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The 2014 SMT Competition

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Abstract

The 2014 SMT Competition was held in conjunction with the SMT Workshop, affiliated with the CAV, IJCAR, and SAT conferences at FLoC 2014, at the Vienna Summer of Logic in July 2014. Eighteen solvers participated from thirteen different research groups, across 34 different logic divisions. The competition was also part of the FLoC Olympic Games event, which gave combined visibility to 14 different competitions related to automated logic problem solving. The 2014 edition of the SMT Competition was executed for the first time on the StarExec logic solving service. Several records were broken: number of participating solvers, number of new entrants, number of logic divisions, number of benchmarks, and amount of computation. The detailed performance of each solver on each benchmark from this first year using StarExec will be a solid baseline to measure improvements in the state-of-the-art of solver performance in future years.

Keywords: *SMT solver, SMT-COMP, SMT-LIB, Satisfiability Modulo Theories, competitions*

1. Introduction

The SAT decision problem can be generalized by replacing Boolean variables with atomic predicates built with symbols from a background theory, or a combination of background theories. The resulting decision problem is called *Satisfiability Modulo Theories* [32]. The background theories of interest arise from application domains, such as formal verification or scheduling problems, and include arrays, bit-vectors, equality with uninterpreted functions, linear and non-linear arithmetics over integers and real numbers. Also, a theory may explicitly allow or disallow quantification. Tools addressing the SMT problem are called *SMT solvers*. An SMT solver is often built by combining a SAT solver with (semi-)decision procedures for specific theories.

The 2014 SMT Competition (SMT-COMP) continued the series of annual competitions in SMT solver capability and performance that began in 2005. This is the 9th competition in the series, skipping only 2013; in that year an evaluation [17] was performed, rather than a competition.[1]

The competition is held to spur advances in SMT solver implementations acting on benchmark formulas of practical interest. Public competitions are a well-known means of stimulating advancement in software tools. For example, in automated reasoning, the SAT and CASC competitions for propositional and first-order reasoning tools, respectively, have spurred significant innovation in their fields [1, 23, 8, 28].

The competition is sponsored by the SMT Workshop, which was held in conjunction with the CAV, IJCAR, and SAT conferences at FLoC 2014 [33], at the Vienna Summer of Logic [34] in July 2014. Information about the winners and results of the competition is summarized in this report and is available online at `www.smtcomp.org`. Information about previous years' competitions is also available at that website and in published summary reports [4, 16, 17].

In the succeeding sections we describe the competition goals (§2), the SMT-LIB language that is the basis for the competition (§3), the competition benchmarks (§4), participants (§5), procedure (§6), computational infrastructure (§7), comparisons with other competitions (§8), the results (§9), the place of SMT-COMP in the FLoC Olympic Games (§10), and post-competition activities (§11). Section 12 presents observations on this competition and recommendations for the future.

2. The Competition Goals and Organization

In planning the 2014 competition, the organizers' overall goal was to encourage breadth in the capability of SMT solvers. SMT-COMP 2014 benefited from the evaluation that was performed in 2013 and the experience of previous competitions. As a result we established the following emphases. Note that, as described in later sections, the competition is divided into a number of divisions, each focuses on a given logic, and each has its own set of benchmark problems and solvers.

- In 2012 the competition was narrowed to a smaller number of more significant logics. In response to feedback, in 2014 we reverted to the practice of evaluating solvers in all available divisions.
- A significant result of the 2013 Evaluation was that the results of previous competitions were highly sensitive to the selection of benchmarks: different random selections of benchmarks resulted in different winning orders in a large fraction of samples. Hence, an aim for 2014 was to use as large a benchmark set as possible in the competition to minimize this effect. We were able to run the competition with all eligible benchmarks. This point is discussed further in §4.2.

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[1] The evaluation did not measure solvers against each other, as in a competition. Rather it assessed concerns such as how the design of the competition (e.g., random choice of benchmarks) affects the outcome, the variety and distribution of benchmarks, and the extent to which the competition is dominated by single solvers or by a few solvers or is broadly competitive.

- In 2012 some experimental tracks were held: parallel performance, unsat cores, and proof generation. The participation in those tracks was light. Since in 2014 we also had to migrate to using the new StarExec cluster to execute the competition, we held only a main track and an application (incremental) track in the 2014 competition. The organizers still appreciate the value of measuring the performance of solvers on new features such as parallel processing, model generation, unsat core determination, and proof generation, and recommend that these tracks be reinstated in some future edition of the competition.
- An additional goal was to be able to evaluate the effect of the timeout setting on the competition. Thus a change in 2014 was to increase the timeout limit for a solver processing a given benchmark from 25 minutes (in 2012) to 40 minutes (see §6 for details on the competition parameters and §9.1 for a discussion on their effects).

An important difference between the 2014 competition and previous competitions was that this year's competition was executed on the StarExec cluster, described below in §7. All the supporting tools and related procedures needed to be ported to this new framework. With watchful eyes by the organizers and the StarExec team, and with some debugging, the StarExec framework worked well and enabled a larger scale of competition than in previous years.

3. SMT-LIB Logic, Language and Solvers

The SMT Competition is a competition among SMT solvers on a set of benchmark logic problems. Each benchmark problem is a combination of definitions and logical assertions expressed with respect to an underlying logical theory and, perhaps, some constraints on the kinds of expressions in that theory. For example, the logic of linear arithmetic includes the multiplication operation, but only allows multiplication by constants. Each problem is a set of closed formulas (possibly including quantification over variables) over a set of constant or function symbols; a solution to the problem is an assignment of each constant and function evaluation to values in a way that satisfies all the problem's assertions. That is, the task is to find a *satisfying assignment* for the benchmark problem or to determine that there is no such assignment. Since the presence of quantified expressions introduces incompleteness, solvers may also produce a potential solution that may be marked as possibly spurious.

As stated, the goal of SMT-COMP is similar to the goal of the SAT competition. The SMT logic extends SAT by incorporating defined theories, such as the theory of arrays, or of uninterpreted functions, or of arithmetic, or of bit-vectors. In addition, there may be constraints on the set of expressions allowed, such as only linear arithmetic, or only integer difference arithmetic. The theories also define *sorts*, which make the theories a typed first-order logic. Examples of sorts used in current theories are Boolean, Int, Real, bit-vectors of various lengths, and arrays with arbitrary sorts as index and value. Each combination of underlying theories and language constraints is a *logic*. The names of the logics as used in SMT-LIB are combinations of initials. For example, AUFLIA is the logic with a combination of Arrays (A), Uninterpreted Functions (UF), and linear integer arithmetic (LIA). Table 1 can be used to interpret these names.

QF_	Quantifier-Free
A	Arrays
UF	Uninterpreted Functions
BV	Bit-Vector
L	Linear (arithmetic)
N	Non-Linear (arithmetic)
IA/RA/IRA	Integer/Real/Mixed arithmetic
IDL/RDL	Integer/Real Difference Logic

Table 1: Abbreviations used in logic names

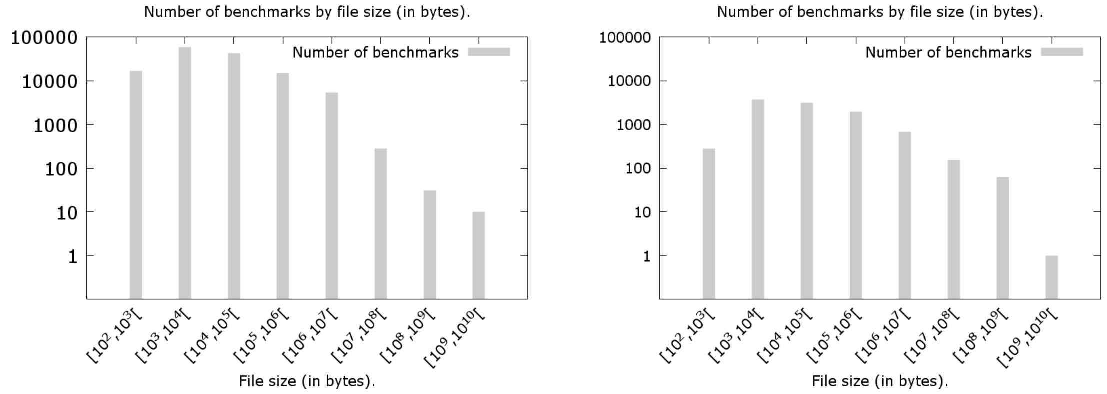
A competition based on benchmark problems needs a standard language in which to express those problems. For SMT-COMP, that language is the SMT-LIB language (cf. `http://www.smtlib.org`) [5, 6, 15]. In 2010, a significantly reworked version of the language was agreed upon. This version 2 increased the flexibility and expressiveness of the language while also simplifying the syntax. It also includes a command language that improves the language's usefulness for interactive applications. In particular, the standard specifies a typed (sorted), first-order logical language for terms and formulas, a language for specifying background logical theories and logics, and a command language. Some other tools that process SMT-LIB v2 are listed in the SMT-LIB web pages (cf. `http://www.smtlib.org/utilities.shtml`). Further revisions were discussed at the SMT Workshop 2014. One of the goals of the SMT Competition is to encourage use and tool implementations of the SMT-LIB standard.

Optional features such as incrementality, proof production, and determining unsat cores are evaluated in specialized tracks, separate from the main competition. The presence of such tracks in the competition has varied from year to year.

The following example illustrates part of the language's concrete syntax:

```
(set-logic UFLIA)
(declare-fun max (Int Int) Int)
(assert (forall ((x Int) (y Int))
   (let ((m (max x y)))
      (and (>= m x) (>= m y) (or (= m x) (= m y))))))
(assert (not (forall ((x Int) (y Int))
   (let ((m (max x y)))
      (= (max m x) m)))))
(check-sat)
```

Commands to the SMT solver are typeset in bold here. The command **set−logic** sets the background theory: UFLIA is the combination of equality with uninterpreted functions (UF) and linear integer arithmetic (LIA). Next, the command **declare−fun** introduces a function symbol, named max, which has two arguments of sort Int and returns an Int value. Next, two formulas are asserted. The first essentially restricts the interpretation of the function named max to the standard interpretation. The second expresses the negation of a property of this operator. The command **check−sat** instructs the SMT solver to check if the conjunction of



Non-incremental benchmarks

Incremental benchmarks

Figure 1: Distribution of SMT-LIB benchmarks by file size.

the assertions is satisfiable. Here the expected result is `unsat`, indicating that the combination of the two assertions is unsatisfiable and so, equivalently, the desired property is valid, given the first assertion.

SMT *solvers* are automated tools that seek a satisfying assignment for a given SMT-LIB problem, or assure that the problem is *unsatisfiable*. Tools may not be able to solve a given problem, because, for example the tool exhausts available memory or time; a tool is permitted to answer *unknown*. However, giving an incorrect answer (*sat* instead of *unsat*, or vice versa) is considered *unsound* and a serious fault in the tool.

4. Competition Divisions and Benchmarks

The SMT-LIB benchmarks each belong to a specific logic. Each logic is one competition division. For each division, we ran the solvers that entered that division on the benchmarks for that division as one event in the overall competition.

As of June 2014, the SMT-LIB repository contained over 130,000 main-track benchmarks divided into 34 background theories, and close to 10,000 incremental benchmarks distributed across 8 background theories. The size of a benchmark file may vary from a few hundred bytes to several gigabytes. Fig. 1 shows the distribution of the benchmarks by file size.

A sizeable number of benchmarks, on the order of 30,000, were added during the lead up to the competition. Some of these were submitted in previous years but never assessed and uploaded. Many others were supplied by solver developers (including some competitors). All of them went through an iterative curation process to be sure that they were syntactically valid, appropriate metadata was included, and a correct result was established. (Not all of these submissions were through the competition organizers.)

The SMT-LIB coordinators performed a curation step on the entire benchmark library prior to the competition, determining the actual logic to which a benchmark belonged, rather than the super-logic to which it had previously been assigned. This resulted in an expansion of logics with benchmarks from 23 to 34, and also created a number of divisions with only a very few benchmarks. Two divisions were not held because they had no eligible benchmarks.

The 34 logics are shown in Table 2. The rightmost column shows the number of benchmarks for that logic in the SMT-LIB collection. Two considerations may make a benchmark ineligible for a competition. First, the benchmark may not have a known result. For newly submitted benchmarks we made an attempt to determine the correct result of the benchmark; the SMT-LIB coordinators require that two different solvers solve the benchmark and report the same result. However, for benchmarks with unknown results already in the collection we did not have time to determine their results. We did do this analysis after the competition was over (see §11).

The second consideration is that the benchmark must be *non-trivial*; a benchmark is deemed trivial if all solvers managed to solve it in less than five seconds during SMT-EVAL 2013.

The numbers of unknown, trivial, and remaining eligible benchmarks are shown in Table 2. Note that these numbers vary widely from division to division. As we discuss in Section 4.2 below, all eligible benchmarks were actually used in the competition; these numbers are shown in bold.

Solvers could participate in any or all divisions at their team's discretion. Most solvers are designed for just one selected logic, but others are intended to be as broadly applicable as their developers have had time to implement. Table 3 shows the participation of solvers in various divisions.

4.1 Application benchmarks

The language includes commands that allow a fine-grained interaction with the solver, whereby client tools may incrementally push and pop symbol declarations and assertions while running various satisfiability checks, inspecting models, or obtaining unsatisfiability proofs. Benchmark problems that have more than one **check−sat** command are called *application* or *incremental benchmarks*. Not all SMT solvers support all of these interaction facilities, and the main track of the competition does not use such application benchmarks.

4.2 Selection of benchmarks

Due to the mismatch between the amount of available compute time and the number of jobs to run, benchmark selection has been an historical issue for SMT-COMP. In addition to whether a benchmark has a known result or is trivial, the SMT-COMP organizers chose two other factors that affect the selection of benchmarks for SMT-COMP: the benchmark's difficulty and the desire for a distribution of problems. In 2014, the amount of available CPU time was enough to process all benchmarks on all solvers within the timeout defined in the rules. However this could not be anticipated, and the issues described hereafter may

Table 2: Numbers of main-track benchmarks. The second column shows the number of competitive solvers and, in square brackets, the number of demonstration-only solvers. Entries marked * exclude some benchmarks containing partial functions.

	# of	# of benchmarks			
Logic	solvers	**eligible**	unknown	trivial	total
ALIA	3+[1]	**29**	0	13	42
AUFLIA	3+[1]	**4**	0	0	4
AUFLIRA	3+[1]	**10791**	168	9055	20014
AUFNIRA	2+[2]	**564**	468	463	1495
BV	2+[1]	**0**	191	0	191
LIA	3+[1]	**46**	0	0	46
LRA	3+[1]	**171**	450	0	621
NIA	2+[1]	**9**	0	0	9
NRA	2+[1]	**3747**	66	0	3813
QF_ABV	7+[2]	**6457***	4191	4423	15091
QF_ALIA	3+[2]	**97**	0	29	126
QF_AUFBV	2+[2]	**37**	0	0	37
QF_AUFLIA	4+[2]	**610**	0	399	1009
QF_AX	3+[2]	**335**	0	216	551
QF_BV	8+[3]	**2488***	28138	546	32500
QF_IDL	3+[1]	**1315**	537	337	2189
QF_LIA	4+[3]	**4381**	1279	481	6141
QF_LRA	4+[2]	**1343**	208	131	1682
QF_NIA	3+[1]	**8327**	927	105	9359
QF_NRA	3+[1]	**10121**	1392	27	11540
QF_RDL	3+[1]	**132**	85	38	255
QF_UF	5+[2]	**4124**	4	2522	6650
QF_UFBV	2+[2]	**31**	0	0	31
QF_UFIDL	3+[1]	**311**	0	130	441
QF_UFLIA	4+[2]	**484**	0	114	598
QF_UFLRA	4+[2]	**1176**	87	367	1630
QF_UFNIA	2+[1]	**7**	0	0	7
QF_UFNRA	2+[1]	**32**	11	0	43
UF	3+[1]	**2830**	2911	7	5748
UFBV	2+[1]	**0**	191	0	191
UFIDL	2+[1]	**49**	12	19	80
UFLIA	3+[1]	**5766**	5499	873	12138
UFLRA	3+[1]	**25**	0	0	25
UFNIA	2+[1]	**1587**	1052	712	3351
Total	18+[3]	**67426**	47867	21007	137648

Table 3: Solver participation in logic divisions

Solver	ALIA	AUFLIA	AUFLIRA	AUFNIRA	BV	LIA	LRA	NIA	NRA	QF_ABV	QF_ALIA	QF_AUFBV	QF_AUFLIA	QF_AX	QF_BV	QF_IDL	QF_LIA	QF_LRA	QF_NIA	QF_NRA	QF_RDL	QF_UF	QF_UFBV	QF_UFIDL	QF_UFLIA	QF_UFLRA	QF_UFNIA	QF_UFNRA	UF	UFBV	UFIDL	UFLIA	UFLRA	UFNIA
4Simp															✓																			
Abziz															✓																			
Abziz2															✓																			
AProVE																			✓															
Boolector															✓																			
Boolector-d										✓																								
Boolector-j										✓																								
CVC3	✓	✓	✓	✓	✓	✓	✓	✓	✓										✓	✓							✓	✓	✓	✓	✓	✓	✓	✓
CVC4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Kleaver-STP										✓																								
Kleaver-portfolio										✓																								
OpenSMT2																						✓												
raSAT																				✓														
SMTInterpol											✓		✓	✓			✓	✓				✓			✓	✓								
SONOLAR										✓					✓																			
STP-Crypto...															✓																			
veriT	✓	✓	✓			✓	✓						✓			✓	✓	✓			✓	✓		✓	✓	✓			✓			✓	✓	
Yices2										✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓								
[MathSAT5]										✓	✓	✓	✓	✓	✓		✓	✓				✓	✓		✓	✓								
[Z3]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[CVC4-with-bugfix]				✓											✓		✓																	

happen again, e.g., in case the number or difficulty of benchmarks, number of solvers, or the timeout increase significantly, or the organizers wish to compress the time-frame in which the competition is executed.

Each benchmark is assigned a *difficulty rating*; in 2014, we used the time taken to solve the benchmark by the best performing solver in the 2013 SMT Evaluation. These values were publicly available prior to the competition. The difficulty ratings are used to divide the benchmarks into 5 quintiles. The rules describe a procedure for randomly selecting N out of the eligible benchmarks for a division, with the intent of selecting roughly equal numbers, if they are available, from each of the quintiles. The seed for the random number generator used for selection is obtained by summing a number supplied by each solver team and the integer portion of the New York Stock Exchange Composite Index at its opening on the day the competition begins.

Benchmarks are also labeled by *category* (not shown in the tables): simple checks, randomly generated problems from some template (e.g., N-queens problems for various values of N), problems crafted to test a certain capability, and problems obtained from industrial applications. The selection rules in previous years favored industrial benchmarks.

Another selection criterion, though not used historically, is to balance the numbers of *sat* and *unsat* benchmarks.

In addition, some kinds of problems may be over-represented in the benchmarks. This may be the case particularly because benchmarks may be submitted by solver developers; a team might add a large number of benchmarks that would then over-represent problems that a particular solver is known to handle well. The rules allow the organizers to limit the selections from sub-populations.

In the end, in 2014, there was sufficient time to use all eligible benchmarks and no further selection was performed. The 2014 organizers did not have the data to make a principled decision on over-representation of particular problem types and so did not select on this basis either. The absence of such selection may have affected the competition results and future organizing teams should reconsider this aspect even if there are sufficient computational resources to execute all benchmarks. The data from SMT-COMP 2014 could be used to inform this decision.

5. Participants

The competition registration requires participants to submit information about each competing solver. In addition, some solver groups provided summaries of their solvers and their recent technical advances. Note that although one person is listed as the "submitter," there is generally a team of contributors behind each tool. Some teams submitted more than one tool. The 2014 participants were the following:

- 4Simp – submitted by Trevor Hansen (U. Melbourne)
- AbzizPortfolio – two versions – submitted by Mohammed Adbul Aziz (U. Cairo). This solver is atypical in that it is a portfolio solver: based on automated learning over

benchmark characteristics, it chooses among other solvers to apply to the problem at hand.

- AProVe [22] – submitted by Carsten Fuhs (University College London)
- Boolector [26] – three versions: Boolector (default), Boolector-d (dual propagation), Boolector-j (justification) – submitted by Armin Biere, Aina Niemetz, Mathias Preiner (Johnnes Kepler University)
- CVC3 v. 2.4.3 [7] – submitted by Morgan Deters (New York University)
- CVC4 v. 1.4 [3] – submitted by the ACSys Group (New York University)
- Kleaver – 2 versions – submitted by Hristina Palikareva, Cristian Cadar (Imperial College)
- OpenSMT2 – submitted by Antti Hyvärinen (U. Lugano)
- raSAT [24] – submitted by Xuan-Tung Vu (Japan Advanced Insitute of Science and Technology)
- SMTInterpol [13, 19] – submitted by Jochen Hoenicke, Jürgen Christ (U. Freiburg)
- SONOLAR [27] – submitted by Florian Lapschies (U. Bremen)
- STP-CryptoMiniSat4 [21, 18] – submitted by Mate Soos (Security Research Lab.), based on previous work by Trevor Hansen (U. Melbourne) and Vijay Ganesh (Massachusetts Institute of Technology)
- veriT [10] – submitted by David Déharbe (UFRN - Universidade Federal do Rio Grande do Norte) and Pascal Fontaine (U. Lorraine, INRIA - Institut national de recherche en informatique et en automatique)
- Yices2 [20] – submitted by Bruno Dutertre (SRI)

There were a few solvers that the organizers hoped would be submitted but were not: Tiffany de Wintermonte was submitted in the past by Trevor Hansen, but could not be prepared in time for this competition; similarly SMT-RAT was withdrawn because of last minute bugs; MathSat has been a frequent competitor in the past, but changes in priorities of the development team caused it not to compete in 2014; MiniSMT also was not able to be submitted; similarly, the Z3 team, from Microsoft Research, though Z3 is a strong tool, has chosen not to take the time to prepare competition versions.

Other than those omissions, every competitive solver known to the organizers was represented. Indeed, the participation by solver teams was a record high in 2014. In addition, four teams submitting five solvers had not participated in previous competitions.

Table 4: History of solver participation (numbers in parenthesis indicate the number of versions submitted for the tool). Complete records of early competitions were not available to the 2014 organizers.

Solver	Affiliation	2005	2006	2007	2008	2009	2010	2011	2012	2014
4Simp	U. Melbourne									✓
AbzizPortfolio	U. Cairo								✓	(2)
Alt-Ergo	U. Paris Sud				✓					
AProVE NIA	RWTH Aachen						✓	✓		✓
ArgoLib				✓						
Ario		✓	✓							
barcelogic	UPC	✓	✓	✓	✓	✓				
beaver	UC Berkeley				✓	✓				
Boolector	JKU				✓	✓		✓	✓	(3)
clsat	Washington U.				✓	✓				
CVC/CVCLite/CVC3	NYU, U. Iowa	✓	✓	✓	✓	✓	✓	✓	✓	✓
CVC4	NYU, U. Iowa						✓	✓	✓	✓
ExtSat			✓							
Fx7				✓						
HTP		✓	✓							
Jat			✓							
Kleaver	Imperial									(2)
MathSAT 3,4,5	U. Trento, FBK	✓	✓	✓	✓	✓	✓	✓	✓	
MathSat-HeavyBV	U. Trento								✓	
MiniSMT	U. Innsbruck						✓			
NuSMV	FBK		✓							
OpenSMT, OpenSMT2	U. Lugano				✓	✓	✓	✓		✓
raSAT	JAIST									✓
Sammy		✓								
Sateen	U. Col-Boulder	✓	✓	✓	✓	✓				
SBT		✓								
Simplics	SRI	✓								
simplifyingSTP	U. Melbourne						✓			
SMTInterpol	U. Freiburg							✓	✓	✓
SONOLAR	U. Bremen						✓	✓	✓	✓
Spear				✓	✓					
STP, STP2	MIT		✓			✓		✓	✓	
STP-CryptoMiniSat4	Security Res. Lab.									✓
SVC	Stanford U.	✓								
sword	U. Bremen				✓	✓				
test_pmathsat	FBK-IRST						✓			
Tiffany de Wintermonte	U. Melbourne								✓	
veriT	Loria, UFRN					✓	✓	✓		✓
Yices, Yices2	SRI	✓	✓	✓	✓	✓				✓
Z3	Microsoft Res.			✓	✓			✓		
Total		11	11	9	13	12	10	11	11	18

Table 5: Changes in participation

	2005	2006	2007	2008	2009	2010	2011	2012	2014
Participants	12	12	9	13	12	10	11	10	18
New in given year	12	4	4	6	2	6	1	4	5
Continuing to the next year	8	6	7	10	4	7	7	6	10
Not ever participating again	4	5	2	2	6	3	4	4	

As in past competitions, the organizers included some publicly available historical solvers. These solvers are run in the competition for comparison, but are designated as demonstration only and are not eligible for any awards or designations of having won the competition. In result tables, these solvers are listed with their names in square brackets (e.g., [MathSat]). The organizers included current versions of MathSat and Z3. Also, during the competition, a bug-fix release of CVC4 (named CVC4-with-bugfix) was submitted and included as a demonstration only version (cf. §10).

History. Table 4 shows the historical participation of each solver. Note that sometimes versions and names change, or there are multiple related versions from the same team; generally speaking, though not always, a solver is improved from year to year. Table 5 summarizes that data in numbers of continuing participants. Except for the record turnout in 2014, there has been a steady 9-13 participants each year; each year there are an average of 4 new participants, about the same number of drop-outs, and an average of 7 continuing participants.

The introduction in 2010 of SMT-LIB v2 as the standard language for benchmarks was a significant event. The new language required solvers to revise their front-ends and to add new capabilities. As a result, some solvers did not continue participating, at least not immediately. The added expressivity of the command language permitted to add benchmarks representing the needs of industrial applications, and the application track of the competition was added to demonstrate the interactive capability and the corresponding abilities of solvers.

6. Competition Procedure

The full description of the 2014 SMT Competition's rules is found in the rules document (`http://smtcomp.sourceforge.net/2014/rules14.pdf`). The document describes the procedures for determining benchmark difficulties, selecting benchmarks for competition, and judging the results. The preparation and execution of the competition required the following matters to be decided and executed.

Decide the competition parameters. We set a timeout of 40 minutes for both wall clock and CPU time; the memory limit was 100 GB. A single solver-benchmark combination (job-pair) was run on a node at a given time. The benchmarks were scrambled; all benchmarks were run, rather than just a subset. StarExec made about 150 nodes available for the duration of the competition. The effect of the new timeout is discussed in §9.1. Though the memory limit was fairly generous, there were still a small number (202) of jobs that were killed during the competition because of excessive memory use.

Settle any adjustments on the rules and competition timeline, with time for comment. The competition rules are largely the same from year to year, but each year there are adjustments and improvements. Matters to be decided are the timeline for the competition, communication vehicles (including instantiating the website for the new competition), the various tracks and divisions, any adjustments to the benchmark selection procedure, the scoring rules, and policies on similar submissions and portfolio solvers. A novel aspect in 2014 was the need for policies regarding the FLoC Olympic Games [25], described in §10. During the competition, the organizers had to rule on two issues.

- First, whether solvers could be withdrawn from divisions after the competition began; our ruling was no, because that could raise a solver's overall performance score and could change which divisions were deemed competitive. This decision did affect the results of the FLoC medal competition.
- Second, whether a job-pair that responded with a result before the timeout limit, but did not exit until after the timeout limit, is to be considered a timeout or a correct or wrong answer; the ruling was that it is not a timeout. Only one benchmark was affected by this decision and the decision did not affect any winning order, just a slight change in one solver's score.

The organizers also received and adjudicated an appeal after the competition completed (cf. §10).

Undefined behavior. During the testing period prior to the competition beginning, different solvers exhibited different behavior on some benchmarks. Investigation revealed that these differences were the result of different treatments of partial operations; in particular, divide by zero. The semantics of SMT-LIB is based on a logic of total functions, meaning that division by zero cannot raise an exception (or the like), but must have *some* value. The SMT-LIB standard leaves this value unspecified (i.e., it could be anything). In contrast, some solvers assume a specific, fixed value. This question had been discussed at length over previous years, with proposals to clarify the SMT-LIB standard. There was certainly not time to resolve this matter prior to the competition, not to mention correcting solvers to the agreed behavior.[2] Thus, for the competition, we decided to omit all benchmarks (6060 of them, 1348 of which were otherwise eligible) that were potentially affected by divide-by-zero behavior. This question, however, remains open.

Invite and validate solver submissions. The 2014 competition saw the first use of the StarExec computational cluster (cf. §7) for executing the competition. Each solver had to be wrapped in appropriate scripts to be able to run in the StarExec environment. Though this was largely the responsibility of the solver submitter, teams submitting solvers for the first time required guidance and assistance from the organizers and the StarExec development

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[2] The discussion this time around can be found in the archives of the `smtcomp-discussion@lists.sourceforge.net` mailing list, in the few days near 2014-06-16.

team. This was a significant hurdle; not all solver teams were able to complete it in time. The most significant problem was the need to create a fully statically linked version of the solver that ran on the particular version of Linux used by StarExec. The organizers stipulated a first solver submission deadline and a final solver submission deadline, separated by two weeks, to enable (and encourage) trials and debugging of solver submissions.

Solver submissions comprise the solver itself, a short system description outlining what is new or novel about the solver, and an integer seed used as input to the scrambler (as described in §4.2).

Invite and validate benchmark submissions. New benchmarks are always welcome and an impending competition is a particular opportunity to encourage new submissions. Benchmarks are the responsibility of SMT-LIB coordinators, not the competition organizers. Nevertheless, the organizers worked with the coordinators to ensure that new benchmarks were included in SMT-LIB in time for the competition. Initial submissions are often incomplete; to be useful they must be syntactically correct, include a designation of the logic in which they fit, contain relevant metadata about the source and category of the benchmark, and have a known, validated answer. Benchmarks with unknown answers may also be interesting and worth keeping, but cannot be used in the competition.

Create an appropriate selection of benchmarks. Not all benchmarks in the SMT-LIB database are necessarily used in the competition. The details of this selection, as executed for the 2014 competition, are described in §4. Part of the work in preparing the competition to run on the StarExec cluster was to port the benchmark selector to StarExec.

Prepare the benchmark scrambler. All the benchmarks are public and known to the solver developers beforehand. Indeed, part of the point of the benchmark database is to serve as a testbed for solver development, outside of competitions. However, that raises the possibility that a solver will recognize a benchmark problem by its syntactic structure and look up an answer from a learned database, without doing any logic solving. This is explicitly considered cheating. As a slight impediment against such behavior, the benchmarks are individually scrambled before being presented to a solver, using the random seed described above. For 2014, the benchmark scrambler had to be ported to StarExec.

The scrambling does not change the semantic meaning of the benchmark. It does rename identifiers, alter the order of assertions and the position of the arguments in the application of associative-commutative operators.

The scrambling had another effect, previously unappreciated. Although most of the solvers are deterministic for a given input, scrambling can change the order of search. For example, iterating over the contents of a hashed set may occur in a different order if identifiers have different names. Consequently, the success of the solver on a given benchmark, the time it takes to find an answer, and even whether a latent bug in the solver is triggered may all depend on just how the benchmark is scrambled. Thus the scrambling adds a measure of uncertainty to the competition and prevents full testing on the benchmark set before the competition. Indeed, one solver encountered a bug during the competition that was directly related to the specific, randomly-chosen scrambling used during the competition. The effect of the possible variations in performance caused by scrambling is expected to be balanced by the large number of benchmarks employed in the competition to compare the solvers, as also observed in the SAT community [8]. Nevertheless, this point is worthy of future further investigation.

Prepare the real-time results display. The participants are interested in the progress of the competition as it proceeds. The organizers also need to know if the competition is proceeding correctly and at a reasonable pace. As the competition takes several days, an automatic real-time display of results is helpful and encourages interest. StarExec does not have such a facility, since different competitions have different needs. Instead the organizers used StarExec's command-line API to regularly (every 10 minutes or so) download the status of all of the executing jobs, extract the results for each solver-benchmark pair, create HTML web pages displaying the current status, and upload them to the competition website. The current (now final) status of each division and a summary page can be seen at `http://smtcomp.sourceforge.net/2014/results-toc.shtml`.

Execute the competition. Executing the competition required preparing a StarExec job for each division. A job executes the cross-product of a set of solvers and a set of benchmarks. Because each division has different sets of solvers and benchmarks, each division was represented by one or more jobs. Splitting a division into multiple jobs allowed a restart of portions of the competition if a particular division was incorrectly configured or if a StarExec job stalled for some reason (both of which happened).

In addition, with the new cluster, the new benchmarks, and a longer timeout period, the organizers were unsure how long the competition would take. Our conservative estimate was that a month of computing was needed; in fact it only took about a week, because we had three times more StarExec nodes available than anticipated and jobs took on average less time than estimated. However, to hedge against the competition taking longer than anticipated, we divided larger divisions into *heats*, with each heat comprising about 1000 benchmarks, and with the option (stated in the rules) to terminate the competition before all heats were executed to ensure a timely end prior to FLoC. This required handling a much larger number of StarExec jobs. In the end it was entirely unnecessary for timely completion, but, as mentioned, dividing the jobs into manageable pieces was useful for restarting portions of the computation when StarExec stalled.[3]

In past competitions, the competition was timed to have its last portion overlap with the conference with which it was affiliated. In 2014, because the computation took less time than anticipated, the competition finished well before the conference.

Report the results. The results of the competition were reported at the SMT Workshop and in this paper.

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[3] Stalling—that is, no longer making forward progress on a job—was less a concern after some bug fixes during the competition, but was still observed during some post-competition computations.

Table 6: Competition timeline

Jul. 2013	Cok appointed as chair of the organizing committee
Dec. 2013	Déharbe and Weber appointed as co-organizers
21 Jan. 2014	call for applications and benchmarks
15 May 2014	deadline for new benchmarks; benchmarks were being corrected and curated throughout May and June, until the final solver deadline
19 May 2014	revised competition rules posted
1 Jun. 2014	deadline for initial solver registration; final competition rules posted
15 Jun. 2014	deadline for final solver registration
16 Jun. 2014	computation begins
22 Jun. 2014	main track computation ends; official results posted on 27 June
22 Jun. 2014	deadline for application track solvers
28 Jun. 2014	application track computation
17 Jul. 2014	SMT Workshop at which results were announced
21 Jul. 2014	FLoC Olympic Games Awards Ceremony

Competition timeline. The preparation and execution of SMT-COMP 2014 took place over about 7 months, relying on the experience of previous competitions, the 2013 SMT Evaluation, and development activity on StarExec. The timeline is provided in Table 6 for transparency and as a guideline for forthcoming editions of the competition.

7. StarExec

The competition used the NSF-funded StarExec [31] computational cluster at the University of Iowa for executing solvers on benchmarks. Past instances of SMT-COMP used a previous SMT-Exec infrastructure. StarExec was used for several other competitions in 2014 as well.

StarExec currently consists of 192 2.4 GHz computational nodes, running Red Hat Linux 6.3. Each node has two quad-core CPUs (model Intel Xeon E5-2609, 2.4 GHz, 10 MB cache), and either 129022 MB (32 nodes) or 258294 MB of memory (160 nodes). In competition, processes were limited to 100 GB memory. To avoid interference among job-pairs, only one job-pair was executed at a time on each node. The software configuration contains

- Linux kernel 2.6.32-573.1.1.el6.x86_64
- GNU C Library stable release version 2.12
- gcc (GCC) 4.4.7 20120313 (Red Hat 4.4.7-11)

For comparison, the previous computational cluster (SMT-Exec) had just 11 nodes:

- Nine were 2.4 GHz AMD Opteron 250s, configured for single core, 64-bit processing, 1 MB cache, 4 GB main memory
- Two were 2.53 GHz Intel Xeon E5540s, configured for single core, 64-bit processing, 8 MB cache, 12 GB main memory

All SMT-Exec nodes had been running Red Hat Enterprise Linux Client release 5.2 (Tikanga), with the following software configuration:

- Linux kernel 2.6.18-128.2.1.el5
- glibc-2.5-24.el5_2.2
- runtime libraries from gcc-4.1.2-42.el5

The raw CPU speed is not significantly different, but memory size, number of cores, and number of nodes is greatly increased.

As this was the first year SMT-COMP used StarExec, a variety of tools and procedures needed to be ported to the new infrastructure, as described in §6. The execution of SMT-COMP on StarExec went well, though not flawlessly: there were some bugs to work through. The organizers had some bugs of their own: the scripts to create sets of benchmarks and jobs did not account for spaces in filenames; some initial report generation was incorrect; the postprocessor for translating textual output from solvers into official results needed fine-tuning. These problems were all fixed before or early in the competition. The main issue with StarExec itself was that sometimes jobs would hang or the StarExec infrastructure would fail to make progress or would report results incorrectly. Bugs in scheduling were fixed during the competition but are not entirely resolved. Accordingly, jobs need regular monitoring to insure they are making progress.

Overall, however, StarExec performed its function well and the support team was responsive in fixing any difficulties: evaluations of 339,714 job-pairs were completed for the competition over a period of about 9 days, including the restarts necessary because of bugs or misconfigurations.

8. Other Competitions

Competitions among tools for a specific purpose are now common. Indeed SMT-COMP participated among a dozen or so competitions in the FLoC Olympic Games in 2014 [33]. The competitions differ, of course, in their target problem set, but also in their overall goals, scoring policies, and organization.

CASC SMT differs from the CASC competition [28] in directly addressing sorted logics. SMT also focuses on fragments of first-order logic that are *decidable*. For example, a subset of the benchmarks are problems in an integer-difference logic, for which there are specific decision procedures. The competition among tools is to create very efficient implementations of a breadth of decision procedures. Accordingly, SMT solvers have historically not handled logics with quantified expressions, though several solvers now do so, responding to strong encouragement from industrial users to include quantification in SMT solvers; there are benchmarks and competition divisions corresponding to logics with quantification. Including quantified expressions can, in general, make the satisfiability problem undecidable and the solvers necessarily rely on heuristics. Solvers may respond that the answer to a problem is unknown; that is, although there may be a candidate satisfying value assignment, the solver cannot assure that some combination of instantiations of quantified formulas might not invalidate the assignment. Nevertheless, the inclusion of logics with quantification has been welcome by users. With SMT solvers moving to include quantification and CASC solvers moving to include types and arithmetic, we see a basis for fruitful future collaboration and perhaps merging between these communities.

The organizers of SMT-COMP helped organize and execute the first edition of SL-COMP [29, 30] as a sibling competition. SL-COMP is a competition among solvers for separation logic. The formal logical underpinnings of SL-COMP are still being defined and the relationship between the logic used in SL-COMP and the SMT-LIB logic is under discussion. However, SL-COMP did express its benchmark problems in the same syntax as SMT-COMP, used the same StarExec hardware, and used similar organization and scoring rules.

SL-COMP Besides the subject material, the most interesting difference among competitions is in scoring. (The scoring procedure for SMT-COMP is described in detail in Section 10.) Competitions are currently mostly focused on raw solver capability—that is, the numbers and difficulty of problems that can be solved. Thus competition winners are primarily determined by the total number of problems solved correctly, with the time taken to produce the solutions used only as a tie-breaker. This is the case for SMT-COMP, SAT, and SV-COMP, for example.

Scoring differences. A more significant issue is how solver errors are taken into account in the metrics. A solver error indicates an unsoundness in the tool, which is highly undesirable; however, highly penalizing errors may discourage new entrants whose tools are not yet mature. Different competitions vary on this aspect. SMT-COMP has historically emphasized soundness; a single error in a division caused the solver to be scored lower than any other solver with no errors, even if the other solvers solved very few problems. In its inaugural edition, the Separation Logic Competition (SL-COMP) adopted the same rules as SMT-COMP. For the SAT competition, however, an error outright disqualifies a tool in the category it occurs.[4.] In the QBF Gallery, a competitive evaluation of solvers for Quantified Boolean Logic, the score is the number of solved instances. In contrast, in the SV-competition [9], successful runs account positively towards the final score, while errors count negatively (with an increased weight). A few other sibling competitions with scoring variations are the Answer-Set Programming competition (ASP-COMP: wrong answers for some problem instance cause an overall score of zero for the problem), the Confluence Competition (CoCo: implausible answers disqualify from winning), and Syntax-Guided Synthesis (SyGuS-COMP: no points for wrong answers, extra points for succinct answers).

[4.] See `http://satcompetition.org/2014/rules.shtml`.

9. Results

9.1 Main track results

Table 7 shows a summary of the main track results. The detailed data for each division is on the competition website: `http://smtcomp.sourceforge.net/2014/results-toc.shtml`.

The results of the competition per se were not surprising. The solvers that performed best in previous years continued to do so. Boolector wins those divisions that focus on bit-vector problems; CVC4 has the most breadth of application and wins most of the other divisions, with Yices2 also having a strong showing. Solvers that were optimized with particular decision procedures for particular logics can capture individual wins: AProVE for QF_NIA; veriT for UFLRA. If Z3 had competed, with the current version entered by the organizers, it would have won many divisions, but not all; CVC4 is definitely competitive with it.

In the medal ceremony for the competition at the SMT Workshop, the organizers took care not to focus only on the winning solvers. The competition was also successful in attracting new interest and many new entrants, even when the new entrants did not score highly or had errors in their submissions. In that sense the decision of the SMT steering committee to pause the competition for a year, to 'reboot' it and give contestants some breathing room, was also successful.

The organizers chose not to try to make a detailed comparison with previous years' results. Such a comparison had just been completed in the 2013 Evaluation exercise. Furthermore, with the change in computation hardware, an accurate comparison would have required running all of the 2012 solvers along with the 2014 solvers and making a comparison on just the benchmarks used in the 2012 competition. While this is certainly possible, the organizers were not confident enough of the ability of the new StarExec to complete even the 2014 competition to contemplate doubling the computational load. In addition, such an exercise was out of the scope of their mandate and would have required considerable extra effort. However, knowing now that StarExec is fully capable of executing all of the competition benchmarks, such a comparative exercise would be definitely possible in the future. The organizers are confident that the 2014 data will be a solid baseline for evaluating progress in solver performance in future years.

Fastest solvers. The competition does not weight time to solve a problem significantly. However, this is an important characteristic to any user. Hence we analyzed the competition results for each division to answer this question: for each solver, what fraction of the benchmarks for the division does that solver solve the fastest? The data answering this question is shown in Table 8. For each division and each benchmark, we determined the solver that solved that benchmark the fastest, and for each solver counted the number of benchmarks for which it was the fastest. The table lists the three solvers with the most such benchmarks, with the fraction of benchmarks that it won. The winning solvers are a mix of Z3, CVC, Yices2, and a few for veriT. In some divisions, the winning solver does dominate the competition. Yices2, for example tends to win in those divisions in which it participates, with Z3 winning most of the others. Note that this analysis does not take into account the

Table 7: Main track results

Logic	Solvers	Benchmarks	Order (winner in bold)
ALIA	4	29	[Z3]; **CVC4**; veriT; CVC3.
AUFLIA	4	4	**CVC4**; [Z3]; CVC3; veriT.
AUFLIRA	4	10791	[Z3]; **CVC4**; CVC3; veriT.
AUFNIRA	4	564	[CVC4-with-bugfix]; [Z3]; **CVC3**; CVC4.
LIA	4	46	[Z3]; **CVC4**; CVC3; veriT.
LRA	4	171	**CVC4**; [Z3]; CVC3; veriT.
NIA	3	9	[Z3]; **CVC4**; CVC3.
NRA	3	3747	[Z3]; **CVC4**; CVC3.
QF_ABV	9	6457	**Boolector-j**; Boolector-d; [MathSAT]; SONOLAR; CVC4; [Z3]; Yices2; Kleaver-STP; Kleaver-portfolio.
QF_ALIA	5	97	**Yices2**; SMTInterpol; [Z3]; [MathSAT]; CVC4.
QF_AUFBV	4	37	**CVC4**; Yices2; [Z3]; [MathSAT].
QF_AUFLIA	6	610	**Yices2**; [MathSAT]; [Z3] SMTInterpol; CVC4; veriT.
QF_AX	5	335	**Yices2**; [MathSAT]; [Z3]; CVC4; SMTInterpol.
QF_BV	11	2488	**Boolector**; STP-CryptoMiniSat4; [CVC4-with-bugfix]; [MathSAT]; [Z3]; CVC4; 4Simp; SONOLAR; Yices2; abziz_min_features; abziz_all_features.
QF_IDL	4	1315	[Z3]; **Yices2**; CVC4; veriT.
QF_LIA	7	4381	[CVC4-with-bugfix]; [MathSAT]; **SMTInterpol**; Yices2; [Z3]; veriT; CVC4.
QF_LRA	6	1343	**CVC4**; Yices2; [MathSAT]; SMTInterpol; veriT; [Z3].
QF_NIA	4	8327	[Z3]; **AProVE**; CVC3; CVC4.
QF_NRA	4	10121	[Z3]; **CVC3**; CVC4; raSAT.
QF_RDL	4	132	**Yices2**; [Z3]; veriT; CVC4.
QF_UF	7	4124	**Yices2**; veriT; CVC4; OpenSMT2; [Z3]; [MathSAT]; SMTInterpol.
QF_UFBV	4	31	**Yices2**; [Z3]; [MathSAT]; CVC4.
QF_UFIDL	4	311	[Z3]; **Yices2**; CVC4; veriT.
QF_UFLIA	6	484	[Z3]; **Yices2**; CVC4; SMTInterpol; [MathSAT]; veriT.
QF_UFLRA	6	1176	[Z3]; **Yices2**; [MathSAT]; CVC4; SMTInterpol; veriT.
QF_UFNIA	3	7	**CVC4**; [Z3]; CVC3.
QF_UFNRA	3	32	[Z3]; **CVC3**; CVC4.
UF	4	2830	**CVC4**; [Z3]; CVC3; veriT.
UFIDL	3	49	[Z3]; **CVC4**; CVC3.
UFLIA	4	5766	**CVC4**; [Z3]; veriT; CVC3.
UFLRA	4	25	[Z3]; **veriT**; CVC3; CVC4.
UFNIA	3	1587	[Z3]; **CVC4**; CVC3.

Table 8: Fraction of benchmarks solved fastest (cpu-time) by each solver (top 3)

Logic	Fraction solved fastest		
ALIA	51% [Z3]	48% veriT	
AUFLIA	66% [Z3]	33% CVC3	
AUFLIRA	60% [Z3]	37% veriT	1% CVC3
AUFNIRA	72% [Z3]	23% CVC3	2% CVC4
LIA	43% CVC4	30% [Z3]	17% CVC3
LRA	42% CVC4	38% veriT	18% [Z3]
NIA	66% [Z3]	33% CVC4	
NRA	96% CVC4	3% [Z3]	
QF_ABV	78% Yices2	9% SONOLAR	7% Kleaver-STP
QF_ALIA	95% Yices2	4% [Z3]	
QF_AUFBV	81% Yices2	10% [MathSAT]	5% [Z3]
QF_AUFLIA	60% Yices2	38% [Z3]	1% CVC4
QF_AX	92% Yices2	6% [Z3]	0% CVC4
QF_BV	33% Yices2	25% [Z3]	13% 4Simp
QF_IDL	87% Yices2	11% [Z3]	0% veriT
QF_LIA	76% Yices2	11% [Z3]	7% CVC4
QF_LRA	86% Yices2	3% veriT	3% CVC4
QF_NIA	90% [Z3]	7% AProVE	1% CVC3
QF_NRA	88% [Z3]	6% CVC4	4% CVC3
QF_RDL	71% Yices2	25% [Z3]	3% veriT
QF_UF	96% Yices2	1% veriT	1% [Z3]
QF_UFBV	96% Yices2	3% [MathSAT]	
QF_UFIDL	59% [Z3]	36% Yices2	3% veriT
QF_UFLIA	97% Yices2	2% [Z3]	0% CVC4
QF_UFLRA	91% Yices2	4% [Z3]	2% veriT
QF_UFNIA	100% CVC4		
QF_UFNRA	59% CVC3	37% [Z3]	3% CVC4
UF	37% veriT	32% CVC4	24% [Z3]
UFIDL	57% CVC4	42% [Z3]	
UFLIA	56% [Z3]	35% veriT	7% CVC4
UFLRA	95% veriT	4% [Z3]	
UFNIA	80% [Z3]	10% CVC3	9% CVC4

margin by which the times are better. The times used here are cpu-times; using wall-clock times changes the fractions and sometimes the order, but not the overall observation.

Solver contribution. A second comparison that can be made is to determine what a solver adds in addition to what other solvers contribute. We measure this 'solver contribution' as follows. For each benchmark in a division, we award each solver that solves the benchmark $1/n$ points, where n is the number of solvers that solved the benchmark (within the timeout). These points are then summed over all the benchmarks in the division and scaled by the number of benchmarks. The sum is a measure of the unique contribution pro-

Table 9: Contribution from each solver (top 3)

Logic	Unique contribution		
ALIA	0.4253 [Z3]	0.4080 CVC4	0.1667 veriT
AUFLIA	0.3889 CVC4	0.2778 [Z3]	0.2222 CVC3
AUFLIRA	0.2615 [Z3]	0.2521 CVC4	0.2503 CVC3
AUFNIRA	0.2509 [Z3]	0.2506 CVC4	0.2497 CVC3
LIA	0.3949 [Z3]	0.3514 CVC4	0.2319 CVC3
LRA	0.3070 CVC4	0.3070 [Z3]	0.2895 CVC3
NIA	0.8333 [Z3]	0.1667 CVC4	0.0000 Yices2
NRA	0.5071 [Z3]	0.4929 CVC4	0.0000 Yices2
QF_ABV	0.1147 Yices2	0.1146 Boolector-just...	0.1144 Boolector-dual...
QF_ALIA	0.2235 Yices2	0.2235 SMTInterpol	0.2235 [Z3]
QF_AUFBV	0.2635 [MathSAT]	0.2635 CVC4	0.2500 Yices2
QF_AUFLIA	0.1996 Yices2	0.1996 [MathSAT]	0.1996 CVC4
QF_AX	0.2000 Yices2	0.2000 [MathSAT]	0.2000 CVC4
QF_BV	0.1051 Boolector	0.0976 STP-Crypto...	0.0934 abziz_min_f...
QF_IDL	0.2893 [Z3]	0.2731 Yices2	0.2395 CVC4
QF_LIA	0.1620 [CVC4-...fix]	0.1610 [Z3]	0.1610 SMTInterpol
QF_LRA	0.1772 CVC4	0.1689 Yices2	0.1678 SMTInterpol
QF_NIA	0.4990 [Z3]	0.4912 AProVE	0.0084 CVC3
QF_NRA	0.7714 [Z3]	0.1347 CVC3	0.0898 CVC4
QF_RDL	0.2734 Yices2	0.2431 veriT	0.2431 [Z3]
QF_UF	0.1451 Yices2	0.1449 veriT	0.1446 CVC4
QF_UFBV	0.4140 Yices2	0.3172 [Z3]	0.1720 [MathSAT]
QF_UFIDL	0.2708 Yices2	0.2708 [Z3]	0.2309 CVC4
QF_UFLIA	0.1698 Yices2	0.1698 [MathSAT]	0.1698 CVC4
QF_UFLRA	0.1715 [Z3]	0.1681 Yices2	0.1681 [MathSAT]
QF_UFNIA	0.5000 CVC4	0.5000 [Z3]	0.0000 Yices2
QF_UFNRA	0.5802 [Z3]	0.2099 CVC4	0.2099 CVC3
UF	0.4921 CVC4	0.1988 [Z3]	0.1759 CVC3
UFIDL	0.5204 [Z3]	0.4796 CVC4	0.0000 Yices2
UFLIA	0.4069 CVC4	0.3502 [Z3]	0.2425 veriT
UFLRA	0.2857 [Z3]	0.2381 CVC4	0.2381 veriT
UFNIA	0.4156 [Z3]	0.3860 CVC4	0.1984 CVC3

vided by a solver; a value of 1.0 would indicate that that solver was the only solver to solve all of the benchmarks in the division. The results are shown in Table 9. The results show again that no one solver dominates in all categories, but that there are several contributing solvers among which users can choose.

Effect of timeout. For the main track of the competition, the organizers set a timeout of 40 minutes, much longer than in previous competitions (e.g., 25 minutes in 2012). The timeout values cannot be directly compared because the hardware changed as well. The larger timeout simply reflected the organizers' goal to allow solvers as much time as possible

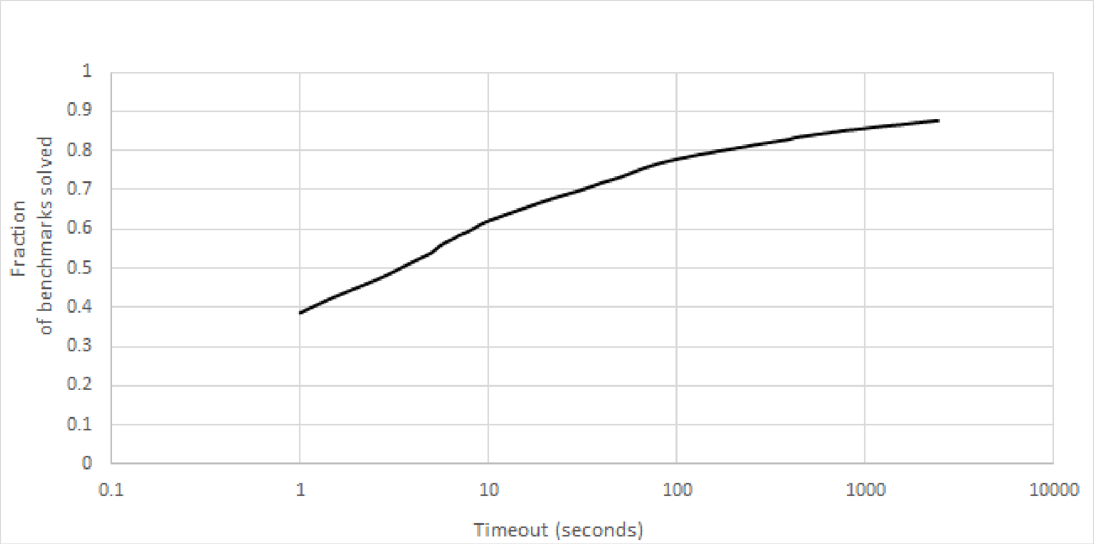

Figure 2: Solver success for QF_BV benchmarks over time.

to complete each benchmark problem. A common practical question users have is how much benefit is gained by longer timeouts. The data from the competition allows us to analyze this question somewhat.

A first question is how many additional problems are solved if the timeout is lengthened. An approximation of an answer is shown in Fig. 2. This figure shows the number of benchmarks solved, combined over all the solvers participating in the competition, with a solution time less than given timeout values, for the QF_BV benchmark set. Most of the benchmarks are solved quickly: 39% in less than a second, more than half in under 3.5 seconds, 62% by 10 seconds, and then a slow increase to 88% by 2400 seconds. There is continual improvement for long timeouts, but the return on time invested certainly decreases.

There are two caveats to this observation. First, the results depend heavily on the character of the benchmarks set. Some logics have only easy benchmarks, some have purposefully crafted difficult benchmarks, others are a mix. The benchmarks are not a representative sampling of problems that might be encountered in practice. Second, the results described are obtained by observing the wall-clock solution time when the timeout value is set at 2400 seconds. Solvers, if told what the timeout value is, have the option to adjust their search strategies based on the timeout; the solvers might then exhibit better behavior for shorter timeout.[5.]

Table 10 shows a different view of the same data. Here we present the number of problems solved by each solver within a given wall-clock solution time, subject to the same caveats. The point to observe is that the winning solver changes depending on the timeout chosen.

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[5] Though solvers could use the timeout value to alter their processing algorithms, current versions of those queried—Yices2, Z3, Boolector—do not do so. However, CVC4 and CVC3 do build in the stated timeout into the script used for competition (though it is not used by the core solver) and so might show differences from the behavior stated here.

Table 10: Solver success per individual solver for 2488 QF_BV benchmarks, for different timeouts (in seconds).

	4Simp	Boolector	CVC4	SONOLAR	STP-CryptoMiniSat4	Yices2	[CVC4-with-bugfix]	[MathSAT]	[Z3]	abziz-all-features	abziz-min-features
0.5	824	683	886	712	728	**963**	830	608	919	839	840
1.0	1058	787	1089	928	923	**1101**	1003	841	1084	1043	1045
2.0	1184	979	**1293**	1139	1015	1187	1174	957	1224	1253	1252
4.0	1306	1158	**1532**	1249	1250	1261	1410	1078	1434	1444	1447
10.0	1581	1441	**1826**	1494	1433	1359	1695	1255	1620	1771	1818
20.0	1698	1693	**1946**	1563	1551	1426	1802	1424	1771	1866	1888
40.0	1762	2009	**2155**	1633	1680	1484	2017	1560	1865	1951	1961
100.0	1850	2150	**2226**	1726	1858	1563	2114	1736	1953	2091	2111
200.0	1912	2220	**2257**	1802	2025	1623	2153	1869	1997	2108	2142
400.0	1970	2275	**2279**	1892	2163	1660	2183	1999	2033	2131	2171
800.0	2042	**2310**	2296	1964	2241	1702	2222	2116	2077	2187	2223
1200.0	2074	**2336**	2307	1998	2256	1718	2239	2145	2106	2207	2241
2400.0	2121	**2361**	2307	2026	2283	1770	2239	2199	2180	2234	2277

For these benchmarks and this set of solvers Yices2 performs best for timeouts under a second, CVC4 does best in the middle range from 1 to 200 seconds, and Boolector does best above 400 seconds. Other logics, but not all, show changes in winning order as well. This phenomenon could be a result of differences in engineering of the individual solvers or it could be a result of characteristics of the benchmark set.

The data in Table 10 also shows that most solvers have a similar trend in success as the timeout is increased. For example, most solvers solve about 50% (ranging from 40% to 62%) of the benchmarks that solver solves within the timeout by 1.0 second and about 75% (ranging from 65% to 79%) of those solved within the timeout by 10 seconds. However, some solvers, such as Boolector, are outliers: Boolector is slow off the mark—solving only 33% and 61% of the benchmarks it eventually solves by 1 second and 10 seconds, respectively, even though by 2400 seconds it solves more benchmarks than any other tool, in this division.

9.2 Application (incremental) track results

Most solvers are only concerned with raw performance on single benchmarks. However, an important application area for SMT solvers requires what the SMT-LIB standard calls ‘incremental’ operation. In this mode, a user or some application interacts with the solver repeatedly, issuing various commands to define a problem, check for satisfiability, inspect resulting counterexample models, adjust the problem by retracting some assertions and adding other assertions, and so on. An example use case is a tool that allows a user to author formal specifications in conjunction with software. The tool would check using a back-end SMT solver whether the specifications are consistent with the code. If not, it might supply a counterexample that could be inspected in conjunction with the source code. As the user edits the source or the specifications, the problem presented to the SMT solver is modified.

The application track of the competition presents to the solver a series of SMT-LIB commands through a driver program; the solver replies to the driver with a response to each command. The driver presents commands only one at a time to emulate a realistic environment and so that the solver cannot "work ahead." The driver also measures the accumulated time taken for each response. Note that the time measured includes the response time to every command, not just to the satisfiability-checking commands; while **check−sat** commands might be the most time-consuming, **assert** commands, and others, might also instigate significant processing. The benchmark text contains (**set−info** :status ...) commands that indicate the expected result for subsequent **check−sat** commands; status information is used only by the driver program and not passed on to the solver. Such **set−info** command might indicate a status of unknown; in that case, the driver considers the benchmark to end after the *previous* **check−sat** command for competition purposes. The driver originally used to collect the answers had a bug that was detected and reported by Kshitij Bansal [2], who also provided a corrected version of the driver. The results discussed in this section were obtained with this new driver and differ from those reported earlier, such as at the 2014 SMT Workshop.

The application track was first introduced in 2011; a report on that year's application track and the overall design was presented by Griggio and Bruttomesso at the 2012 COMPARE Workshop [12]. A significantly adapted driver was implemented by the organizers for 2014 on the StarExec framework.

In 2014, the SMT-LIB contains 9,926 benchmarks that specifically exercise the incremental solving capability of solvers. Table 11 lists the numbers of benchmarks in various logics; UFLRA, QF_UFLRA, and QF_UFLIA are the only logics with significant numbers of benchmarks. For now, AUFNIRA does not contain any valid **check−sat** command. All the benchmarks were used in the competition.

Four solvers participated in this competition track: CVC3, CVC4, SMTInterpol, and Yices2; Z3 was added as a demonstration-only historical comparison. The winner is the solver that solved the most **check−sat** commands correctly within the timeout period. No solver produced an erroneous result. The time out (40 minutes) is applied to the entire benchmark, not to individual commands. The track was run for 8 divisions; the results are shown in Table 12. Within each division, solvers are listed in winning order: Yices2 won four of the eight divisions, out of six in which it participated. CVC3, CVC4 and SMTInterpol won one division each. Since the previous execution of the application track was in 2012 and not on StarExec, we did not attempt a comparison with previous results.

Table 11: Numbers of application benchmarks and distribution of **check−sat** commands for different logics.

All benchmarks

Logic	Benchmarks	**check−sat** commands total	min	max	avg.
AUFNIRA	165	3452	2	615	20.9
QF_AUFLIA	72	4699864	5	1109912	65275.9
QF_BV	18	2727	101	202	151.5
QF_LIA	65	19690826	101	2630828	302935.8
QF_LRA	10	1515	101	202	151.5
QF_UFLIA	905	790630	1	474174	873.6
QF_UFLRA	3333	22103	2	3384	6.6
UFLRA	5358	3514613	2	40758	656.0

Eligible benchmarks

Logic	Benchmarks	**check−sat** commands total	min	max	avg.
AUFNIRA	165	0	0	0	0
QF_AUFLIA	72	4699864	5	1109912	65275.9
QF_BV	18	2141	52	202	118.9
QF_LIA	65	19689957	30	2630828	302922.4
QF_LRA	10	795	45	107	79.5
QF_UFLIA	905	766079	1	474174	846.5
QF_UFLRA	3333	22066	0	3384	6.6
UFLRA	5358	223820	2	201	41.8

We can also consider the effect of the choice of timeout on the application track. This effect is more complicated than for the main track since an application track benchmark can have partial results. For example, if a benchmark contains 100 check-sat commands, a solver may report correct answers on 0 to 100 of them prior to timing out. Furthermore the seven divisions that have results show very different characteristics. In four of the divisions (QF_AUFLIA, QF_UFLIA, QF_UFLRA, UFLRA) over 90% of the solver-benchmarks jobs were completed before the timeout; for QF_UFLRA it was over 99%. The other three divisions (QF_BV, QF_LIA, QF_LRA) had much harder benchmarks. For example, for QF_BV, only 1% of solver-benchmark pairs were completely solved by 1 second and only 42% by the timeout. These three divisions also have many fewer benchmarks—a few hundred, rather than several thousand. Changing the timeouts further might affect the results of these divisions significantly, but not those of the four divisions with many more benchmarks.

Table 12: Results of the incremental track, across eight divisions. In each division, solvers are listed in winning order.

Solver	Commands
QF_BV (18 benchmarks, 2141 commands)	
[MathSAT]	2022
Yices	1749
CVC4	1706
[Z3]	1621
AUFNIRA (165 benchmarks, 0 commands)	
CVC4	0
[Z3]	0
CVC3	0
QF_AUFLIA (72 benchmarks, 4699864 commands)	
Yices	3244375 (CPU time: 2182.6s)
[Z3]	3244375 (CPU time: 8564.3)
SMTInterpol	3244375 (CPU time: 9442.9)
CVC4	1051256
[MathSAT]	377
QF_LIA (65 benchmarks, 19689957 commands)	
Yices	19689907
[Z3]	19689683
SMTInterpol	19689059
[MathSAT]	17619155
CVC4	12648373
QF_LRA (10 benchmarks, 795 commands)	
[MathSAT]	793
SMTInterpol	746
Yices	742
[Z3]	728
CVC4	651
QF_UFLIA (905 benchmarks, 766079 commands)	
[Z3]	766078
CVC4	765522
SMTInterpol	764699
Yices	762831
[MathSAT]	761910
QF_UFLRA (3333 benchmarks, 22066 commands)	
Yices	22054
[Z3]	22053
SMTInterpol	22006
CVC4	21775
[MathSAT]	21515
UFLRA (5358 benchmarks, 223820 commands)	
[Z3]	223365
CVC3	67802
CVC4	66315

10. FLoC Olympic Games Scoring

The main track and the application track described in previous sections are staples of recent SMT Competitions. The 2014 edition was unique in also being associated with the FLoC Olympic Games [25]. This association was positive in providing a platform, along with the other competitions, to present the rationale, methodology and results of the SMT Competition to a wider audience than just the SMT community.

One additional aspect that resulted from the Olympic Games was the awarding of three medals to the three "winners" of the competition. Since SMT-COMP is organized into many separate divisions, with winners determined in each division independently, the organizers had to determine how to award three global prizes. The metrics for doing so were the subject of significant discussion both before and after the competition. The metrics were decided by the organizers before the competition began (and before the deadline for solver registration) and were maintained unchanged after the competition.

The organizers chose to award the bronze medal for the best performance in a single division. We chose the QF_BV division for this medal because it is significant to applications and because it traditionally received the most solver submissions. Indeed in 2014, there were 8 participants. Determining the winner was straightforward: we used the same metric as is used for each division—the most problems solved without errors, with ties broken by speed of solution. The Boolector [11] solver won this division and therefore the bronze medal. The results for all participating solvers are shown in Table 14.

The organizers chose to award the silver and gold medals for best performance across the most divisions. Thus we needed a metric that combined the results across divisions. We considered two metrics. For a given solver, let

- e_i be the number of benchmarks in division i for which an incorrect result was produced (that excludes timeouts, runtime errors and `unknown` answers);
- c_i be the number of benchmarks in division i solved correctly;
- t_i be the total time to solve the benchmarks in division i that were solved correctly;
- N_i be the total number of benchmarks in division i, used in the competition.

The normal metric for a division is that the winning solver is the one with the smallest value of e_i, the largest value of c_i and then the smallest value of t_i, for each division taken separately; that is, the metric is a lexicographic ordering by smallest value of $\langle e_i, -c_i, t_i \rangle$. The two global metrics we considered are

- Metric A: The winning solver is the one with the smallest value of $\sum_i e_i \log N_i$, then the largest value of $\sum_i (c_i/N_i)^2 \log N_i$, then the smallest value of $\sum_i t_i \log N_i$, where for a given solver the sums are over all competitive divisions in which that solver participated.
- Metric B: The winning solver is the one with the largest value of $\sum_i (e_i == 0\,?\,(c_i/N_i)^2 : -e_i) \log N_i$, then the smallest value of $\sum_i t_i \log N_i$, where for a given solver the sums are over all competitive divisions in which that solver participated.

Note that incorrect results are very rare in SMT-COMP, but do occur; for almost all solvers and divisions the value of e_i is 0 and the competition hinges on the values of c_i. The speed of the solver is important in two ways. First, if the solver is slow, it will time out before a solution is found and thus the value of c_i will be lower. Second, if there is a tie in the number of errors and correctly solved problems, the total time taken on the correctly solved problems is used as the tie-breaker (even if the solvers solve different subsets of benchmarks); this is a rare occurrence but does happen if, for example, all the benchmark problems in a division are solvable within the time limit—the only situation in the competition in which tie-breaking has been needed.

Only *competitive divisions* were included in the scoring (although all divisions were run and results reported). For determining medals, a division is competitive if there are at least two officially registered, participating solvers *from different teams.* This prevents a team from gaming the scoring by submitting multiple solvers to divisions in which no one else is participating. This criterion excluded a number of divisions from medal scoring: AUFNIRA, BV, NIA, NRA, QF_UFNIA, QF_UFNRA, UFBV, UFIDL, UFNIA.

The log scaling of the scores for each division is a somewhat arbitrary means to adjust the scores for the wide variety of numbers of benchmarks. If each division is treated equally, with a score, say, of 1.0 for the division for solving all the benchmarks in the division correctly, then the benchmarks for small divisions would count significantly more toward a composite score than those of divisions with many benchmarks. On the other hand, counting each benchmark equally appeared to underweight the effect of a solver's effort to participate in multiple divisions. The log scaling seemed a reasonable compromise between these two extremes. Similarly, the square of the fraction successfully solved is an approximate mechanism to give more weight to solving the harder problems.

Metrics A and B above differ in how errors are treated. If a solver has no errors, it is always better off to participate in as many divisions as possible. However, an error in a division penalizes a solver so that it would be better not to have participated in the division; hence the organizers ruled that once the competition had started, a solver could not be withdrawn from a division in which it was registered.

The penalty for an error is globally significant in Metric A: a single error in one division out of many would put the solver behind any other solver with no errors, even if that other solver participated in just one division. The penalty for an error is more local for Metric B: the error results in a large negative score for that division, which might be compensated by good performance in other divisions. Both metrics satisfy the criterion of putting heavy weight on correctness of solvers. The organizers published the choice of Metric A as the metric for the Olympic Games gold and silver medals in the rules prior to the beginning of the competition, with no objection during the comment period.

Though all solvers were scored for the medal metrics, five solvers participated in more than two divisions and were the most competitive during the course of the competition. The final results are shown in Table 13. The choice of metric did have a significant effect on the result. CVC4 and Yices2 participated in the most divisions, solved the most problems, and did so the most efficiently. However, Yices2 had a crash on one problem in QF_ABV, but had

Table 13: Gold and silver medal competition, in winning order by Metric A. By Metric B the order is the same except that CVC4 and Yices2 are in first and second place.

Solver	Competitive Divisions	Metric A Weighted errors	Weighted solved	Metric B
veriT	17	0.000	25.325	25.325
SMTInterpol	8	0.000	22.831	22.831
CVC3	10	0.000	9.618	9.618
SONOLAR	2	0.000	5.978	5.978
AProVE	1	0.000	3.776	3.776
Boolector-j	1	0.000	3.758	3.758
Boolector-d	1	0.000	3.755	3.755
OpenSMT2	1	0.000	3.582	3.582
Boolector	1	0.000	3.058	3.058
STP-CryptoMiniSat4	1	0.000	2.859	2.859
4Simp	1	0.000	2.468	2.468
raSAT	1	0.000	0.000	0.000
Yices2	15	3.810	38.624	31.059
CVC4	25	7.283	54.152	43.509
abziz_min_features	1	30.563	2.548	-30.563
abziz_all_features	1	30.563	2.403	-30.563
Kleaver-STP	1	213.362	3.103	-213.362
Kleaver-portfolio	1	346.713	3.073	-346.713

emitted an erroneous answer prior to the crash (a simple crash without an answer is scored the same as an 'unknown' response, marked neither wrong nor correct). CVC4 had bugs that affected AUFNIRA, which was not a competitive division, and QF_LIA, which was competitive. Consequently, by the competition metric, these two otherwise leading solvers placed much further back in the pack.

When the results were published, the resulting winning teams, veriT and SMTInterpol, put an appeal to the organizers to use Metric B instead, arguing that (i) CVC4 and Yices2 were clearly the more capable solvers and (ii) there were known bugs in the winning solvers as well, which, simply by good fortune, were not triggered by the competition benchmarks. However, after public comment acknowledging the good will of the winners, the appeal was not accepted by the organizers. The medal ceremony did highlight the differing contributions of all four teams as well as those of the bronze medal winner. Note that the discovered bugs were promptly fixed. In fact, CVC4 submitted an additional demonstration-only version, named CVC4-with-bugfix in the result tables, which the organizers ran in conjunction with the rest of the competition.

Table 14: Bronze medal competition (QF_BV division, 2488 benchmarks), in winning order.

Solver	Errors	Solved	Time (sec)
Boolector	0	2361	138077.59
STP-CryptoMiniSat4	0	2283	190660.82
[CVC4-with-bugfix]	0	2237	139205.24
[MathSAT]	0	2199	262349.39
[Z3]	0	2180	214087.66
CVC4	0	2166	87954.62
4Simp	0	2121	187966.86
SONOLAR	0	2026	174134.49
Yices2	0	1770	159991.55
abziz_min_features	9	2155	134385.22
abziz_all_features	9	2093	122540.04

11. Post-Competition Activity

After the competition, David Cok (competition chair) and Clark Barrett and Morgan Deters (SMT-LIB coordinators) collaborated, with the assistance of Aaron Stump (StarExec lead), in attempting to discover the status of the SMT-LIB benchmarks that were marked as unknown. For this computation, the timeout was set to 10 hours. This activity required several weeks of computation. A result confirmed by at least two solvers was obtained for 75% of the unknown benchmarks, with another 4% having a tentative result from just one solver. The results are shown in Table 15.

The unknown incremental benchmarks have yet to be resolved.

12. Concluding Observations and Recommendations

SMT-COMP 2014 successfully executed the comparison among solvers that is the main goal of the competition. The new computational infrastructure, StarExec, worked very well for the purpose. The competition saw a renewed interest in participation—there were record numbers of teams participating, solvers entered, teams and solvers that had never before participated, benchmarks used, and amount of computation performed. Although the 2014 results are not readily comparable to previous years (because of changes in benchmarks and equipment), the detailed performance of each solver on each benchmark from this first year using StarExec will be a solid baseline to measure improvements in the state-of-the-art of solver performance in future years. As a partial comparison, solvers that performed well in previous years were included in this year's competition.

The SMT steering committee proposed that SMT-COMP 2015 be held in association with the SMT Workshop, which itself will be affiliated with CAV 2015 in San Francisco, CA, USA from July 18-24, 2015. The SMT Workshop is being organized by Vijay Ganesh and Dejan Jovanović; the organizers of the competition are Tjark Weber, David Déharbe, and Sylvain Conchon.

Table 15: Benchmarks resolved in post-competition computation

Logic	Solvers	Unknown Benchmarks	Resolved by 2+ solvers as		Resolved by 1 solver as		Still unknown
			sat	unsat	sat	unsat	
AUFLIRA	2	168	0	3	0	3	162
AUFNIRA	2	468	0	23	0	23	422
BV	2	191	29	56	42	37	27
LRA	2	450	20	148	241	23	18
NRA	2	66	0	41	0	16	9
QF_ABV	4	4190	3629	373	0	1	187
QF_BV	4	28138	8838	19166	20	10	100
QF_IDL	3	537	324	118	20	14	61
QF_LIA	3	1279	743	230	234	4	68
QF_LRA	2	208	127	25	44	8	4
QF_NIA	3	927	2	0	39	246	640
QF_NRA	2	1392	0	36	283	168	905
QF_RDL	2	85	50	0	2	1	32
QF_UF	3	4	0	3	0	1	0
QF_UFLRA	3	87	82	2	2	0	1
QF_UFNRA	2	11	0	2	7	0	2
UF	2	2911	0	2	51	50	2808
UFBV	2	191	17	49	51	44	30
UFIDL	2	12	0	0	0	0	12
UFLIA	2	5499	0	1765	4	113	3617
UFNIA	2	1052	0	20	2	90	940
Total		47866	13861	22062	1042	852	10045

Observations Solver implementors continue to focus primarily on raw numbers of problems solved. We think that future competitions can help broaden the focus to encompass breadth of problems addressed, fast solutions on simple problems, and other features provided by the SMT-LIB command language.

An unexpected observation is that there is indeed a difference in outcome of even a straightforward competition depending on the value of timeout chosen. As a result, there might indeed be an interest and valuable result from trying a competition track focused on fast solving of relatively simple problems.

A satisfying observation is that there is reasonable competition among several highly-performing solvers, as measured by the unique contributions each makes and the distribution of fastest times.

Recommendations. Based on the experience of 2014, the 2014 organizers have the following recommendations or topics for consideration for future competitions.

- The 2014 competition used all available benchmarks; though the computation resources enable using all benchmarks, future competitions should consider how to make a principled selection to avoid over-representing benchmarks of particular types or origin.
- The competition has used numbers of solved benchmarks as the primary success criterion. Time to solve benchmarks should be considered more strongly. In particular, a separate track that emphasizes fast solution of fairly simple problems might be informative.
- Related to the previous point, currently if a solver times-out or issues a response of ‘unknown’, the time taken to do so is not counted in the accumulated time. Only the time taken to compute correct responses is counted towards the evaluation metric. A user’s experience, however, is that the time taken for a solver to say “I don’t know” is just as important as time to produce a useful answer. Thus we recommend that such computation time be included in the evaluation metric. Omitting this time has had no effect so far because time was little used in the overall metric.
- The comparison to a previous years’ results will now be easier because common hardware will be used and benchmark selection is simplified. Future organizers might also include a larger selection of the specific solver versions that were entered in previous competitions.
- A key improvement needed is better benchmark sets. Though the accumulation of benchmark problems since the inception of the competition is impressive, attention now needs to be paid to the quality and distribution of benchmarks. Some divisions are represented by only a few benchmarks; others have large numbers of similar benchmarks. Benchmarks representative of application scenarios are particularly important.
- Subsequent to SMT-COMP 2014, David Cok, Aaron Stump, Morgan Deters, and Clark Barrett collaborated in resolving the status of many previously unknown benchmarks. Those new expected results are not yet included in the SMT-LIB benchmarks on

StarExec. They should be incorporated into SMT-LIB on StarExec prior to the next competition.

- If a global metric is needed again in the future (per §10), a review and re-discussion of the appropriate metric should be instigated.
- Solvers with breadth of application across many logics and solvers that address problems in new logics such as string and floating point computations are important to users. Future competitions should add tracks or otherwise find means to reward solvers that implement such capabilities.
- Various competition tracks used in the past should be rejuvenated: parallel processing, computation of unsat cores, production of proofs, computation of symbolic models, and computation of concrete counterexamples.
- One missing tool is a standard SMT-LIB syntax checker. jSMTLIB [14] has been proposed for this purpose, but is not yet integrated into StarExec. The tool also needs to be updated to include the proposed new SMT-LIB features.
- The difficulty in preparing a new solver for submission to StarExec for participation in SMT-COMP should be reduced.
- A general means to resolve questions surrounding partial definitions is needed in SMT-LIB, e.g., for divide-by-zero (cf. §6).
- An item for study is the effect of benchmark scrambling on the outcome of solver comparisons.
- Clearly define the subset of SMT-LIB v2 that solvers must support for a competition and that benchmarks must use.

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