

Fourth Pseudo-Boolean Competition PB09

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- ▶ Pseudo-Boolean formalism
- ▶ Judges
- ▶ Benchmarks and Solvers
- ▶ Evaluation Environment
- ▶ Results

Linear Pseudo-Boolean Constraints

- ▶ A **linear** pseudo-Boolean constraint may be defined over boolean variables by

$$\sum_i a_i \cdot l_i \geq d \text{ with } a_i, d \in \mathbb{Z}, l_i \in \{x_i, \bar{x}_i\}, x_i \in \mathbb{B}$$

Example: $3x_1 - 3x_2 + 2\bar{x}_3 + \bar{x}_4 + x_5 \geq 5$

- ▶ Extends both clauses and cardinality constraints
 - ▶ cardinalities: all $a_i = 1$ and $d > 1$
 - ▶ clauses: all $a_i = 1$ and $d = 1$
- ▶ PB constraints are more expressive than clauses (one PB constraint may replace an exponential number of clauses)
- ▶ A pseudo-Boolean instance is a conjunction of PB constraints

Non-Linear Pseudo-Boolean Constraints

- ▶ A **non-linear** pseudo-Boolean constraint may be defined over boolean variables by

$$\sum_i a_i \left(\prod_j l_{i,j} \right) \geq d \text{ with } a_i, d \in \mathbb{Z}, l_{i,j} \in \{x_{i,j}, \bar{x}_{i,j}\}, x_{i,j} \in \mathbb{B}$$

Example: $3x_1\bar{x}_2 - 3x_2x_4 + 2\bar{x}_3 + \bar{x}_4 + x_5x_6x_7 \geq 5$

- ▶ A product is a AND
- ▶ Compact encoding for several problems (e.g. factoring problem encoded by one constraint)
- ▶ Can be easily translated into linear pseudo-Boolean by introducing new variables and constraints s.t.

$$p \leftrightarrow x_0 \wedge x_1 \wedge \dots \wedge x_n$$

(requires 2 PB constraints or $n+1$ clauses)

Optimization

- ▶ Another difference with SAT is that most PB problems contain a linear cost function to optimize. For example,

$$\text{minimize } f = \sum_i c_i \cdot x_i \text{ with } c_i \in \mathbb{Z}, x_i \in \mathbb{B}$$

- ▶ Example of an optimization instance

$$\left\{ \begin{array}{l} \text{minimize} \quad 5x_1 + x_2 + 8x_3 + 2x_4 + 3x_5 \\ \text{subject to} \quad x_1 + \bar{x}_2 + x_3 \geq 1 \\ \quad \quad \quad \bar{x}_1 + x_2 + \bar{x}_3 + x_4 \geq 3 \\ \quad \quad \quad 2\bar{x}_1 + 4x_2 + 2x_3 + x_4 + 5x_5 \geq 5 \\ \quad \quad \quad 5x_1 + 4x_2 + 6x_3 + x_4 + 3x_5 \geq 10 \end{array} \right.$$

Optimum: 8

$$x_1 = x_2 = x_4 = 1$$

$$x_3 = x_5 = 0$$

- ▶ The cost function may contain products (no such instance in the PB09 evaluation)

- ▶ 2 judges
 - ▶ Heidi Dixon (pbChaff solver)
 - ▶ Peter Barth (opbdp solver)
- ▶ decided of the selection of instances
 - all PB07 instances except the reduced ones and all instances submitted this year
- ▶ approved the ranking scheme

Based on the objective function

DEC No objective function to optimize (decision problem). The solver must simply find a solution.

OPT An objective function is present. The solver must find a solution with the best possible value of the objective function.

Benchmark categories (2)

Based on the size of coefficients

SMALLINT small integers: no constraint with a sum of coefficients greater than 2^{20} (20 bits)

- ▶ Expected to be safe for solvers using 32 bits integers and simple techniques (be careful with learning)
- ▶ Strong limit to the encoding of concrete problems.

BIGINT big integers: at least one constraint with a sum of coefficients greater than 2^{20} (20 bits)
requires handling of big integers

Benchmark categories (3)

Based on the linearity of constraints

LIN All constraints are linear

NLC At least one constraint is non linear (contains products of literals)

Additional special category

PURE-SAT All constraints are clauses.

This is a proper subset of DEC-SMALLINT-LIN

Contains pigeon-hole instances and some easy instances from the SAT09 competition (which were solved by a majority of solvers in the first phase).

- ▶ **DEC-SMALLINT-LIN (371 instances)**
- ▶ **DEC-SMALLINT-NLC (100 instances)**
- ▶ DEC-BIGINT-LIN (14 instances)
- ▶ DEC-BIGINT-NLC
- ▶ **OPT-SMALLINT-LIN (554 instances)**
- ▶ **OPT-SMALLINT-NLC (405 instances)**
- ▶ OPT-BIGINT-LIN (452 instances) only 1 solver!
- ▶ OPT-BIGINT-NLC
- ▶ PURE-SAT (189 instances)

Submitted solvers

5 teams, 6 solvers

BoolVar Olivier Bailleux

no optimization, translation to SAT, see paper SAT09

bsolo Vasco Manquinho and José Santos

3 versions run, one is hors-concours

pbclasp Benjamin Kaufmann

SAT4J Pseudo Daniel Le Berre and Anne Parrain

2 versions, handles big integers

SCIPclp/spx Timo Berthold, Stefan Heinz, Marc Pfetsch, and Michael Winkler

2 versions, see paper SAT09

wbo Vasco Manquinho

see paper SAT09

- ▶ feature subscription problems (Luis Quesada)
actually weighted MaxSAT,
20 instances, OPT-SMALLINT-LIN
- ▶ FlexRay scheduling instances (Martin Lukasiewicz)
special two-dimensional bin packing problem
9 instances, OPT-SMALLINT-LIN
- ▶ optical routing problems (Miroslav Velev)
70 instances, OPT-BIGINT-LIN

- ▶ Cluster of bi-Xeon 3 GHz, 2MB cache, 2GB RAM (all solvers were run in 32 bits mode)
kindly provided by the CRIL, University of Artois, France
The same environment was used for the SAT competition
- ▶ Each solver was given a time limit of 30 minutes (1800s) and a memory limit of 1800 MB (to avoid swapping).
- ▶ 157 days of CPU time used

Verification of results

- ▶ The environment performs the following, efficient checks:
 - ▶ for SATISFIABLE answers, solvers must output a complete instantiation and the system checks that it satisfies all constraints
 - ▶ for UNSATISFIABLE answers, the system only checks that no other solver proved satisfiability
 - ▶ for OPTIMUM FOUND answers, the system only checks that no other solver found a better solution
- ▶ UNSATISFIABLE and OPTIMUM FOUND answers cannot be completely checked efficiently and therefore should be taken with caution.
- ▶ Solvers giving a wrong answer in a category are disqualified in that category.

Ranking of solvers and Virtual Best Solver (VBS)

Ranking based on two criteria:

1. the number of solved instances
2. ties are broken by considering the cumulated time on solved instances

The Virtual Best Solver (VBS)

- ▶ is the virtual solver obtained by combining the best results of all submitted solvers.
- ▶ could be obtained by running in parallel all submitted solvers
- ▶ represents the current state of the art (SOTA)
- ▶ is a reference for the evaluation of the other solvers

Results for DEC-SMALLINT-LIN

371 instances

Rank	Solver	solved	detail	%inst	%VBS
	<i>VBS</i>	363	145 S/218 U	98%	100%
3	wbo	309	137 S/172 U	83%	85%

Results for DEC-SMALLINT-LIN

371 instances

Rank	Solver	solved	detail	%inst	%VBS
	<i>VBS</i>	363	145 S/218 U	98%	100%
1	bsolo	325	137 S/188 U	88%	90%
2	SCIPspx	310	119 S/191 U	84%	85%
3	wbo	309	137 S/172 U	83%	85%

Results for DEC-SMALLINT-LIN

371 instances

Rank	Solver	solved	detail	%inst	%VBS
	VBS	363	145 S/218 U	98%	100%
1	bsolo	325	137 S/188 U	88%	90%
2	SCIPspx	310	119 S/191 U	84%	85%
3	wbo	309	137 S/172 U	83%	85%
4	SCIPclp	308	119 S/189 U	83%	85%
5	pbclasp	300	126 S/174 U	81%	83%
	<i>bsolo cl (*)</i>	290	136 S/154 U	78%	80%
6	BoolVar	288	111 S/177 U	78%	79%
7	bsolo pb	284	136 S/148 U	77%	78%
8	SAT4J Resol.	278	106 S/172 U	75%	77%
9	SAT4J CP	164	72 S/92 U	44%	45%

Results for DEC-SMALLINT-NLC

100 instances

Rank	Solver	solved	detail	%inst	%VBS
	VBS	75	55 S/20 U	75%	100%
3	pbclasp	65	50 S/15 U	65%	87%

Results for DEC-SMALLINT-NLC

100 instances

Rank	Solver	solved	detail	%inst	%VBS
VBS		75	55 S/20 U	75%	100%
2	SCIPspx	74	54 S/20 U	74%	99%
3	pbclasp	65	50 S/15 U	65%	87%

Results for DEC-SMALLINT-NLC

100 instances

Rank	Solver	solved	detail	%inst	%VBS
	VBS	75	55 S/20 U	75%	100%
1	SCIPclp	74	54 S/20 U	74%	99%
2	SCIPspj	74	54 S/20 U	74%	99%
3	pbclasp	65	50 S/15 U	65%	87%
4	SAT4J CP	65	50 S/15 U	65%	87%
5	bsolo pb	64	49 S/15 U	64%	85%
6	SAT4J Resol.	64	51 S/13 U	64%	85%
7	bsolo	61	46 S/15 U	61%	81%
8	wbo	59	44 S/15 U	59%	79%
9	BoolVar	57	42 S/15 U	57%	76%
	<i>bsolo cl (*)</i>	26	16 S/10 U	26%	35%

Results for OPT-SMALLINT-LIN

554 instances

Rank	Solver	solved	detail	%inst	%VBS
	<i>VBS</i>	343	330 O/13 U	62%	100%

Results for OPT-SMALLINT-LIN

554 instances

Rank	Solver	solved	detail	%inst	%VBS
	<i>VBS</i>	343	330 O/13 U	62%	100%
3	pbclasp	188	175 O/13 U	34%	55%

Results for OPT-SMALLINT-LIN

554 instances

Rank	Solver	solved	detail	%inst	%VBS
	<i>VBS</i>	343	330 O/13 U	62%	100%
2	bsolo pb	231	218 O/13 U	42%	67%
	<i>bsolo cl (*)</i>	230	217 O/13 U	42%	67%
3	pbclasp	188	175 O/13 U	34%	55%

Results for OPT-SMALLINT-LIN

554 instances

Rank	Solver	solved	detail	%inst	%VBS
	VBS	343	330 O/13 U	62%	100%
1	SCIPspx	295	282 O/13 U	53%	86%
2	bsolo pb	231	218 O/13 U	42%	67%
	<i>bsolo cl (*)</i>	230	217 O/13 U	42%	67%
3	pbclasp	188	175 O/13 U	34%	55%

Results for OPT-SMALLINT-LIN

554 instances

Rank	Solver	solved	detail	%inst	%VBS
	VBS	343	330 O/13 U	62%	100%
1	SCIPspx	295	282 O/13 U	53%	86%
2	bsolo pb	231	218 O/13 U	42%	67%
	<i>bsolo cl (*)</i>	230	217 O/13 U	42%	67%
3	pbclasp	188	175 O/13 U	34%	55%
4	SAT4J Resol.	169	158 O/11 U	31%	49%
5	SAT4J CP	140	131 O/9 U	25%	41%
6	wbo	136	124 O/12 U	25%	40%

Results for OPT-SMALLINT-NLC

405 instances

Rank	Solver	solved	detail	%inst	%VBS
	<i>VBS</i>	290	290 O	72%	100%

Results for OPT-SMALLINT-NLC

405 instances

Rank	Solver	solved	detail	%inst	%VBS
	<i>VBS</i>	290	290 O	72%	100%
3	pbclasp	263	263 O	65%	91%

Results for OPT-SMALLINT-NLC

405 instances

Rank	Solver	solved	detail	%inst	%VBS
<i>VBS</i>		290	290 O	72%	100%
2	SCIPclp	286	286 O	71%	99%
3	pbclasp	263	263 O	65%	91%

Results for OPT-SMALLINT-NLC

405 instances

Rank	Solver	solved	detail	%inst	%VBS
<i>VBS</i>		290	290 O	72%	100%
1	SCIPspx	289	289 O	71%	100%
2	SCIPclp	286	286 O	71%	99%
3	pbclasp	263	263 O	65%	91%

Results for OPT-SMALLINT-NLC

405 instances

Rank	Solver	solved	detail	%inst	%VBS
	VBS	290	290 O	72%	100%
1	SCIPspx	289	289 O	71%	100%
2	SCIPclp	286	286 O	71%	99%
3	pbclasp	263	263 O	65%	91%
	<i>bsolo cl (*)</i>	232	232 O	57%	80%
4	SAT4J Resol.	226	226 O	56%	78%
5	wbo	223	223 O	55%	77%
6	SAT4J CP	118	118 O	29%	41%

- ▶ Several solvers of the PB07 evaluation were not submitted this year.
- ▶ What if they had been submitted?
- ▶ Here's a comparison **on the set of instances common to PB07 and PB09**

PB09/PB07: DEC-SMALLINT-LIN (371 inst.)

Rank	Solver	solved	detail
1	PB07: Pueblo	341	139 S/202 U
2	PB07: PBS4_v2	327	130 S/197 U
3	PB07: PBS4	327	130 S/197 U
4	bsolo	325	137 S/188 U
5	PB07: PB-clasp	312	137 S/175 U
6	SCIPspx	310	119 S/191 U
7	wbo	309	137 S/172 U
8	SCIPclp	308	119 S/189 U
9	PB07: minisat+	305	135 S/170 U
10	pbclasp	300	126 S/174 U
11	<i>bsolo cl (*)</i>	290	136 S/154 U
12	BoolVar	288	111 S/177 U
.../...			

PB09/PB07: DEC-SMALLINT-LIN (cont'd)

Rank	Solver	solved	detail
13	bsolo pb	284	136 S/148 U
14	PB07: PB-clasp	283	112 S/171 U
15	SAT4J Resol.	278	106 S/172 U
16	PB07: SAT4JPseudoResol.	273	106 S/167 U
17	PB07: bsolo 3.0.16	271	134 S/137 U
18	PB07: bsolo 3.0.17	271	134 S/137 U
19	PB07: glpPB	200	79 S/121 U
20	SAT4J CP	164	72 S/92 U
more PB07 solvers			

PB09/PB07: DEC-SMALLINT-NLC (100 inst.)

Rank	Solver	solved	detail
1	SCIPclp	74	54 S/20 U
2	SCIPspx	74	54 S/20 U
3	pbclasp	65	50 S/15 U
4	PB07: minisat+	65	50 S/15 U
5	PB07: PBS4	65	50 S/15 U
6	PB07: PBS4_v2	65	50 S/15 U
7	SAT4J CP	65	50 S/15 U
8	PB07: glpPB	65	45 S/20 U
9	PB07: PB-clasp	64	49 S/15 U
10	PB07: Pueblo	64	50 S/14 U
11	bsolo pb	64	49 S/15 U
12	SAT4J Resol.	64	51 S/13 U
.../...			

PB09/PB07: DEC-SMALLINT-NLC (cont'd)

Rank	Solver	solved	detail
13	PB07: PB-clasp	62	47 S/15 U
14	bsolo	61	46 S/15 U
15	PB07: wildcat-rnp	60	60 S
16	PB07: wildcat-skc	60	60 S
17	wbo	59	44 S/15 U
18	BoolVar	57	42 S/15 U
19	PB07: oree	55	45 S/10 U
20	PB07: absconPseudo	50	40 S/10 U
21	PB07: bsolo 3.0.17	28	18 S/10 U
22	PB07: bsolo 3.0.16	27	17 S/10 U
23	<i>bsolo cl (*)</i>	26	16 S/10 U

PB09/PB07: OPT-SMALLINT-LIN (525 inst.)

Rank	Solver	solved	detail
1	SCIPspx	293	280 O/13 U
2	PB07: bsolo 3.0.17	231	218 O/13 U
3	bsolo pb	215	202 O/13 U
4	<i>bsolo cl (*)</i>	210	197 O/13 U
5	PB07: minisat+	201	191 O/10 U
6	PB07: glpPB	186	182 O/4 U
7	PB07: Pueblo	179	166 O/13 U
8	pbclasp	164	151 O/13 U
9	PB07: PB-clasp	155	143 O/12 U
10	PB07: SAT4JPseudoResol.	153	140 O/13 U
11	PB07: PB-clasp	150	142 O/8 U
12	SAT4J Pseudo Resol.	146	135 O/11 U
.../...			

PB09/PB07: OPT-SMALLINT-LIN (cont'd)

Rank	Solver	solved	detail
13	SAT4J Pseudo CP	140	131 O/9 U
14	PB07: sat4jPseudoCP	140	131 O/9 U
15	PB07: sat4jPseudoCPClause	139	130 O/9 U
16	PB07: PBS4_v2	137	128 O/9 U
17	PB07: PBS4	137	128 O/9 U
18	wbo	134	122 O/12 U
more PB07 solvers			

PB09/PB07: OPT-SMALLINT-NLC (405 inst.)

Rank	Solver	solved	detail
1	SCIPspx	289	289 O
2	SCIPclp	286	286 O
3	PB07: minisat+	275	275 O
4	pbclasp	263	263 O
5	PB07: Pueblo	248	248 O
6	PB07: bsolo 3.0.17	239	239 O
7	<i>bsolo cl (*)</i>	232	232 O
8	SAT4J Pseudo Resol.	226	226 O
9	wbo	223	223 O
10	PB07: SAT4JPseudoResol.	216	216 O
11	PB07: PBS4	171	171 O
12	PB07: PBS4_v2	171	171 O
13	SAT4J Pseudo CP	118	118 O
more PB07 solvers			

Comparing SAT and PB solvers

Since

- ▶ PB is an extension of SAT
- ▶ the SAT competition and the PB evaluation were run in the same environment
- ▶ it's easy to translate a SAT instance in the PB syntax

we may try to compare SAT and PB solvers.

But of course

- ▶ PB solvers generally are disadvantaged (must handle coefficients)
- ▶ PB solvers may not be optimized for clauses

Context of the comparison

- ▶ subset of instances from the CRAFTED and INDUSTRIAL categories which were solved by a majority of solvers in the first phase of the SAT competition
- ▶ 20 minutes timeout for all solvers
- ▶ all SAT solvers from the Competition or Demonstration division

PB vs SAT solvers (1/4)

Rank	Solver	Version	Solved	Time
1	picosat	913	123	8033
2	ManySAT 1.1	aimd 1/2009-03-20	122	7833
3	precosat	236	122	10257
4	glucose	1.0	121	6677
5	ManySAT 1.1	aimd 2/2009-03-20	121	9567
6	MXC	2009-03-10	120	7011
7	minisat_cumr	p-2009-03-18	120	9534
8	SATzilla2009_I	2009-03-22	120	10621
9	MiniSat	2.1 (Sat-race'08 Edition)	119	3883
10	Rsat	2009-03-22	119	7073
11	LySAT	i/2009-03-20	119	8711
12	MiniSAT 09z	2009-03-22	118	7843
13	ManySAT 1.1	aimd 0/2009-03-20	118	8010
14	kw	2009-03-20	118	8445
15	SApperloT	base	118	8738

PB vs SAT solvers (2/4)

Rank	Solver	Version	Solved	Time
16	HydraSAT-Flat	2009-03-22-Flat	118	11389
17	clasp	1.2.0-SAT09-32	117	5809
18	CircUs	2009-03-23	117	8522
19	LySAT	c/2009-03-20	117	9182
20	HydraSAT	2009-03-22-Base	117	10614
21	VARSAT-industrial	2009-03-22	116	11412
22	IUT_BMB_SAT	1.0	115	10042
23	HydraSAT-Multi	2009-03-22-Multi	114	10582
24	pbclasp	2009-04-24	114	12758
25	SApperloT	hrp	112	9847
26	SATzilla2009_C	2009-03-22	108	8544
27	satake	2009-03-22	105	11364
28	VARSAT-crafted	2009-03-22	102	10986
29	SAT4J CORE	2.1 RC1	101	14186
30	SAT4J Pseudo Resol.	2.1.1	101	14920

PB vs SAT solvers (3/4)

Rank	Solver	Version	Solved	Time
31	CSat	2009-03-22	99	10307
32	SATzilla2009_R	2009-03-22	96	5676
33	wbo	1.0	93	13808
34	SAT4J Pseudo CP	2.1.1	90	15233
35	bsolo	3.1 cl	86	16275
36	VARSAT-random	2009-03-22	76	12816
37	bsolo	3.1 pb	74	12989
38	bsolo	3.1	74	14338
39	march_hi	hi	52	6503
40	march_nn	nn	52	7250
41	adaptg2wsat2009	2009-03-23	50	4370
42	iPAWS	2009-03-22	48	1852
43	gnovelty+	2009-03-22	45	3540
44	gNovelty+-T	2009-03-22	44	4100
45	Hybrid2	2009-03-22	44	4605

PB vs SAT solvers (4/4)

Rank	Solver	Version	Solved	Time
46	TNM	2009-03-22	44	4621
47	adaptg2wsat2009++	2009-03-23	43	2136
48	hybridGM3	3	41	4388
49	hybridGM	1	39	1465
50	NCVWr	2009-03-22	37	6720
51	gnovelty+2	2009-03-22	35	2405
52	SCIPspx	with SoPLEX	35	5554
54	hybridGM7	7	34	1199
53	tts	tts-5-0	34	2906
55	slstc	1.0	33	3202
56	SCIPclp	with CLP	32	3795
57	ttsth-5-0	2009-03-19	32	4048

- ▶ All details are on the web site
<http://www.cril.univ-artois.fr/PB09>
- ▶ Thanks to all participants!