Hardware Model Checking Competition 2011

HWMCC'11

Chairs

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Technical Advisors

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presented at

Formal Methods in Computer Aided Design 2011

FMCAD'11

Austin, TX, USA

November 2, 2011

aposterio updated version from 21st Nov. 2011

Motivation

- revive interest in improving symbolic model checking technology
  - symbolic model checking does not scale *enough* in practice
  - only recently new academic research results
  - benchmarks have been lacking
- try to repeat success story of SAT/SMT competitions
  - simple standardized input format ⇒ AIGER
  - motivation for young researchers to enter this field
  - provide “standard set” of benchmarks
- relies on active support by submitters of benchmarks and model checkers

History

AIGER format AVM’06 Ascona	1st HWMCC CAV’07 Berlin	2nd HWMCC CAV’08 Princeton	3rd HWMCC CAV’10 FLOC’10 Edinburgh	**4th** **HWMCC** **FMCAD’11** **Austin**
Founding Lunch CAV’06 FLOC’06 Seattle		HWMCC Lunch FMCAD’08 Portland		
2006	2007	2008	2010	**2011**

- founding lunch CAV’06: Biere, Cimatti, Claessen, McMillan, Somenzi

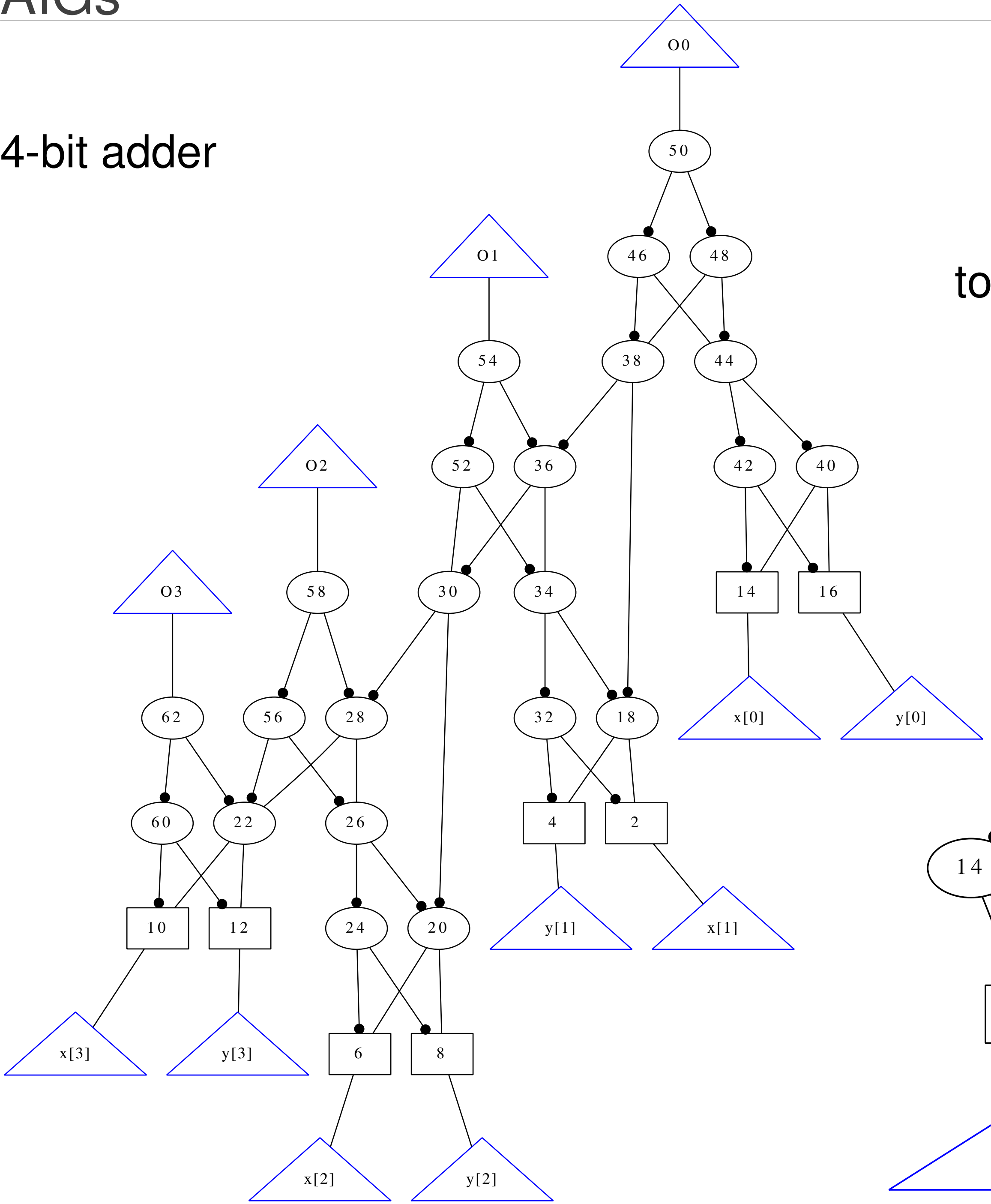
- HWMCC lunch at FMCAD’08: should have benchmarks with multiple properties !!!

- HWMCC’10 with reduced committee: Biere, Claessen
  - still no *multiple properties* ⇒ same competition mode as before

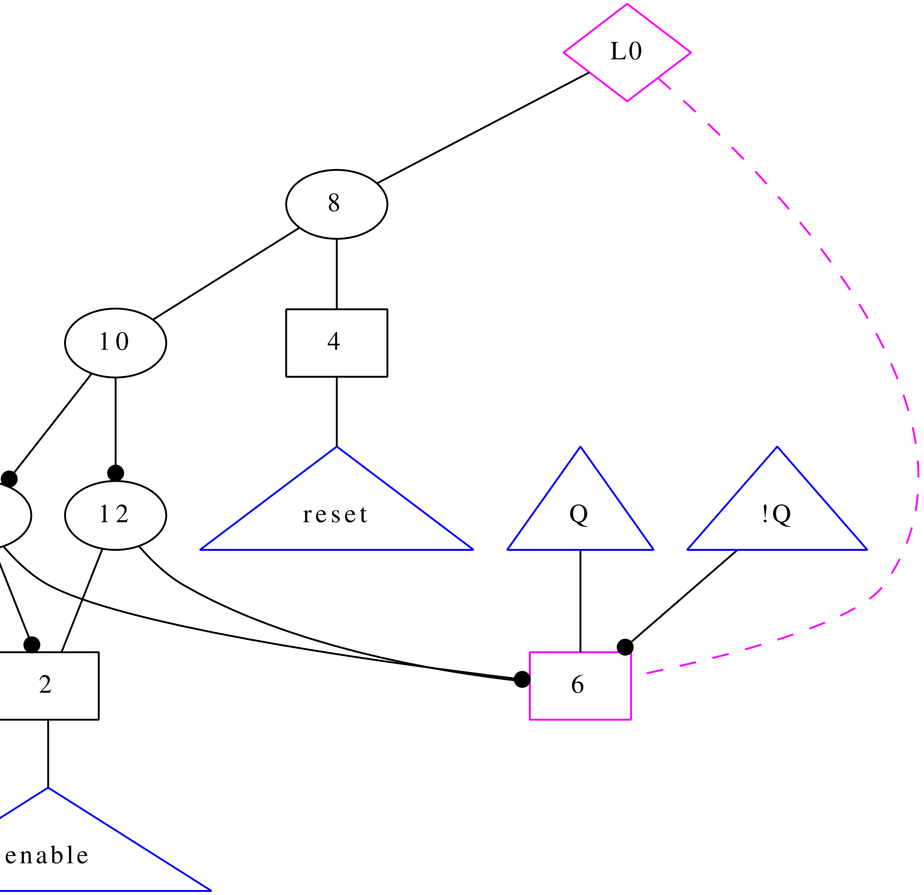
- HWMCC’11: old single property track, new live’ness and new multi property track

AIGs

4-bit adder



toggle flip-flop with reset & enable



AIGER (ASCII Version)

```
add4 1st part

 aag 31 8 0 4 23
 2
 4
 6
 8
 10
 12
 14
 16
 50
 54
 58
 62
 18 4 2
 20 8 6
 22 12 10
 24 9 7
 26 25 21
 28 26 22
 30 29 21
```

```
add4 continued

 32 5 3
 34 33 19
 36 34 31
 38 37 19
 40 16 14
 42 17 15
 44 43 41
 46 44 39
 48 45 38
 50 49 47
 52 35 30
 54 53 37
 56 27 23
 58 57 29
 60 13 11
 62 61 23
 i0 x[1]
 i1 y[1]
 i2 x[2]
 i3 y[2]
 i4 x[3]
 i5 y[3]
 i6 x[0]
 i7 y[0]
```

```
togglere

aag 7 2 1 2 4
2              input 0
4              input 1
6 8            latch po/next
6              output 0
7              output 1
8 4 10          8 =   4 &  10
10 13 15       10 = !12 & !14
12 2 6         12 =   2 &   6
14 3 7         14 =  !2 &  !7
i0 enable      symbol table
i1 reset
o0 Q
o1 !Q
```

```
aig M I L O A
M = max vars
I = #inputs
L = #latches
O = #outputs
A = #ands
```

Version 1.9

- 0 / 1 initialized latches or uninitialized latches — before only 0-initialized

- multiple properties and liveness properties — before only bad states properties
  - ‘`b`’ section of bad state properties — negation of safety
  - ‘`j`’ section of justice properties — negation of liveness

- environment / fairness constraints
  - ‘`c`’ section of invariant environment constraints — $c\,\mathbf{U}\,(c \wedge b)$
  - ‘`f`’ section of fairness constraints — $(\mathbf{G}c) \wedge (\bigwedge \mathbf{GF}\, f_i) \wedge \bigwedge \mathbf{GF}\, j_k$

- new witness / trace definition

```
aig M I L O A B C J F
```

Tools from README

aigand	conjunction of all outputs
aigbmc	new bounded model checker for format 1.9.x including liveness
aigdd	delta debugger for AIGs in AIGER format
aigflip	flip/negate all outputs
aigfuzz	fuzzer for AIGS in AIGER format
aiginfo	show comments of AIG
aigjoin	join AIGs over common inputs
aigmiter	generate miter of AIGER models
aigmove	treat non-primary outputs as primary outputs
aignm	show symbol table of AIG
aigor	disjunction of all outputs
aigsim	simulate AIG from stimulus or randomly
aigsplit	split outputs into separate files
aigstrip	strip simbols from AIG
aigtoaig	converts AIG formats (ascii, binary, stripped, compressed)
aigtocnf	translate combinational AIG into a CNF
aigtoblif	translate AIG into BLIF
aigtodot	visualizer for AIGs using ’dot’ format
aigtosmv	translate sequential AIG to SMV format
andtoaig	translate file of AND gates into AIG
aigunroll	time frame expansion for bmc (previously called ’aigbmc’)
bliftoaig	translate flat BLIF model into AIG
mc.sh	SAT based model checker for AIGER using these tools
smvtoaig	translate flat boolean encoded SMV model into AIG
soltostim	extract input vector from DIMACS solution
wrapstim	sequential stimulus from expanded combinational stimulus

Single Safety (Bad State) Property Benchmarks

- selected 297 = 73 sat + 198 unsat + 26 unsolved from HWMCC'10 out of 818
  sorted by: #solved, #solved in 100 sec, #solved in 10 sec, #solved in 1 sec
  removed instances which half of the model checkers solved within 10 seconds

- added 43 “negated” properties from HWMCC'11 detected by Håkan Hjort

- 58 single property **6s** benchmarks submitted by Jason Baumgartner
  includes 5 from 2 new multi property benchmarks

- 67 single property benchmarks from Torino submitted by Cabodi,Nocco,Quer
  except one all from 2 new multi property benchmarks

- $\boxed{\text{168 new benchmarks}}$ $+$ 297 HWMCC'10 benchmarks $=$ $\boxed{\textbf{465 benchmarks}}$

Single **Live**'ness (Justice) Property Benchmarks

- 61 benchmarks used in LMCS'06 paper submitted by Siert Wieringa

  actually from 14 benchmarks with multiple liveness properties

  but we do not have a multiple liveness properties track – at least this year

- 41 benchmarks used in FMCAD'11 paper sub. by Hassan,Bradley,Somenzi

  all single liveness property benchmarks

- 16 arbiter benchmarks submitted by Koen Claessen

  scalable benchmark set with (assumed) symmetric properties

  only picked some sizes and one property

- altogether 61 + 41 + 16 = **118 benchmarks**

Multiple Bad-State Properties

- was most requested new feature
  - lot of multiple properties in old benchmark set (e.g. HWMCC'10)
  - but already separated and **hard** to join
- we still “found” some:
  - 2 new from **6s** suite and 2 new from Torino
  - 4 from Bob Brayton's benchmarks suite submitted to HWMCC'10
    actually 8 including the flipped ones
  - 6 from NuSMV distribution
  - 1 submitted from Mentor Graphics to HWMCC'10
  - 5 from Bwolen Yang's benchmark set (from 1998!)

altogether 24

Details on Multiple Property Benchmarks

```
                                 M   I    L O     A    B  C

               6s40.aig  aig 36883 249 5608 0 31026    3
               6s48.aig  aig   934  72   66 0   796    2
   bob9234specmulti.aig  aig   815  36  111 0   668    8
bob9234specnegmulti.aig  aig   815  36  111 0   668    8
   bobmiterbm1multi.aig  aig  3074 122  381 0  2571 1150
bobmiterbm1negmulti.aig  aig  3074 122  381 0  2571 1150
      bobsynthmulti.aig  aig 18623 224 3015 0 15384   14
   bobsynthnegmulti.aig  aig 18623 224 3015 0 15384   14
      bobtuintmulti.aig  aig  2476 213  212 0  2051   32
   bobtuintnegmulti.aig  aig  2476 213  212 0  2051   32
          mentorbm1.aig  aig 36213 224 4376 0 31613   13 70
  nusmvdme1d16multi.aig  aig  2225 288  321 0  1616  120
   nusmvdme1d3multi.aig  aig   379  54   61 0   264    3
  nusmvdme2d16multi.aig  aig  3144 293  326 0  2525  120  1
   nusmvdme2d3multi.aig  aig   548  56   63 0   429    3
nusmvsyncarb10multi.aig  aig   148  10   20 0   118   46
 nusmvsyncarb5multi.aig  aig    63   5   10 0    48   11
     pdtvsar8multip.aig  aig  7174  23  195 0  6956   33
      pdtvsarmultip.aig  aig  2890  17  130 0  2743   33
        sm98a7multi.aig  aig 10178  81   89 0 10008    5  1
    sm98tcas16multi.aig  aig  5677 279  310 0  5088    6  1
   sm98tcas16tmulti.aig  aig  5757 279  310 0  5168    6  1
      sm98tcasmulti.aig  aig  2958 142  170 0  2646    6  1
     sm98tcastmulti.aig  aig  3038 142  170 0  2726    6  1
                                                   ------
                                                    2824
```

Model Checkers

alphabetically

- **aigbmc**, **blimc** by Biere (Linz) **new**
- **iimc** by Bradley, Somenzi, Hassan, Zhang, Cox (Boulder) new version
- **superprove**, **simpleprove**, **simplebip** from Brayton's group (Berkeley) new versions
- **tarmo** by Wieringa (Helsinki): 2 versions **new**
- **tip** by Sörensson, Claessen (Göteborg): 3 variants new version
- **pdtrav** by Cabodi, Nocco, Quer (Torino): 3 variants new versions

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- **ic3*** + last winners **abcdsuperprove***,**abcbmc2***,**pdtrav***

7-18 model checkers

from 6 groups

aigbmc + blimc

aigbmc

- bounded model checker based on FMCAD’04 / CAV’05 papers by Heljanko et.al.
- published before competition as a *proof of concept* for new AIGER format 1.9
  - including liveness (justice) properties
  - but in multiple property mode stops as soon one property has a trace

blimc

- bounded model checker for safety (bad state) properties only
- show- and testcase for the incremental features of our SAT solver Lingeling
- simplifies transition relation with SAT based preprocessing
  no other sequential optimization

Safety: relatively naïve integration

- Some combinational and sequential reduction
- Followed by timed applications of ”reverse” IC3, BMC, forward BDD-based reachability, and finally IC3
- Goal is simply to be able to handle the benchmarks that are easy for BMC or BDDs but not IC3
- Reverse IC3 is sometimes better at finding counterexamples than either BMC or standard IC3

Liveness: only FAIR, as described in the FMCAD paper

- As suggested in the paper, FAIR and BDDs are complementary, so we expect that giving some time to a BDD-based solver would improve results

superprove

superprove is the most complete integrated model checker from Berkeley

- uses concurrency throughout

- initial simplification includes retiming, phase and temporal abstraction, signal correspondence, rewriting

- next, abstraction is attempted based on combined counter-example-based and proof-based abstraction as in FMCAD'10 paper last year by Niklas Eén et.al.

- next, speculation is attempted; the speculative miters are processed concurrently; counter-examples are used to refine the speculation

- if the above fails, the following engines
  PDR, BMC, Interpolation, and BDD reachability
  are run concurrently for the remaining time

simpleprove + **simplebip**

simpleprove simplified integrated model checker based on subset of ABC commands

- uses concurrency throughout
- uses initial simplification as in superprove
- tries to prove the property by running concurrently the following ABC engines (PDRm, INTRPm, BMC3, BMC3J, Reachy)

simplebip simplified integrated model checker based on provers developed by Niklas Eén

- uses concurrency throughout
- uses initial simplification as in superprove
- tries to prove the property by running concurrently the BIP engines (PDR, InterpMC, BMC, BMC3J, Reachy)

Temporal Induction Prover

- Tip is a model checking tool consisting of a collection of inductive transformation and verification techniques:

  k-induction, signal correspondence, constraint extraction, temporal decomp., etc.

- This years submission to the competition is a work-in-progress rewrite that does not yet include as many transformations and engines:
  - Core engines are BMC and IC3
  - Circuit simplification by temporal decomposition

- Supports all new AIGER features:
  - Uninitialized latches
  - Constraints
  - Multiple properties
  - Liveness

although not well yet

- multiple engine tool, submitted in two versions, single and multi-threaded (pthreads)
- features
  - initial transformations/reductions (combinational+sequential).
  - heuristically driven manager (expert system)
  - Includes: cudd, minisat, abc (combinational synthesis)
- engines: BMC, BDDs, k-induction, IC3, Interpolation+.

tarmo

General purpose parallel incremental SAT solver with clause sharing

- Runs multiple instances of MiniSAT-2.2.0 in parallel
- Different solver threads may be solving different jobs from the same incremental sequence
- HWMCC”11 version includes an AIGER front-end, which handles BMC encoding and counterexample printing

Setup

- single property benchmarks (single + live tracks) as in HWMCC’07 - HWMCC’10
  - bad state resp. fair SCC *reachable* ⇒ instance *satisfiable* SAT
  - bad state resp. fair SCC *unreachable* ⇒ instance *unsatisfiable* UNSAT
- multiple properties per benchmarks (multi track)
  - count the number of solved individual properties
- all solvers read AIGER natively but not all produce full witnesses
- 900 seconds *wall clock* time limit, 7 GB memory limit
  - 32 node cluster, Intel Quad Core 2.6 GHz processors, 8 GB, Ubuntu
  - each solver has full access to one node (4 cores)

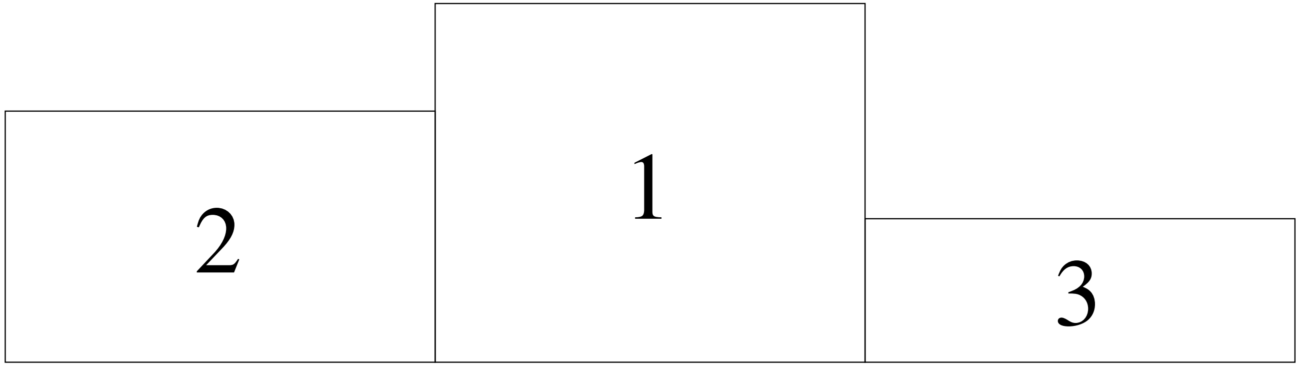
Ranking

- 9 rankings
  - three tracks: live, multi, single
  - three categories: SAT+UNSAT, SAT, UNSAT
  - no additional single threaded versus multi-threaded ranking

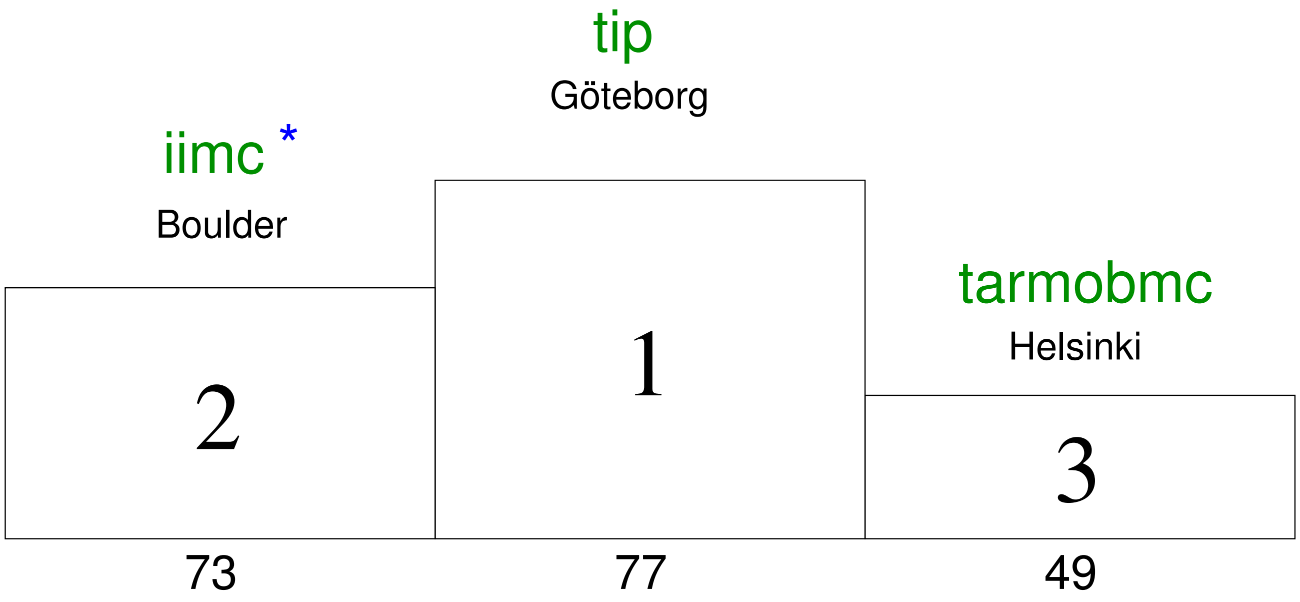
multi threaded ranking	=	wall clock time *limit*	used for ranking
single threaded ranking	=	process time *limit*	not used

- each *group* is only awarded one *virtual medal* per ranking
  - detailed results will be provided for all solvers http://fmv.jku.at/hwmcc11
  - you will also get spread sheets and all the log files there

HWMCC'11 Live Track SAT+UNSAT Category



HWMCC’11 Live Track Winner SAT+UNSAT Category



iimc *
Boulder
2
73

tip
Göteborg
1
77

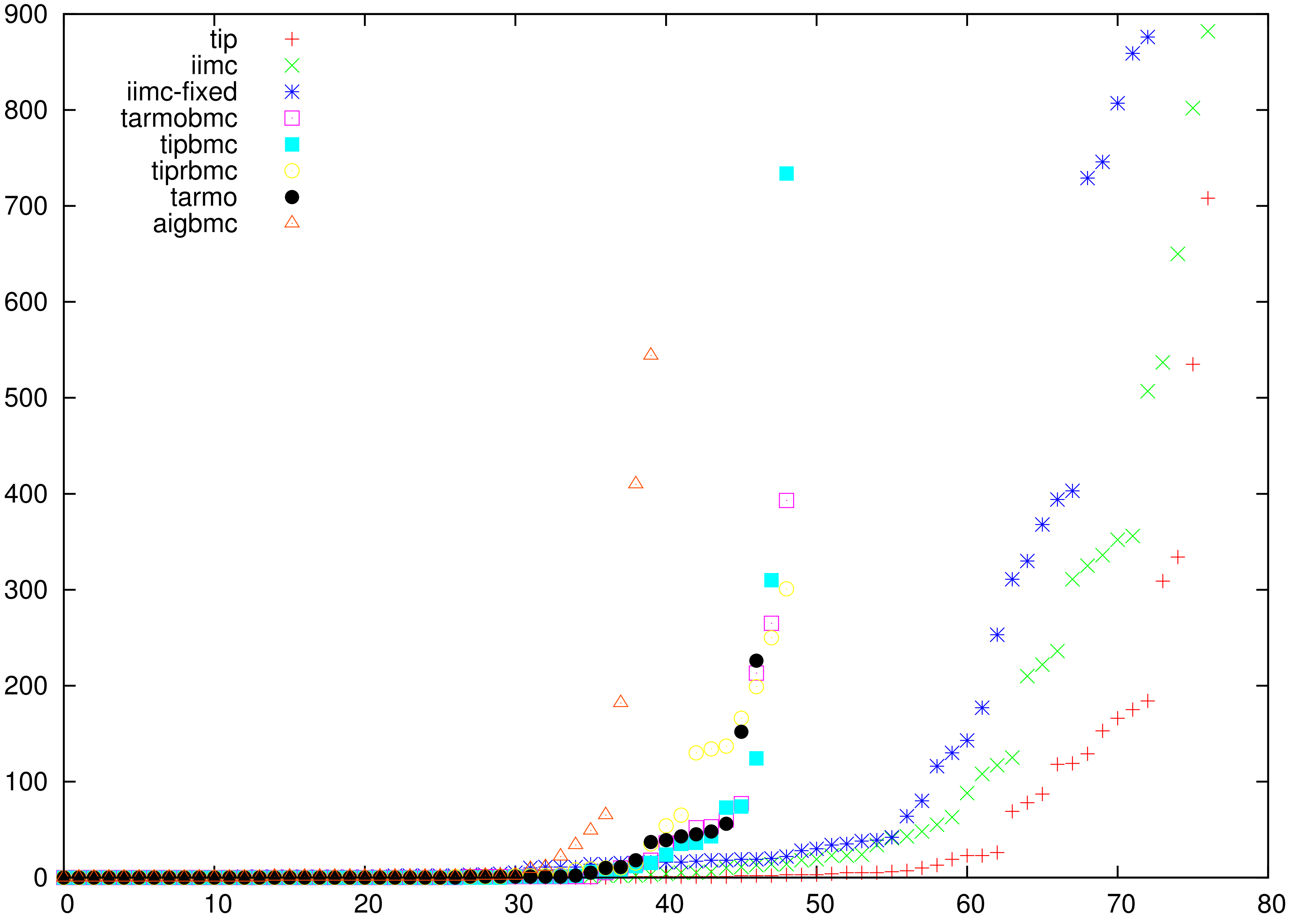
tarmobmc
Helsinki
3
49

* aposterio results for the fixed **iimc**, see http://fmv.jku.at/hwmcc11/results.html#ltrack

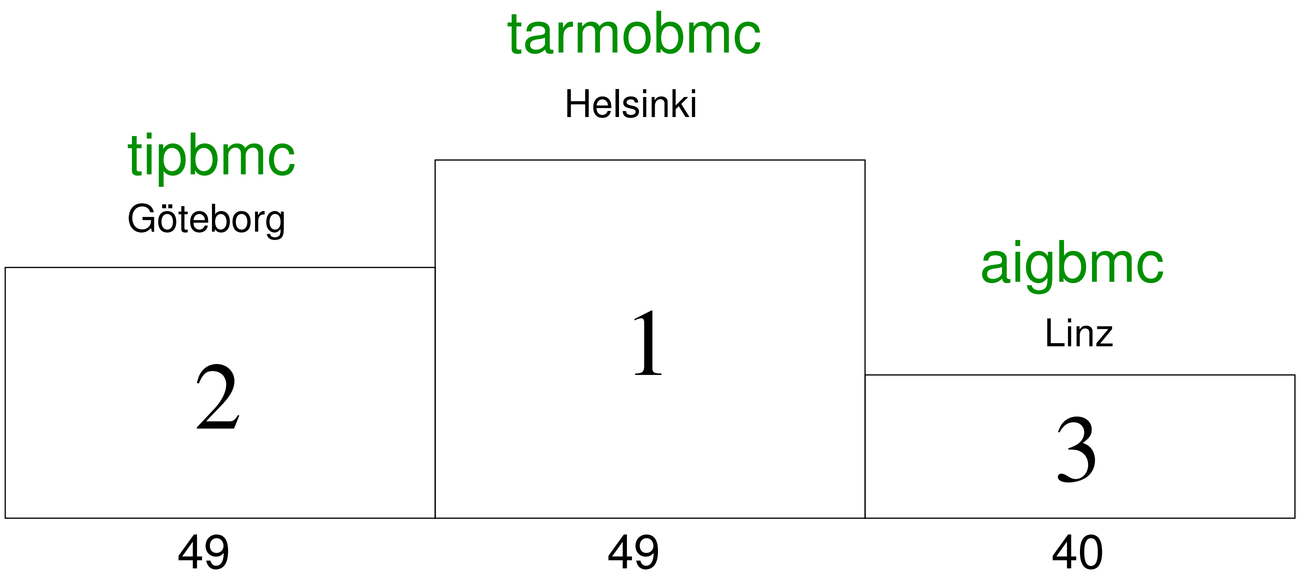
HWMCC'11 Live Track Table SAT+UNSAT

```
SAT+UNSAT ranking (group ranking = solver ranking)
---------------------+----+--------------------------------------
     solver   fnd    | ok | sat uns fld to mo real time space max
                     |    |
                     SAT+UNS
                     |    |
A 1  tip        118  | 77 |  46  31  41 41  0 3338 3306  1539 236
B 2  iimc-fixed 118  | 73 |  29  44  45 45  0 7354 7100  2605 240
C 3  tarmobmc   118  | 49 |  49   0  69 64  5 1243 4907  3870 477
  4  tipbmc     118  | 49 |  49   0  69 66  0 1510 1500   834 235
  5  tiprbmc    118  | 49 |  14  35  69 69  0 1539 1531   262  43
  6  tarmo      118  | 47 |  47   0  71 47 24  704 2740  3593 482
  7  aigbmc     118  | 40 |  40   0  78 78  0 1349 1326   313  52
```

HWMCC’11 Live Track Cactus SAT+UNSAT



HWMCC’11 Live Track Winner SAT Category



tarmobmc

Helsinki

1

49

tipbmc

Göteborg

2

49

aigbmc

Linz

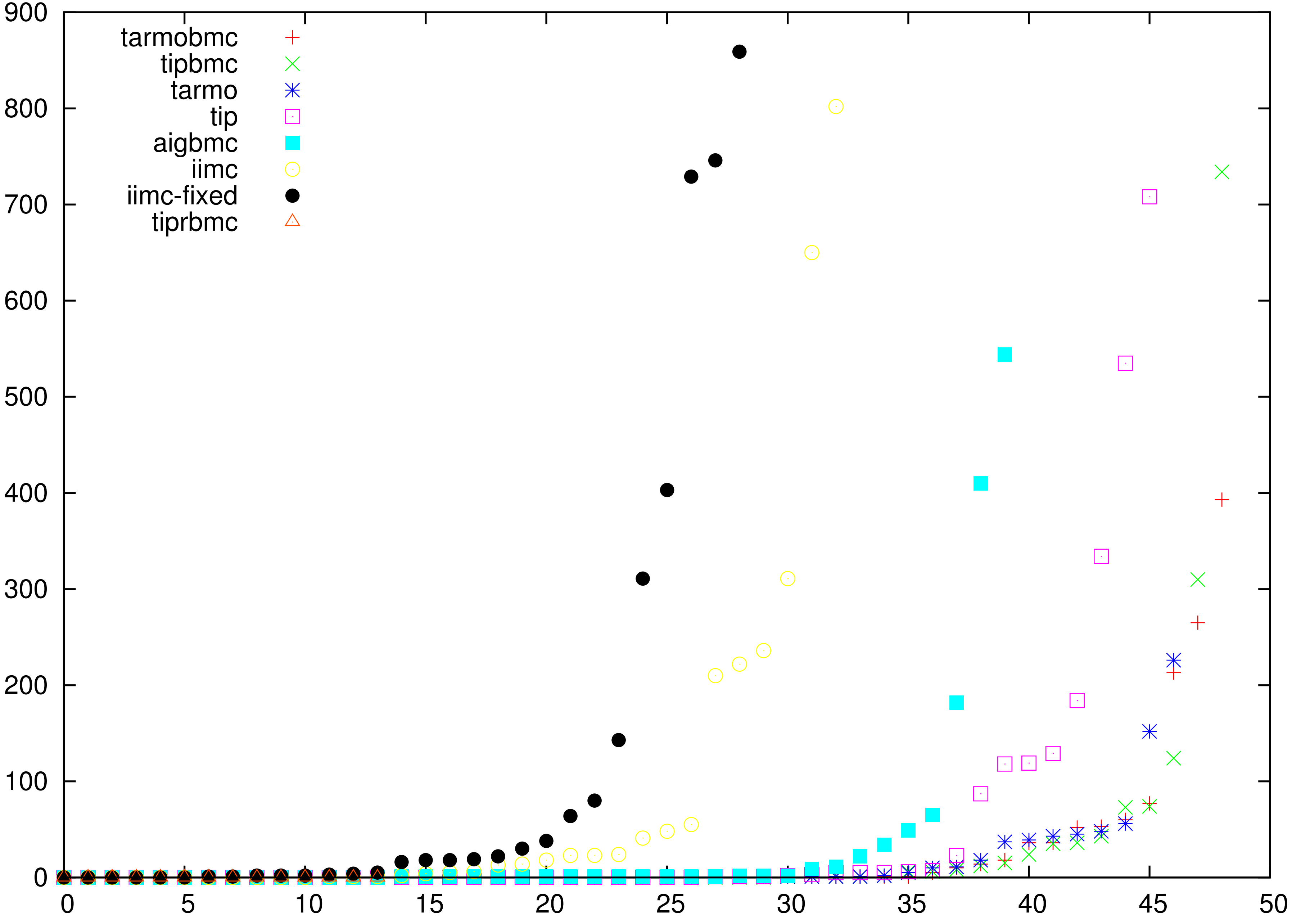
3

40

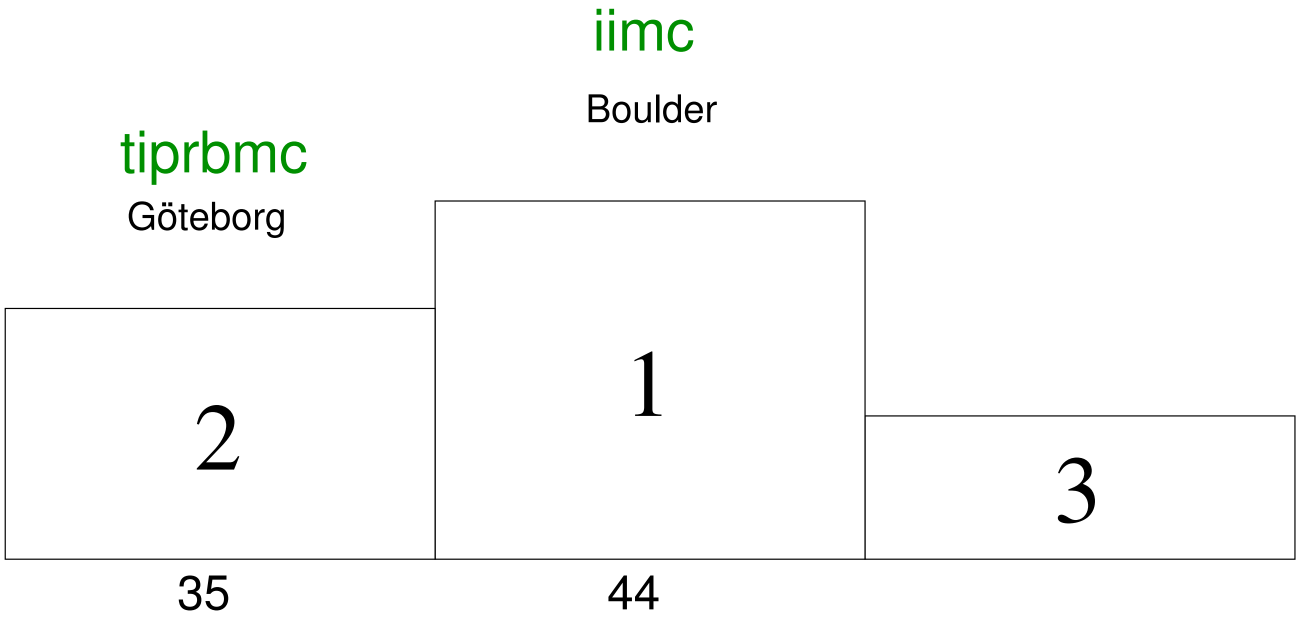
HWMCC’11 Live Track Table SAT

```
SAT ranking (1st column group, 2nd solver)
----------------------+-----+----------------------------------
     solver     fnd ok | SAT | uns fld to mo real time space max
                       |     |
A 1  tarmobmc   118 49 |  49 |   0  69 64  5 1243 4907  3870 477
B 2  tipbmc     118 49 |  49 |   0  69 66  0 1510 1500   834 235
  3  tarmo      118 47 |  47 |   0  71 47 24  704 2740  3593 482
  4  tip        118 77 |  46 |  31  41 41  0 2278 2259   727 236
C 5  aigbmc     118 40 |  40 |   0  78 78  0 1349 1326   313  52
  6  iimc-fixed 118 73 |  29 |  44  45 45  0 7354 7100  2605 240
  7  tiprbmc    118 49 |  14 |  35  69 69  0    2    0     0   0
                       +-----+
```

HWMCC'11 Live Track Cactus SAT



HWMCC'11 Live Track Winner UNSAT Category



iimc

Boulder

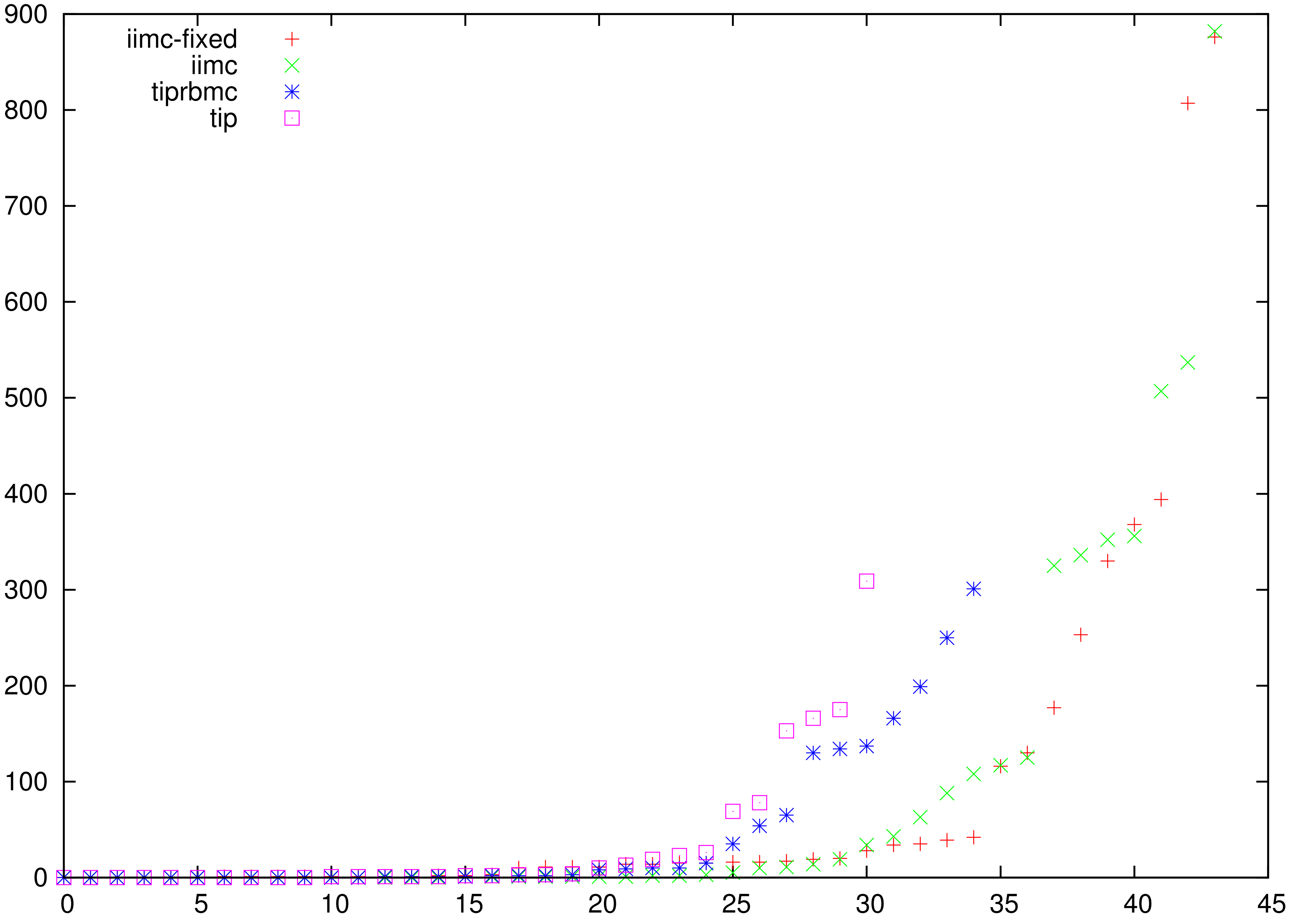
tiprbmc

Göteborg

HWMCC’11 Live Track Table UNSAT

```
UNSAT ranking (no group on third place)
---------------------------+-----+------------------------------
     solver    fnd  ok sat | UNS | fld to mo real time space max
                           |     |
A 1  iimc-fixed 118 73  29 |  44 |  45 45  0 7354 7100  2605 240
B 2  tiprbmc    118 49  14 |  35 |  69 69  0 1538 1531   262  43
  3  tip        118 77  46 |  31 |  41 41  0 1060 1046   811 147
  4  tipbmc     118 49  49 |   0 |  69 66  0    0    0     0   0
  5  tarmo      118 47  47 |   0 |  71 47 24    0    0     0   0
  6  aigbmc     118 40  40 |   0 |  78 78  0    0    0     0   0
  7  tarmobmc   118 49  49 |   0 |  69 64  5    0    0     0   0
```

HWMCC'11 Live Track Cactus UNSAT



HWMCC’11 Multi Track Table

				SAT+UNSAT	SAT	UNSAT
solver	all	sat	uns	ranking	ranking	ranking
tarmo	2252	1253	999	A	A	A
tip	1368	1229	139	B	B	B
tarmobmc	1256	1256	0			
aigbmc	1216	1216	0	C	C	
tipbmc	1210	1210	0			
pdtmulti	412	275	137			*

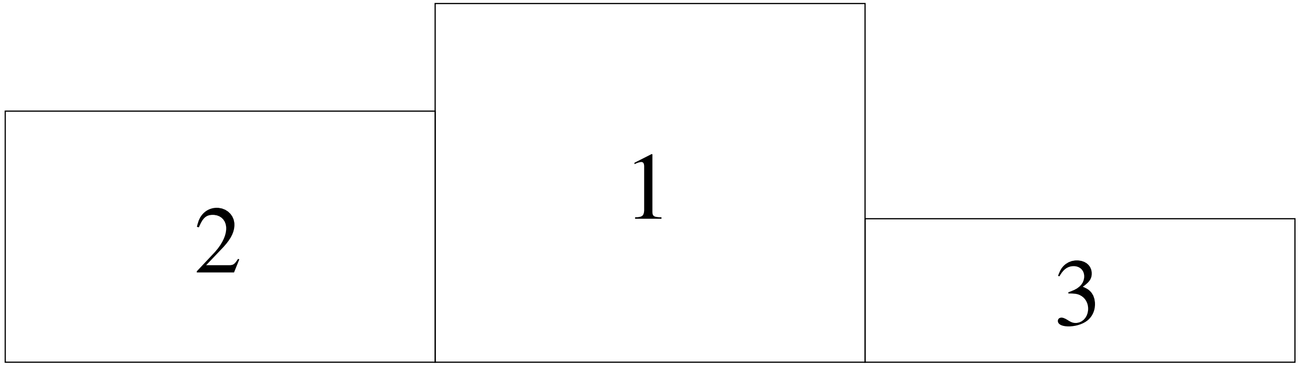
* pdtmulti gave UNSAT on two provable SAT instances

lot of SOTA properties: solved by exactly one “state-of-the-art” solver

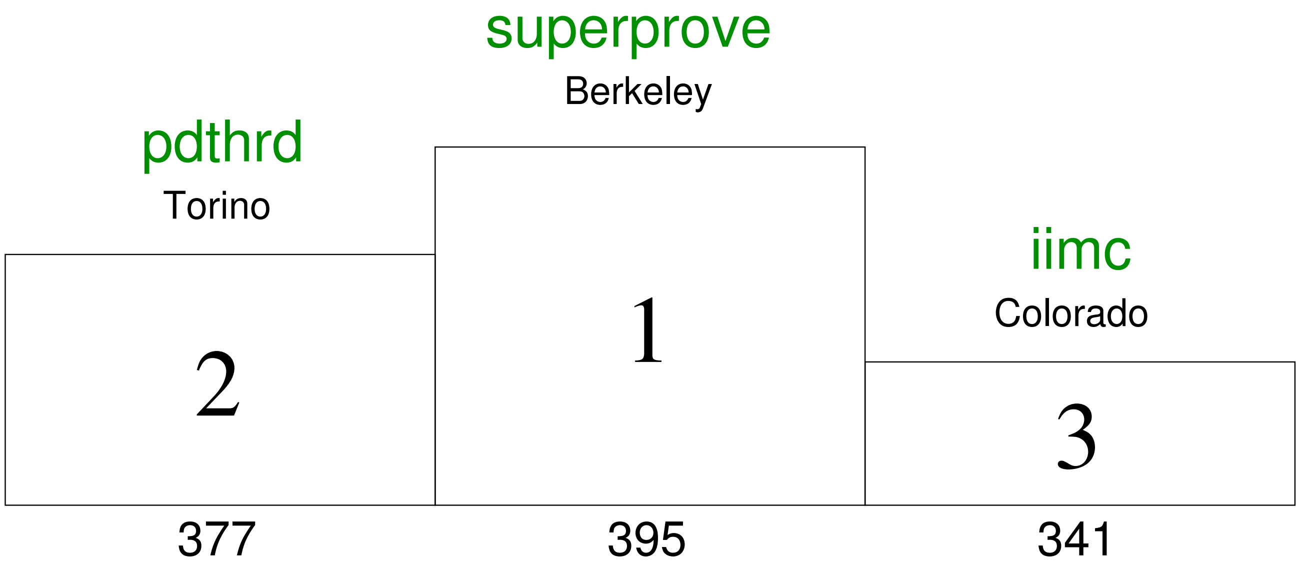
terminology from automated theorem proving competition CASC

- 954 properties from bobmiterbm1multi only proved UNSAT by **tarmo**
- 245 properties from nusmvdme2d16multi only proved SAT by **pdtmulti**
- 9 properties from mentorbm1 only proved UNSAT by **pdtmulti**

HWMCC’11 Single Track SAT+UNSAT Category



HWMCC’11 Single Track Winner SAT+UNSAT Category



superprove

Berkeley

1

395

pdthrd

Torino

2

377

iimc

Colorado

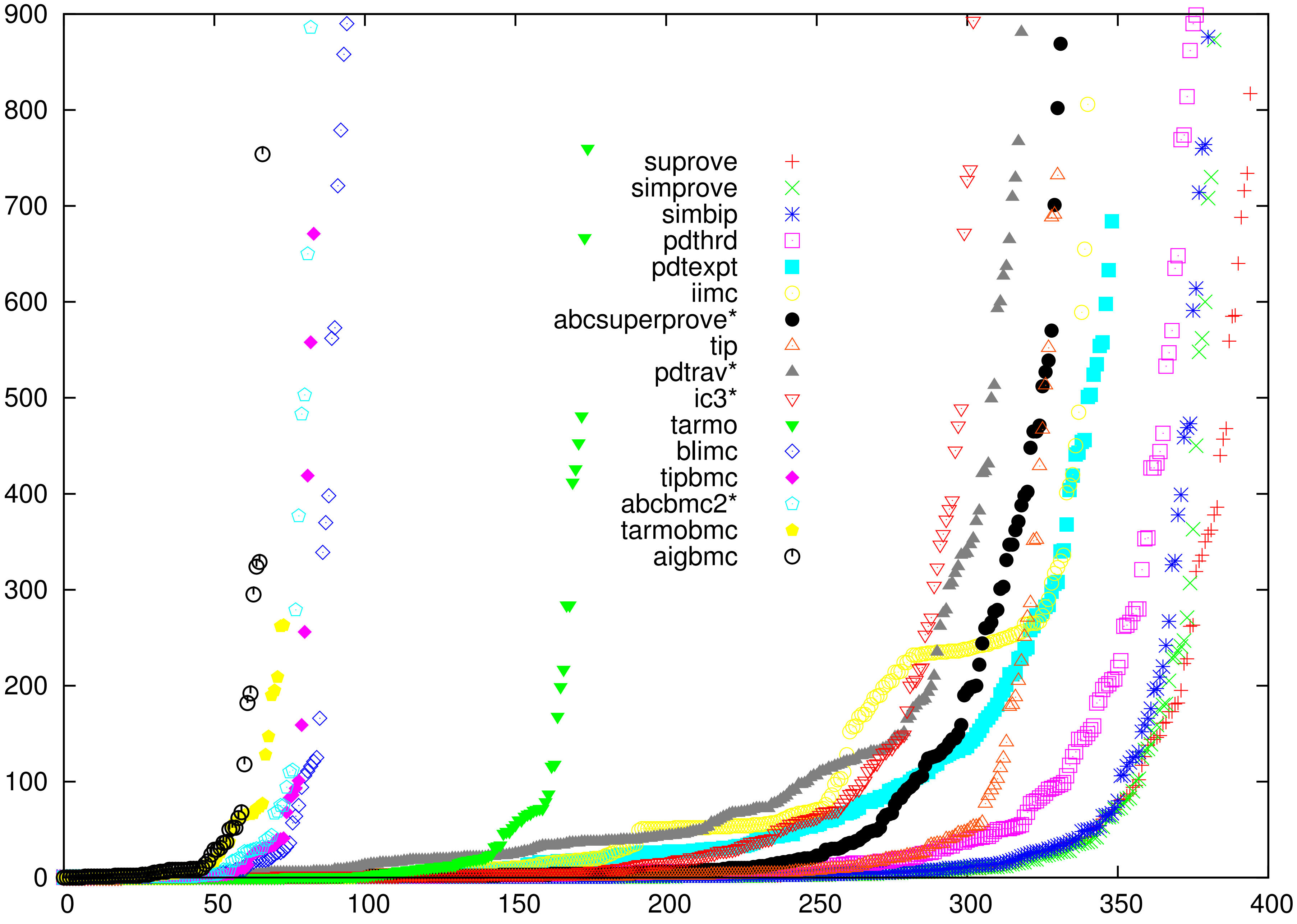
3

341

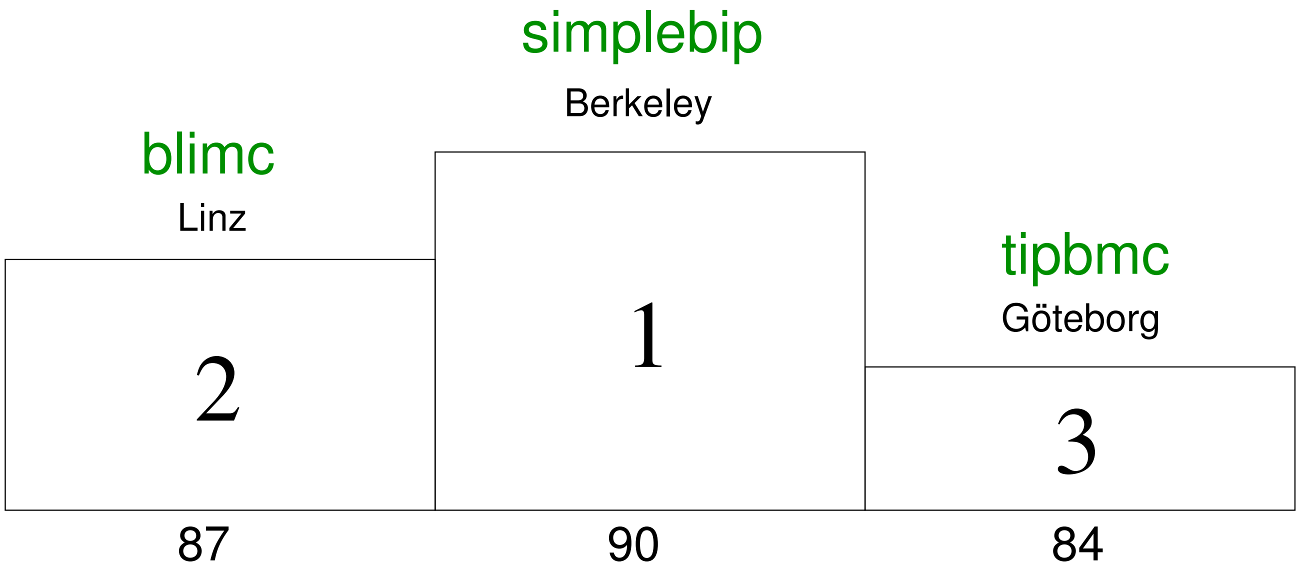
HWMCC'11 Single Track Table SAT+UNSAT

```
SAT+UNSAT ranking (1st column per group, 2nd column per solver)
-----------------------+-----+--------------------------------------------------
    solver         fnd |  ok | sat uns fld  to mo s6 uk  real  time  space  max
                       |     |
                       SAT+UNS
                       |     |
A 1 suprove        465 | 395 |  83 312  70  70  0  0  0 15381 30904  95051 3406
  2 simprove       465 | 383 |  87 296  82  82  0  0  0 10697 35204  93851 3299
  3 simbip         465 | 381 |  90 291  84  84  0  0  0 12234 40909  83738 3074
B 4 pdthrd         465 | 377 |  81 296  88  74  0  9  0 19903 51735 102283 3219
  5 pdtexpt        465 | 349 |  68 281 116 106  0 10  0 23195 23051  34945  884
C 6 iimc           465 | 341 |  75 266 124 124  0  0  0 26540 26334  74975 4411
  7 abcsuperprove* 465 | 332 |  75 257 133 106  0  0 27 17412 14089  23438 1361
  8 tip            465 | 331 |  76 255 134 134  0  0  0  9072  8986   4619  164
  9 pdtrav*        465 | 319 |  61 258 146 142  0  3  1 25321 25141  36538 1078
 10 ic3*           465 | 303 |  58 245 162 162  0  0  0 14377 14224  10783  497
 11 tarmo          465 | 175 |  71 104 290 287  3  0  0  6216 24312  33269 2318
 12 blimc          465 |  95 |  87   8 370 369  0  1  0  7014  6945   9383 1231
 13 tipbmc         465 |  84 |  84   0 381 296 44  0 41  2981  2946   5579  581
 14 abcbmc2*       465 |  83 |  83   0 382 354 28  0  0  4265  4230   9760 1009
 15 tarmobmc       465 |  74 |  74   0 391 311 80  0  0  2442  9532  20944 1972
 16 aigbmc         465 |  67 |  67   0 398 344 54  0  0  2870  2839   8362 1255
                       +-----+
                                       abcsuperprove* winner HWMCC'10 SAT+UNSAT
```

HWMCC'11 Single Track Cactus SAT+UNSAT



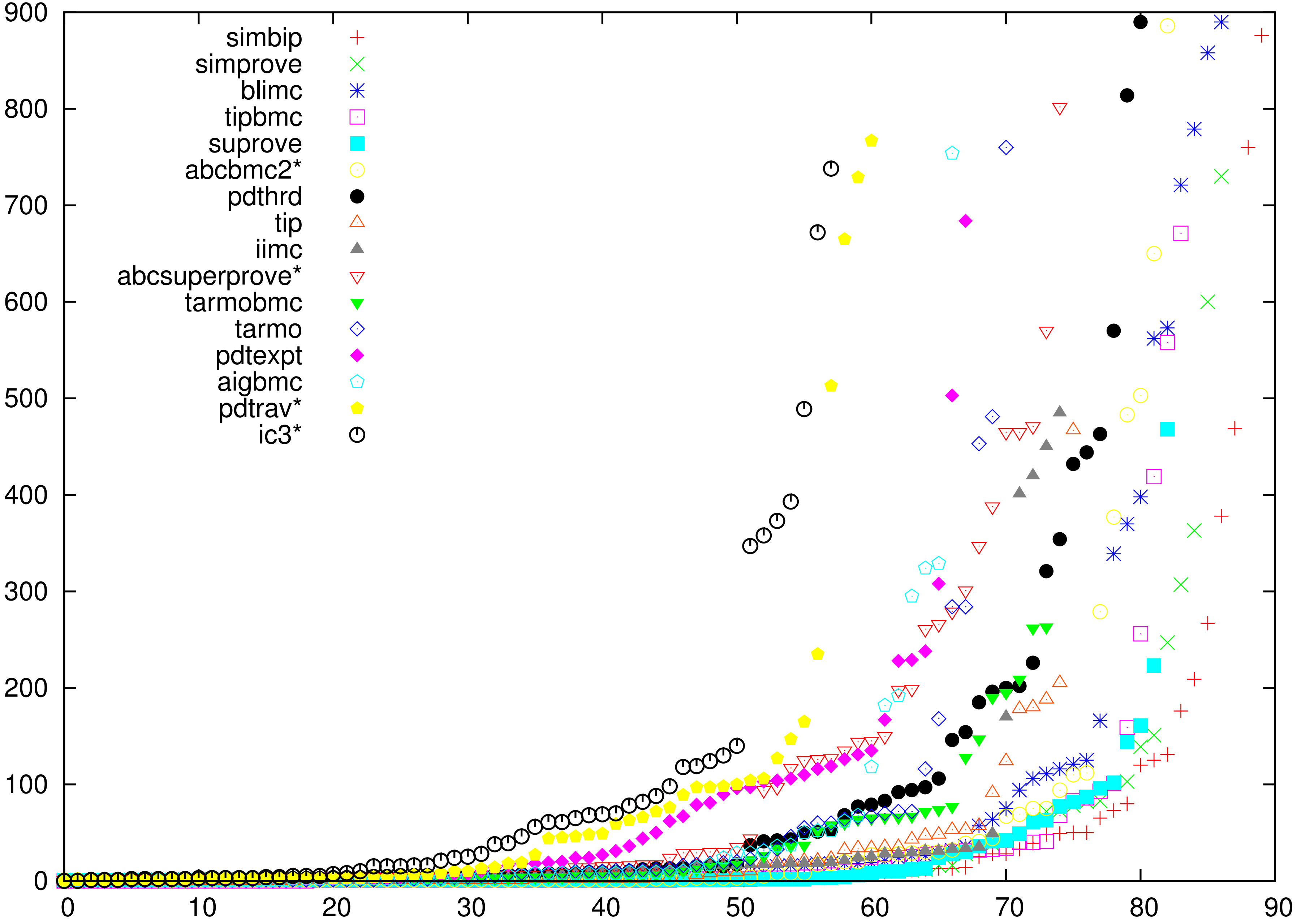
HWMCC'11 Single Track Winner SAT Category



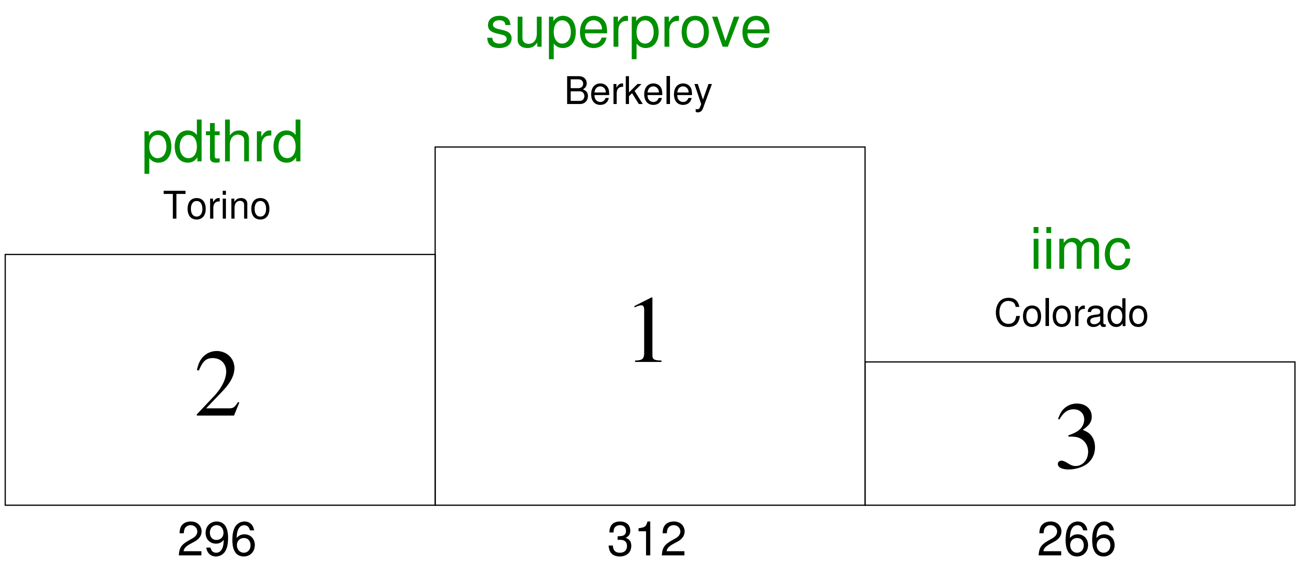
HWMCC'11 Single Track Table SAT

```
SAT ranking (1st column per group, 2nd column per solver)
---------------------------+-----+---------------------------------------
    solver         fnd  ok | SAT | uns fld  to mo s6 uk real  time space  max
                           |     |
A 1 simbip         465 381 |  90 | 291  84  84  0  0  0 4267 13490 32419 2366
  2 simprove       465 383 |  87 | 296  82  82  0  0  0 3546 11224 35996 3299
B 3 blimc          465  95 |  87 |   8 370 369  0  1  0 7012  6944  9376 1231
C 4 tipbmc         465  84 |  84 |   0 381 296 44  0 41 2981  2946  5579  581
  5 suprove        465 395 |  83 | 312  70  70  0  0  0 1943  5101 28922 3298
  6 abcbmc2*       465  83 |  83 |   0 382 354 28  0  0 4265  4230  9760 1009
  7 pdthrd         465 377 |  81 | 296  88  74  0  9  0 6922 15208 28533 1233
  8 tip            465 331 |  76 | 255 134 134  0  0  0 2120  2097   936   68
  9 iimc           465 341 |  75 | 266 124 124  0  0  0 2621  2603  8976 2028
 10 abcsuperprove* 465 332 |  75 | 257 133 106  0  0 27 6728  5880  8727 1361
 11 tarmobmc       465  74 |  74 |   0 391 311 80  0  0 2442  9532 20944 1972
 12 tarmo          465 175 |  71 | 104 290 287  3  0  0 3527 13825 20851 2318
 13 pdtexpt        465 349 |  68 | 281 116 106  0 10  0 4413  4389  9402  884
 14 aigbmc         465  67 |  67 |   0 398 344 54  0  0 2870  2839  8362 1255
 15 pdtrav*        465 319 |  61 | 258 146 142  0  3  1 4796  4761  8491 1078
 16 ic3*           465 303 |  58 | 245 162 162  0  0  0 5169  5141  2019  159
                           +-----+
                                                abcbmc2* winner HWMCC'10 SAT
```

HWMCC’11 Single Track Cactus SAT



HWMCC'11 Single Track Winner UNSAT Category



superprove
Berkeley
1
312

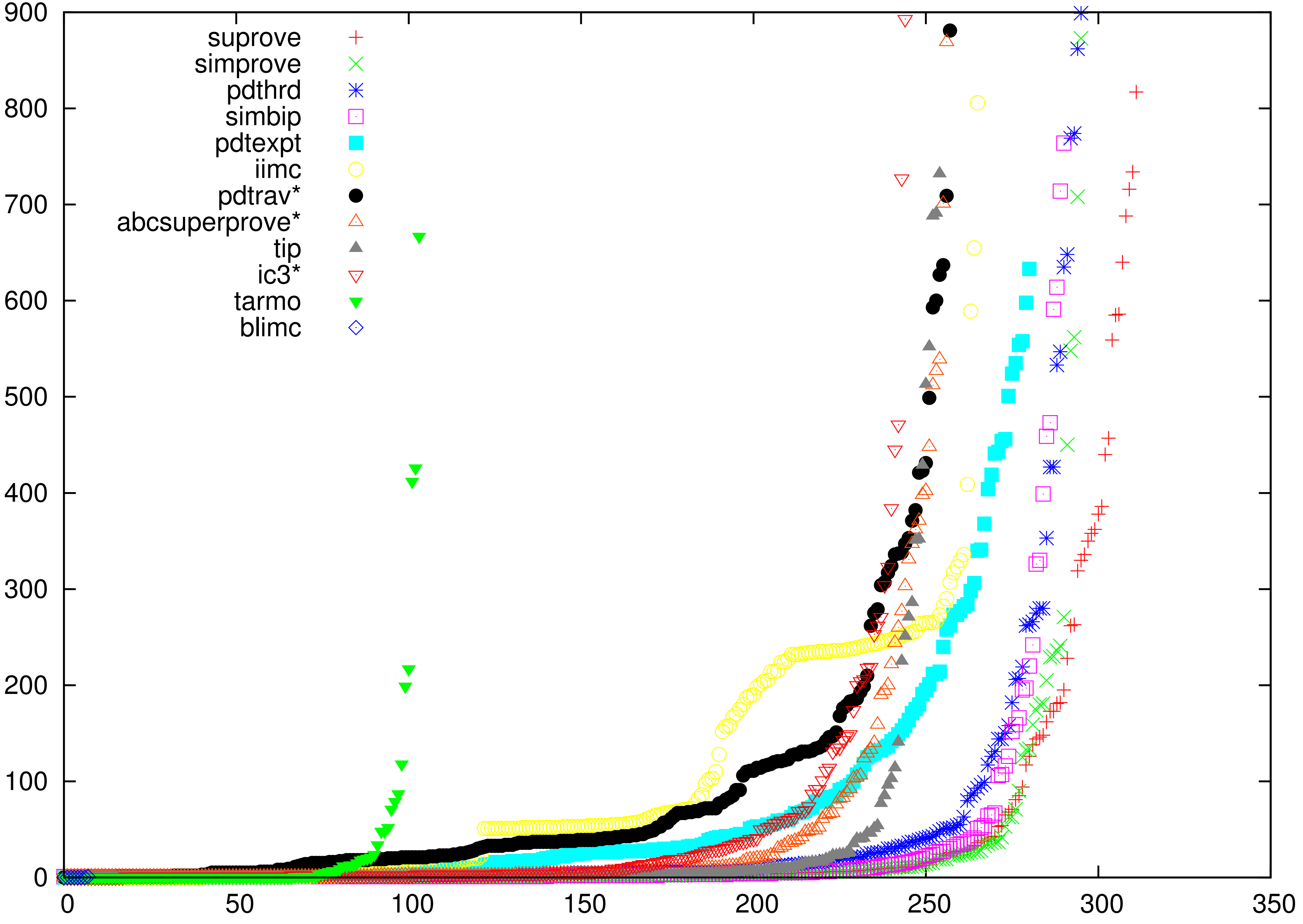
pdthrd
Torino
2
296

iimc
Colorado
3
266

HWMCC’11 Single Track Table UNSAT

```
UNSAT ranking (1st column per group, 2nd column per solver)
-------------------------------+-----+--------------------------------------
    solver          fnd  ok sat | UNS | fld  to mo s6 uk  real  time space  max
                                |     |
A 1 suprove         465 395  83 | 312 |  70  70  0  0  0 13438 25803 66129 3406
  2 simprove        465 383  87 | 296 |  82  82  0  0  0  7151 23980 57856 3266
B 3 pdthrd          465 377  81 | 296 |  88  74  0  9  0 12981 36527 73750 3219
  4 simbip          465 381  90 | 291 |  84  84  0  0  0  7967 27419 51319 3074
  5 pdtexpt         465 349  68 | 281 | 116 106  0 10  0 18782 18662 25543  779
C 6 iimc            465 341  75 | 266 | 124 124  0  0  0 23919 23731 65999 4411
  7 pdtrav*         465 319  61 | 258 | 146 142  0  3  1 20525 20380 28047 1065
  8 abcsuperprove*  465 332  75 | 257 | 133 106  0  0 27 10684  8209 14711  652
  9 tip             465 331  76 | 255 | 134 134  0  0  0  6952  6889  3683  164
 10 ic3*            465 303  58 | 245 | 162 162  0  0  0  9209  9083  8763  497
 11 tarmo           465 175  71 | 104 | 290 287  3  0  0  2689 10486 12419 1186
 12 blimc           465  95  87 |   8 | 370 369  0  1  0     2     1     7    4
 13 tipbmc          465  84  84 |   0 | 381 296 44  0 41     0     0     0    0
 14 aigbmc          465  67  67 |   0 | 398 344 54  0  0     0     0     0    0
 15 tarmobmc        465  74  74 |   0 | 391 311 80  0  0     0     0     0    0
 16 abcbmc2*        465  83  83 |   0 | 382 354 28  0  0     0     0     0    0
                                +-----+
                                                  pdtrav* winner HWMCC’10 UNSAT
```

HWMCC'11 Single Track Cactus UNSAT



Conclusion

- achievements this year
  - new AIGER 1.9 and new tracks
  - new benchmarks, new versions, new model checkers
  - state-of-the-art improved in all previous categories
  - IC3/PDR has been integrated in leading model checkers
  - clear trend towards parallel implementations (portfolio as this point)
- next time
  - (please) provide witnesses
  - AIGER 2.0 with new binary encoding, same semantics
  - more benchmarks, particularly multi & live