the Expressive Power and Complexity of LSCs</td>
<td>351</td>
</tr>
<tr>
<td>David Harel, Shahar Maoz, and Itai Segall</td>
<td></td>
</tr>
<tr>
<td>Finite Dimensional Vector Spaces Are Complete for Traced Symmetric</td>
<td>367</td>
</tr>
<tr>
<td>Monoidal Categories</td>
<td></td>
</tr>
<tr>
<td>Masahito Hasegawa, Martin Hofmann, and Gordon Plotkin</td>
<td></td>
</tr>
<tr>
<td>Tree Automata over Infinite Alphabets</td>
<td>386</td>
</tr>
<tr>
<td>Michael Kaminski and Tony Tan</td>
<td></td>
</tr>
<tr>
<td>Connectives in Cumulative Logics</td>
<td>424</td>
</tr>
<tr>
<td>Daniel Lehmann</td>
<td></td>
</tr>
<tr>
<td>Reasoning in Dynamic Logic about Program Termination</td>
<td>441</td>
</tr>
<tr>
<td>Daniel Leivant</td>
<td></td>
</tr>
<tr>
<td>The Grace of Quadratic Norms: Some Examples</td>
<td>457</td>
</tr>
<tr>
<td>Leonid A. Levin</td>
<td></td>
</tr>
<tr>
<td>Nested Petri Nets for Adaptive Process Modeling</td>
<td>460</td>
</tr>
<tr>
<td>Irina A. Lomazova</td>
<td></td>
</tr>
<tr>
<td>Checking Temporal Properties of Discrete, Timed and Continuous</td>
<td>475</td>
</tr>
<tr>
<td>Behaviors</td>
<td></td>
</tr>
<tr>
<td>Oded Maler, Dejan Nickovic, and Amir Pnueli</td>
<td></td>
</tr>
<tr>
<td>Token-Free Petri Nets</td>
<td>506</td>
</tr>
<tr>
<td>Antoni Mazurkiewicz</td>
<td></td>
</tr>
<tr>
<td>Proof Search Tree and Cut Elimination</td>
<td>521</td>
</tr>
<tr>
<td>Grigori Mints</td>
<td></td>
</tr>
<tr>
<td>Symbolic Verification Method for Definite Iterations over Tuples of</td>
<td>537</td>
</tr>
<tr>
<td>Altered Data Structures and Its Application to Pointer Programs</td>
<td></td>
</tr>
<tr>
<td>Valery Nepomniaschy</td>
<td></td>
</tr>
<tr>
<td>Categories of Elementary Sets over Algebras and Categories of</td>
<td>555</td>
</tr>
<tr>
<td>Elementary Algebraic Knowledge</td>
<td></td>
</tr>
<tr>
<td>Boris Plotkin and Tatjana Plotkin</td>
<td></td>
</tr>
</tbody>
</table>
Selection and Uniformization Problems in the Monadic Theory of Ordinals: A Survey ................................................. 571
   Alexander Rabinovich and Amit Shomrat

The Scholten/Dijkstra Pebble Game Played Straightly, Distributedly, Online and Reversed ........................................ 589
   Wolfgang Reisig

The Reaction Algebra: A Formal Language for Event Correlation .... 596
   César Sánchez, Matteo Slanina, Henny B. Sipma, and Zohar Manna

On Natural Non-dcpo Domains ......................................... 620
   Vladimir Sazonov

Church’s Problem and a Tour through Automata Theory ............... 635
   Wolfgang Thomas

From Monadic Logic to PSL ............................................. 656
   Moshe Y. Vardi

Author Index .............................................................. 683