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# Tools and Algorithms for the Construction and Analysis of Systems


25 Years of TACAS: TOOLympics  
Held as Part of ETAPS 2019  
Prague, Czech Republic, April 6–11, 2019  
Proceedings, Part III

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# ETAPS Foreword

Welcome to the 22nd ETAPS! This is the first time that ETAPS took place in the Czech Republic in its beautiful capital Prague.

ETAPS 2019 was the 22nd instance of the European Joint Conferences on Theory and Practice of Software. ETAPS is an annual federated conference established in 1998, and consists of five conferences: ESOP, FASE, FoSSaCS, TACAS, and POST. Each conference has its own Program Committee (PC) and its own Steering Committee (SC). The conferences cover various aspects of software systems, ranging from theoretical computer science to foundations to programming language developments, analysis tools, formal approaches to software engineering, and security.

Organizing these conferences in a coherent, highly synchronized conference program enables participation in an exciting event, offering the possibility to meet many researchers working in different directions in the field and to easily attend talks of different conferences. ETAPS 2019 featured a new program item: the Mentoring Workshop. This workshop is intended to help students early in the program with advice on research, career, and life in the fields of computing that are covered by the ETAPS conference. On the weekend before the main conference, numerous satellite workshops took place and attracted many researchers from all over the globe.

ETAPS 2019 received 436 submissions in total, 137 of which were accepted, yielding an overall acceptance rate of 31.4%. I thank all the authors for their interest in ETAPS, all the reviewers for their reviewing efforts, the PC members for their contributions, and in particular the PC (co-)chairs for their hard work in running this entire intensive process. Last but not least, my congratulations to all authors of the accepted papers!

ETAPS 2019 featured the unifying invited speakers Marsha Chechik (University of Toronto) and Kathleen Fisher (Tufts University) and the conference-specific invited speakers (FoSSaCS) Thomas Colcombet (IRIF, France) and (TACAS) Cormac Flanagan (University of California at Santa Cruz). Invited tutorials were provided by Dirk Beyer (Ludwig Maximilian University) on software verification and Cesare Tinelli (University of Iowa) on SMT and its applications. On behalf of the ETAPS 2019 attendants, I thank all the speakers for their inspiring and interesting talks!

ETAPS 2019 took place in Prague, Czech Republic, and was organized by Charles University. Charles University was founded in 1348 and was the first university in Central Europe. It currently hosts more than 50,000 students. ETAPS 2019 was further supported by the following associations and societies: ETAPS e.V., EATCS (European Association for Theoretical Computer Science), EAPLS (European Association for Programming Languages and Systems), and EASST (European Association of Software Science and Technology). The local organization team consisted of Jan Vitek and Jan Kofron (general chairs), Barbora Buhnova, Milan Ceska, Ryan Culpepper, Vojtech Horky, Paley Li, Petr Maj, Artem Pelenitsyn, and David Safranek.

The ETAPS SC consists of an Executive Board, and representatives of the individual ETAPS conferences, as well as representatives of EATCS, EAPLS, and EASST. The Executive Board consists of Gilles Barthe (Madrid), Holger Hermanns (Saarbrücken), Joost-Pieter Katoen (chair, Aachen and Twente), Gerald Lüttgen (Bamberg), Vladimiro Sassone (Southampton), Tarmo Uustalu (Reykjavik and Tallinn), and Lenore Zuck (Chicago). Other members of the SC are: Wil van der Aalst (Aachen), Dirk Beyer (Munich), Mikolaj Bojanczyk (Warsaw), Armin Biere (Linz), Luis Caires (Lisbon), Jordi Cabot (Barcelona), Jean Goubault-Larrecq (Cachan), Jurriaan Hage (Utrecht), Rainer Hähnle (Darmstadt), Reiko Heckel (Leicester), Panagiotis Katsaros (Thessaloniki), Barbara König (Duisburg), Kim G. Larsen (Aalborg), Matteo Maffei (Vienna), Tiziana Margaria (Limerick), Peter Müller (Zurich), Flemming Nielson (Copenhagen), Catuscia Palamidessi (Palaiseau), Dave Parker (Birmingham), Andrew M. Pitts (Cambridge), Dave Sands (Gothenburg), Don Sannella (Edinburgh), Alex Simpson (Ljubljana), Gabriele Taentzer (Marburg), Peter Thiemann (Freiburg), Jan Vitek (Prague), Tomas Vojnar (Brno), Heike Wehrheim (Paderborn), Anton Wijs (Eindhoven), and Lijun Zhang (Beijing).

I would like to take this opportunity to thank all speakers, attendants, organizers of the satellite workshops, and Springer for their support. I hope you all enjoy the proceedings of ETAPS 2019. Finally, a big thanks to Jan and Jan and their local organization team for all their enormous efforts enabling a fantastic ETAPS in Prague!

February 2019

Joost-Pieter Katoen  
ETAPS SC Chair  
ETAPS e.V. President

# TACAS Preface

TACAS 2019 was the 25th edition of the International Conference on Tools and Algorithms for the Construction and Analysis of Systems conference series. TACAS 2019 was part of the 22nd European Joint Conferences on Theory and Practice of Software (ETAPS 2019). The conference was held at the Orea Hotel Pyramida in Prague, Czech Republic, during April 6–11, 2019.

*Conference Description.* TACAS is a forum for researchers, developers, and users interested in rigorously based tools and algorithms for the construction and analysis of systems. The conference aims to bridge the gaps between different communities with this common interest and to support them in their quest to improve the utility, reliability, flexibility, and efficiency of tools and algorithms for building systems. TACAS 2019 solicited four types of submissions:

- *Research papers*, identifying and justifying a principled advance to the theoretical foundations for the construction and analysis of systems, where applicable supported by experimental validation.
- *Case-study papers*, reporting on case studies and providing information about the system being studied, the goals of the study, the challenges the system poses to automated analysis, research methodologies and approaches used, the degree to which goals were attained, and how the results can be generalized to other problems and domains.
- *Regular tool papers*, presenting a new tool, a new tool component, or novel extensions to an existing tool, with an emphasis on design and implementation concerns, including software architecture and core data structures, practical applicability, and experimental evaluations.
- *Tool-demonstration papers* (short), focusing on the usage aspects of tools.

*Paper Selection.* This year, 164 papers were submitted to TACAS, among which 119 were research papers, 10 case-study papers, 24 regular tool papers, and 11 were tool-demonstration papers. After a rigorous review process, with each paper reviewed by at least three Program Committee members, followed by an online discussion, the Program Committee accepted 29 research papers, 2 case-study papers, 11 regular tool papers, and 8 tool-demonstration papers (50 papers in total).

*Artifact-Evaluation Process.* The main novelty of TACAS 2019 was that, for the first time, artifact evaluation was compulsory for all regular tool papers and tool demonstration papers. For research papers and case-study papers, artifact evaluation was optional. The artifact evaluation process was organized as follows:

- *Regular tool papers and tool demonstration papers.* The authors of the 35 submitted papers of these categories of papers were required to submit an artifact alongside their paper submission. Each artifact was evaluated independently by three reviewers. Out of the 35 artifact submissions, 28 were successfully evaluated, which corresponds to an acceptance rate of 80%. The AEC used a two-phase

reviewing process: Reviewers first performed an initial check to see whether the artifact was technically usable and whether the accompanying instructions were consistent, followed by a full evaluation of the artifact. The main criterion for artifact acceptance was consistency with the paper, with completeness and documentation being handled in a more lenient manner as long as the artifact was useful overall. The reviewers were instructed to check whether results are consistent with what is described in the paper. Inconsistencies were to be clearly pointed out and explained by the authors. In addition to the textual reviews, reviewers also proposed a numeric value about (potentially weak) acceptance/rejection of the artifact. After the evaluation process, the results of the artifact evaluation were summarized and forwarded to the discussion of the papers, so as to enable the reviewers of the papers to take the evaluation into account. In all but three cases, tool papers whose artifacts did not pass the evaluation were rejected.

- *Research papers and case-study papers.* For this category of papers, artifact evaluation was voluntary. The authors of each of the 25 accepted papers were invited to submit an artifact immediately after the acceptance notification. Owing to the short time available for the process and acceptance of the artifact not being critical for paper acceptance, there was only one round of evaluation for this category, and every artifact was assigned to two reviewers. The artifacts were evaluated using the same criteria as for tool papers. Out of the 18 submitted artifacts of this phase, 15 were successfully evaluated (83% acceptance rate) and were awarded the TACAS 2019 AEC badge, which is added to the title page of the respective paper if desired by the authors.

*TOOLympics.* TOOLympics 2019 was part of the celebration of the 25th anniversary of the TACAS conference. The goal of TOOLympics is to acknowledge the achievements of the various competitions in the field of formal methods, and to understand their commonalities and differences. A total of  $2^4$  competitions joined TOOLympics and were presented at the event. An overview and competition reports of 11 competitions are included in the third volume of the TACAS 2019 proceedings, which are dedicated to the 25th anniversary of TACAS. The extra volume contains a review of the history of TACAS, the TOOLympics papers, and the papers of the annual Competition on Software Verification.

*Competition on Software Verification.* TACAS 2019 also hosted the 8th International Competition on Software Verification (SV-COMP), chaired and organized by Dirk Beyer. The competition again had high participation: 31 verification systems with developers from 14 countries were submitted for the systematic comparative evaluation, including three submissions from industry. The TACAS proceedings includes the competition report and short papers describing 11 of the participating verification systems. These papers were reviewed by a separate Program Committee (PC); each of the papers was assessed by four reviewers. Two sessions in the TACAS program (this year as part of the TOOLympics event) were reserved for the presentation of the results: the summary by the SV-COMP chair and the participating tools by the developer teams in the first session, and the open jury meeting in the second session.

*Acknowledgments.* We would like to thank everyone who helped to make TACAS 2019 successful. In particular, we would like to thank the authors for submitting their



papers to TACAS 2019. We would also like to thank all PC members, additional reviewers, as well as all members of the artifact evaluation committee (AEC) for their detailed and informed reviews and, in the case of the PC and AEC members, also for their discussions during the virtual PC and AEC meetings. We also thank the Steering Committee for their advice. Special thanks go to the Organizing Committee of ETAPS 2019 and its general chairs, Jan Kofroň and Jan Vitek, to the chair of the ETAPS 2019 executive board, Joost-Pieter Katoen, and to the publication team at Springer.

April 2019

Tomáš Vojnar (PC Chair)  
Lijun Zhang (PC Chair)  
Marius Mikucionis (Tools Chair)  
Radu Grosu (Use-Case Chair)  
Dirk Beyer (SV-COMP Chair)  
Ondřej Lengál (AEC Chair)  
Ernst Moritz Hahn (AEC Chair)

# Preface

The celebration of the 25th anniversary of TACAS, the International Conference on Tools and Algorithms for the Construction and Analysis of Systems, was part of the 22nd European Joint Conferences on Theory and Practice of Software (ETAPS 2019). The celebration event was held in Prague, Czech Republic, during April 6–7, 2019.

This year, the TACAS proceedings consist of three volumes, and the third volume is dedicated to the 25th anniversary of TACAS. This extra volume contains a review of the history of TACAS, the TOOLympics papers, and the papers of the annual Competition on Software Verification.

The goal of TOOLympics 2019, as part of the celebration of the 25th anniversary of the TACAS conference, was to acknowledge the achievements of the various competitions in the field of formal methods, and to understand their commonalities and differences. A total of  $2^4$  competitions joined TOOLympics and were presented at the event. An overview and competition reports of 11 competitions are included in the proceedings.

We would like to thank all organizers of competitions in the field of formal methods, in particular those that presented their competition as part of TOOLympics. We would also like to thank the ETAPS 2019 Organizing Committee for accommodating TOOLympics, especially its general chairs, Jan Kofroň and Jan Vitek, the chair of the ETAPS 2019 executive board, Joost-Pieter Katoen, and the team at Springer for the flexible publication schedule.

April 2019

Dirk Beyer  
Marieke Huisman  
Fabrice Kordon  
Bernhard Steffen

# A Short History of TACAS

## Introduction

The International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS) celebrated its 25th anniversary this year. As three of the original co-founders of the meeting, we are proud of this milestone, and also a bit surprised by it! Back in the 1993–1994 timeframe, when we were formulating plans for TACAS, we had no other aspirations than to have an interesting, well-run event interested in the theory and practice of analysis and verification tools. That said, we feel something of an obligation to record the course TACAS has followed over the years. That is the purpose of this note: to give a brief history of the conference, and to highlight some of the decisions that were made as it evolved.

## Pre-history

The idea for TACAS was hatched on a tennis court in Elounda, Greece, during the 1993 Computer-Aided Verification (CAV) Conference. CAV was a relatively young meeting at the time in a field (automated verification) that was experiencing explosive growth. The three of us were playing doubles with another CAV attendee, Ed Brinksmä; the four of us would go on to be the founding members of the TACAS Steering Committee. Immediately after the match we fell to talking about CAV, how great it was to have a conference devoted to verification, but how some topics, especially ones devoted to software, and to system analysis and not necessarily verification, were not on the table. This conversation turned to what another meeting might look like, and thus was the seed for what became TACAS, an event addressing tools for the construction and analysis of systems. (Perhaps interestingly, our original idea of a name for the conference was Tools, Algorithms and Methodologies – TAM. We decided to drop “methodologies” from the title in order to clearly emphasize the tool aspect.)

In subsequent meetings and e-mail exchanges we fleshed out the idea of the conference. We wanted to support papers about tools on equal footing with typical research papers and to further increase the awareness of tools by making case studies and tool demonstrations part of the main conference with dedicated topical parts. At the time, other conferences we were familiar with did not have demos, or if they did, they took place during breaks and social events, meaning the audiences were small.

By scheduling demos during regular conference sessions, we were able to ensure good attendance, and by providing the typical 15 pages for (regular) tool papers and case study papers, and four pages for tool-demo papers, we also gave tool builders an opportunity to present their tool and give something citable for others who wanted to reference the work. In fact, the most highly cited TACAS paper of all time is the 2008

tool-demo paper for the Z3 SMT solver by Leonardo de Mourna and Nikolaj Bjørner, whose citation count just passed 5,000.

## The Early Years

TACAS began its life as a workshop, rather than a conference, although all its proceedings were published by Springer in its *Lecture Notes in Computer Science* series.

The first meeting of TACAS took place May 19–20, 1995, in Aarhus, Denmark as a workshop to the TAPSOFT conference series. Both TAPSOFT and our TACAS workshop were hosted by the prominent BRICS research center. The workshop featured 13 accepted papers and Springer published the proceedings in its *Lecture Notes in Computer Science* (LNCS) series. The Program Committee was chaired by the four Steering Committee members (the three of us, plus Ed Brinksma) and Tiziana Margaria.

The next meeting, March 27–29, 1996, in Passau, Germany, featured 30 papers (including 11 tool-demo papers) and lasted three days, rather than two.

The final workshop instance of TACAS occurred in Enschede, The Netherlands on April 2–4, 1997, and had 28 papers.

## ETAPS

In 1994 during a TAPSOFT business meeting in Aarhus, negotiations began to integrate several European software-focused conferences into a consortium of co-located meetings. The resulting amalgam was christened the Joint European Conferences on Theory and Practice of Software (ETAPS), and has become a prominent meeting in early spring in Europe since its initial iteration in 1998.

TACAS had been a workshop until 1997, but starting in 1998 it became a conference and was one of the five founding conferences of ETAPS, along with the European Symposium on Programming (ESOP), Foundations of Software Systems and Computational Structures (FoSSaCS), Fundamental Aspects of Software Engineering (FASE), and Compiler Construction (CC). This step in the development of TACAS helped cement its status as a premiere venue for system analysis and verification tools, although the increased overhead associated with coordinating its activities with four other conferences presented challenges. The increased exposure, however, did lead to a significant growth in submissions and also in accepted papers. In 1998, the first iteration of ETAPS was held in Lisbon, Portugal; the TACAS program featured 29 presentations. Figure 1 shows a group of people during the 10 years of TACAS celebration in 2004. By 2007, the 10th incarnation of ETAPS, which was held in Braga, Portugal, the program featured 57 presentations (several of these were invited contributions, while others were tool-demo papers). Negotiating this increased presence of TACAS within ETAPS required tact and diplomacy, and it is a testament to the bona fide skills of both the TACAS and ETAPS organizers that this was achievable.



**Fig. 1.** 10 years of TACAS celebration in 2004 in Barcelona, Spain. From left to right: Andreas Podolski, Joost-Pieter Katoen, Lenore Zuck, Bernhard Steffen, Tiziana Margaria, Ed Brinksma, Hubert Garavel, Susanne Graf, Kim Larsen, Nicolas Halbwachs, Wang Yi, and John Hatcliff

As part of becoming a conference and a part of ETAPS, TACAS also institutionalized some of the informal practices that it had used in its early, workshop-based existence. The Steering Committee structure was formalized, with the three of us and Ed Brinksma becoming the official members. (After several years of service, Ed Brinksma left the Steering Committee to pursue leadership positions in Dutch and, subsequently, German universities and research institutions. Joost-Pieter Katoen took Brinksma's place; when he then left to assume leadership of ETAPS, Holger Hermanns ascended to the TACAS Steering Committee. Lenore Zuck and, currently, Dirk Beyer have also held ad hoc positions on the Steering Committee.)

The conference also standardized its approach to Program Committee leadership, with two co-chairs being selected each year, and with a dedicated tool chair for overseeing tool submissions and demonstrations. Today, similar committee structures can be found at other conferences as well, but they were less common when TACAS adopted them.

## Subsequent Developments

Since joining ETAPS, TACAS has experimented with its programmatic aspects. In recent years, the conference has started to increase the emphasis of the four paper categories by explicitly providing four categories of paper submission: regular, tool, case study, and demo. Starting in 2012, it also started to include tool competitions, most notably SV-COMP led by Dirk Beyer, which have proved popular with the community and have attracted increasing numbers of competitors. The conference has also modified its submission and reviewing processes over the years.

At ETAPS 2014 in Grenoble we celebrated the 20th anniversary of TACAS. During this celebration, awards for the most influential papers in the first 20 years of TACAS were given. The regular-paper category went to Armin Biere, Alessandro Cimatti, Edmund Clarke, and Yunshan Zhu for their 1999 paper “Symbolic Model Checking Without BDDs,” and the tool-demo category went to the “Z3: An Efficient SMT Solver” presented by Leonardo de Mourna and Nikolaj Bjørner in 2008. Figure 2 shows Armin Biere, Alessandro Cimatti, and Leonardo de Mourna during the award ceremony.



**Fig. 2.** Most Influential Paper Award Ceremony at the 20 Years of TACAS celebration in 2014. From left to right Rance Cleaveland, Bernhard Steffen, Armin Biere, Alessandro Cimatti, Leonardo de Mourna, Holger Hermanns, and Kim Larsen

## Reflections

As we noted at the beginning of this text, we had no idea when we started TACAS in 1995 that it would become the venue that it is 25 years later. Most of the credit should go to the authors who submitted their work to the conference, to the hard work of the Program Committee chairs and members who reviewed and selected papers for presentation at the conference, to the tool-demo chairs who oversaw the selection of tool demonstrations, and to the local arrangements organizers who ensured the technical infrastructure at conference venues could handle the requirements of tool demonstrators.

That said, we do think that some of the organizational strategies adopted by TACAS have helped its success as well. Here we comment on a few of these.

- Compact Steering Committee. The TACAS Steering Committee has always had four to five members. This is in contrast to other conferences, which may have ten or more members. The small size of the TACAS committee has enabled greater participation on the part of the individual members.
- Steering Committee  $\subseteq$  Program Committee. Unusually, and because the Steering Committee is small in number, Steering Committee members serve on the Program Committee each year. This has sometimes been controversial, but it does ensure institutional memory on the PC so that decisions made one year (about the definition of double-submission, for instance) can be recalled in later years.
- PC Co-chairs. As mentioned earlier, TACAS has two people leading the Program Committee, as well as a tool chair. Originally, this decision was based on the fact that, because TACAS had multiple submission tracks (regular, tool, case study, and tool demo), the PC chairing responsibilities were more complex. Subsequently, though, our observation is that having two leaders can lead to load-sharing and also good decision-making. This is particularly fruitful for dealing with conflicts, as one chair can oversee the papers where the other has a conflict.

This LNCS volume is devoted to the TACAS 25th anniversary event, TOOLympics, which comprises contributions from 16 tool competitions. The maturity of these challenges, as well of the participating tools impressively demonstrates the progress that has been made in the past 25 years. Back in 1994 we would never have imagined the power of today's tools with SAT solvers capable of dealing with hundreds of thousands of variables, powerful SMT solvers, and complex verification tools that make careful use of the power of these solvers. The progress is really impressive, as is still the gap toward true program verification of industrial scale. This requires a better understanding of the developed methods, algorithms, and technologies, the impact of particular heuristics, and, in particular, the interdependencies between them. TOOLympics aims at fostering the required interdisciplinary, problem-oriented cooperation, and as the founders of TACAS, we look forward to observing the results of this cooperation in forthcoming editions of TACAS.

Finally, we would like to thank Alfred Hofmann and his team at Springer for the continuous support in particular during the early phases. Without this support, TACAS would never have developed in the way it did.

February 2019

Rance Cleaveland  
Kim Larsen  
Bernhard Steffen



# Organization

## Program Committee: TACAS

Parosh Aziz Abdulla	Uppsala University, Sweden
Dirk Beyer	LMU Munich, Germany
Armin Biere	Johannes Kepler University Linz, Austria
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