

Sugar: A SAT-based CSP Solver

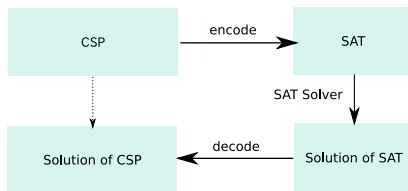
—Results summary of the 3rd international CSP solver competition—

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Sugar CSP solver



- Sugar is a **CSP** (Constraint Satisfaction Problem) solver by encoding the CSP into a **SAT** (Satisfiability Testing) problem and searching a solution with an efficient SAT solver.
- Order encoding method is used for the SAT translation.
- Sugar can also solve COPs (Constraint Optimization Problems) and Max-CSPs by using the SAT solver multiple times.

Sugar [▶ Web](#)

Sugar CSP solver (cont.)

- Sugar solver is participated to the Third International CSP Solver Competition and the Max-CSP Solver Competition held in 2008.

CSP Solver Competition

Sugar v1.13+minisat

Sugar v1.13+picosat

Max-CSP Solver Competition

Sugar v1.13+minisat

Sugar++ v1.13+minisat-inc

CSP solver competition

[▶ Web](#)

- 2005: 15 solvers (10 teams), 1064 instances (2 categories)
- 2006: 21 solvers (12 teams), 3425 instances (5 categories)
- 2008: 24 solvers (14 teams), 3307 instances (5 categories)
- Solvers should answer whether the given CSP is SAT or UNSAT.
- Solvers are ranked with the number of solved instances under specified CPU time and memory limits. In case of tie, ranking is made with the cumulated CPU time on solved instances.
- Solvers giving a wrong answer in a category is disqualified in that category.

Max-CSP solver competition

[▶ Web](#)

- 2006: 9 solvers (5 teams), 1069 instances (4 categories)
- 2008: 8 solvers (4 teams), 1295 instances (5 categories)
- Solvers should answer an assignment which maximizes the number of satisfied constraints.
- Solvers are ranked with the number of solved instances under specified CPU time and memory limits. In case of tie, ranking is made with the cumulated CPU time on solved instances.
- Solvers giving a wrong answer in a category is disqualified in that category.

Class of constraints and categories

- **Extensional constraints:** either a support set or a conflict set is explicitly given for each constraint.
- **Intensional constraints:** constructed from arithmetic, comparison, and logical operators.
- **Global constraints:** alldifferent, cumulative element, weightedsum.

Category	2-ary		N-ary		Global
	Ext.	Int.	Ext.	Int.	
2-ARY-EXT	✓				
2-ARY-INT	✓	✓			
N-ARY-EXT	✓		✓		
N-ARY-INT	✓	✓	✓	✓	
GLOBAL	✓	✓	✓	✓	✓

Benchmark instances

- Benchmark instances are written in XML format (XCSP 2.1), and classified into the following five categories.
- **2-ARY-EXT**: instances of 2-ary extensional constraints. The most of them are random CSPs.
- **2-ARY-INT**: instances of 2-ary intensional and extensional constraints including shop scheduling, frequency assignment, graph coloring, N-queens problems.
- **N-ARY-EXT**: instances of N-ary extensional constraints including random CSPs and crossword puzzles.
- **N-ARY-INT**: instances of N-ary intensional and extensional constraints including bounded model checking, real-time mutual-exclusion protocol verification, multi knapsack, pseudo Boolean algebra, Golomb ruler, social golfer problems.
- **GLOBAL**: instances of global and N-ary intensional and extensional constraints including Latin squares and timetabling problems.

Benchmarks in XCSP 2.1 [▶ Web](#)

Competition environment

- Cluster of bi-Xeon 3 GHz, 2MB cache, 2GB RAM kindly provided by the CRIL, University of Artois, France
- All solvers were run in 32 bits mode
- Each solver was imposed a memory limit of 900 MB (to avoid swapping and to allow two jobs to run concurrently on a node)
- CSP solvers were given a time limit of 30 minutes (1800s).
- Max-CSP solvers were given a time limit of 1 hour (3600s).
- 515 days of CPU time used by CSP solvers
204 days of CPU time used by Max-CSP solvers

Participated solvers of the 2008 CSP Solver Competition

- Abscon : a CSP solver in Java
- bpsolver : a CSP solver with a Prolog engine
- casper : a CSP library in C++
- choco : a CSP library in Java
- CSP4J : a CSP library in Java
- cpHydra : a portfolio solver
- galac : a BDD based solver
- mddc-solv : a CSP solver for extensional constraints
- MDG : derived from Mistral
- Minion/Tailor : a CSP solver in C++
- Mistral : a CSP library in C++
- SAT4J CSP : a SAT based solver
- spider : derived from CPlan
- **Sugar** : a SAT based solver (with MiniSat and PicoSAT)

Results for 2-ARY-EXT (635 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	622	100%
1	cpHydra k_10	574	92%
2	cpHydra k_40	567	91%
3	MDG-probe	561	90%
4	Mistral-option	559	90%
5	MDG-noprobe	558	90%
		
14	Sugar+minisat	470	76%
15	Sugar+picosat	443	71%
		

Results for 2-ARY-INT (696 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	634	100%
1	cpHydra k_40	597	94%
2	cpHydra k_10	596	94%
3	choco2 dwdeg	523	82%
4	Mistral-prime	522	82%
5	choco2 impwdeg	521	82%
		
10	Sugar+picosat	486	77%
11	Sugar+minisat	484	76%
		

Results for N-ARY-EXT (704 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	607	100%
1	cpHydra k_40	587	97%
2	cpHydra k_10	586	97%
3	mddc-solv	576	95%
4	MDG-noprobe	570	94%
5	Mistral-prime	569	94%
		
15	Sugar+minisat	370	61%
16	Sugar+picosat	347	57%
		

Results for N-ARY-INT (716 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	660	100%
1	cpHydra k_10	569	86%
2	cpHydra k_40	569	86%
3	casper zao	562	85%
4	Mistral-prime	560	85%
5	MDG-probe	560	85%
		
12	Sugar+minisat	486	74%
13	Sugar+picosat	481	73%
		

Results for GLOBAL (556 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	501	100%
1	Sugar+picosat	424	85%
2	cpHydra k_40	420	84%
3	cpHydra k_10	419	84%
4	Sugar+minisat	405	81%
5	Mistral-prime	403	80%
		

Participated solvers of the 2008 Max-CSP Solver Competition

- AbsconMax : a CSP solver in Java
- CSP4J : a CSP library in Java
- **Sugar** : a SAT based solver (Sugar and Sugar++)
- toulbar2 : a Weighted CSP solver

Results for 2-ARY-EXT (534 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	440	100%
1	toulbar2	412	94%
2	Sugar+minisat	240	55%
3	Sugar+++minisat-inc	229	52%
4	AbsconMax 112 pc-w	121	28%
5	AbsconMax 112 pc-d	86	20%
6	Concrete + CSP4J - Tabu	32	7%
7	Concrete + CSP4J - MCRW	32	7%

Results for 2-ARY-INT (276 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	103	100%
1	Sugar+minisat	101	98%
2	Sugar++ +minisat-inc	99	96%
3	AbsconMax 112 pc-w	32	31%
4	AbsconMax 112 pc-d	30	29%
5	Concrete + CSP4J - MCRW	0	0%
6	Concrete + CSP4J - Tabu	0	0%

Results for N-ARY-EXT (278 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	171	100%
1	toulbar2/BTD	153	89%
2	Sugar+minisat	118	69%
3	Sugar++ +minisat-inc	118	69%
4	AbsconMax 112 pc-w	103	60%
5	AbsconMax 112 pc-d	71	42%
6	Concrete + CSP4J - Tabu	4	2%
7	Concrete + CSP4J - MCRW	4	2%

Results for N-ARY-INT (109 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	42	100%
1	Sugar+minisat	39	93%
2	Sugar++ +minisat-inc	39	93%
3	AbsconMax 112 pc-w	14	33%
4	AbsconMax 112 pc-d	10	24%
5	Concrete + CSP4J - MCRW	0	0%
6	Concrete + CSP4J - Tabu	0	0%

Results for GLOBAL (98 instances)

Rank	Solver	#solved	% of VBS
	Virtual Best Solver (VBS)	65	100%
1	Sugar+minisat	65	100%
2	Sugar++ +minisat-inc	50	77%

Results of the CSP Solver Competition

- Winners of the four categories except GLOBAL category was CPhydra which is a portfolio solver.
- CPhydra consists of multiple CSP solvers and solves problems by using case-based reasoning to determine how to solve an unseen problem instance by exploiting a case base of problem solving experience.
- CPhydra submitted to the competition used three CSP solvers, Mistral, Choco, and Abscon, and trained on 2006 CSP solver competition instances.

Results of the CSP Solver Competition (cont.)

- Sugar was not good for instances mainly consists of extensional constraints. The extensional constraints usually do not relate on the order relation on integers, and the order encoding is not suitable for that case.
- This is the main reason why Sugar was not good in 2-ARY-EXT and N-ARY-EXT categories.

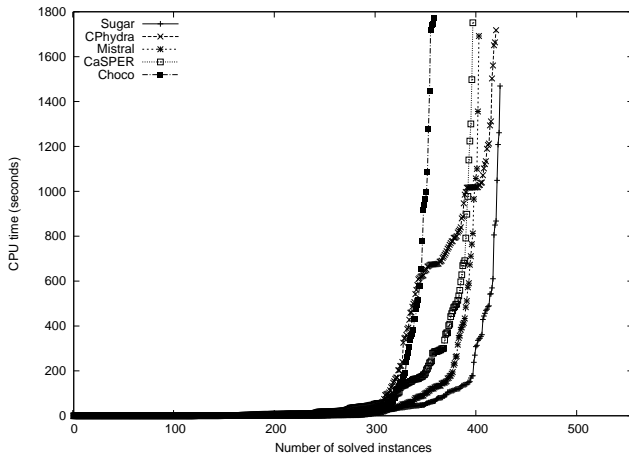
Results of the CSP Solver Competition (cont.)

- In the 2-ARY-INT category, CPhydra solved 597 instances and Sugar solved 486 instances (111 less instances). The most of them consists of 31 instances in graph coloring problems and 72 instances in frequency assignment problems.
- Constraints used in graph coloring problems are not-equals (\neq) on integers which seem to be not suitable for the order encoding.
- As for the frequency assignment problems, the encoded SAT problems became very large and that caused the memory overflow.

Results of the CSP Solver Competition (cont.)

- In the 2-ARY-INT category, CPhydra solved 569 instances and Sugar solved 486 instances (83 less instances). The most of them consists of 58 instances in crossword puzzles and 28 instances in primes problems.
- The crossword problems contain a lot of extensional constraints and are not suitable for Sugar.
- The primes problems contain linear expressions with large prime coefficients. Their encoded SAT problems became very large and that caused the memory overflow.

Results of the CSP Solver Competition (cont.)



GLOBAL: Number of solved instances

Results of the CSP Solver Competition (cont.)

Series	Sugar	CPhydra	Mistral	CaSPER	Choco
BIBD (83)	78*	70	67	57	51
Costas Array (11)	8	9	9	9	9
Latin Square (10)	9*	5	5	6	5
Magic Square (18)	8	8	8	16	6
NengFa (3)	3*	3	3	2	3
Orthogonal Latin Square (9)	3*	2	2	3	2
Perfect Square Packing (74)	53*	52	41	44	49
Pigeons (19)	19*	19	19	19	19
Quasigroup Existence (35)	29	28	28	30	28
Pseudo-Boolean (100)	70*	44	40	69	49
BQWH (20)	20*	20	20	20	20
Cumulative Job-Shop (10)	4*	2	2	2	1
RCPSP (78)	78*	78	78	70	73
Cabinet (40)	0	40	40	40	40
Timetabling (46)	42*	40	41	10	3
TOTAL (556)	424*	420	403	397	358

Results of the CSP Solver Competition (cont.)

- Sugar showed very good performance for the most of series in the GLOBAL category.
- However, Sugar could solve none of the Cabinet problems which contain linear summations of integer variables with two elements domains, such as $\{0, 1610\}$.
- An integer variable with two elements domain can be encoded into one Boolean variable in Sugar.
- However, new integer variables with larger domains are introduced for encoding their linear summations, and their encoded SAT problems became very large and that caused the memory overflow.

Results of the CSP Solver Competition (cont.)

- Comparing the results of Sugar+minisat and Sugar+picosat, Sugar+picosat solved more in 2-ARY-INT and GLOBAL categories, and Sugar+minisat solved more in other categories.
- Sugar+picosat is superior in SAT instances, and Sugar+minisat is superior in UNSAT instances.
- This reflects the improvement of PicoSAT for satisfiable instances by frequent restarts.

Category	Sugar+minisat			Sugar+picosat		
	SAT+UNSAT	SAT	UNSAT	SAT+UNSAT	SAT	UNSAT
2-ARY-EXT	470	278	192	443	280	163
2-ARY-INT	484	257	227	486	261	225
N-ARY-EXT	370	179	191	347	178	169
N-ARY-INT	486	399	87	481	393	88
GLOBAL	405	252	153	424	273	151
TOTAL	2215	1365	850	2181	1385	796

Future works

- Tackling the memory overflow problems
 - by modifying MiniSat source code, and
 - by considering more compact encoding.
- Participating the next CSP Solver Competition.