

Quantify 2015 @ Berlin

Old Challenges and new Solutions: a Comprehensive Assessment of SOTA QBF Solvers

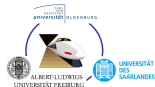


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Background

QBF Evaluation and Gallery

Why Assess progress of SOTA in QBF solving/reasoning field

When Since 2003

Where Along SAT Conference

What happened?

- Every year new techniques/implementations and problems
- (Not really constantly though)
- Correctness: for several years “Majority voting”
(*Another story...*)



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- Long-term picture of SOTA's progress is missing
- Several tools no longer maintained
- Improvement: Technique or implementation?
- More and more benchmarks:
- Old hard-to-break ones still unbreakable?

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- Compare **legacy** against and together with **new tools**



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Closed QBF in Prenex Conjunctive Normal Form

$$\underbrace{\underbrace{\exists z_1 z_2 \cdots \forall z_3 \cdots}_{\text{level } 0} \cdots \underbrace{\exists z_{n-1} z_n}_{\text{level } m}}_{\text{prefix}} \underbrace{\underbrace{\wedge_p \text{ clause}_p}_{\text{matrix}} \underbrace{\vee_{q_p} \text{ lit}_{q_p}}_{\text{clause}_p}}_{\text{matrix}} \phi(z_1, \dots, z_n) \quad m, n, p, q \geq 0$$

Structure of QBFs

(Main) Features

- c total number of clauses
- v total number of variables
- $\frac{c}{v}$ the classic clauses-to-variables ratio
- VG** Variable Graph: a node is a variable, an edge connects variables occurring together in at least one clause
- tw_p (approx.) treewidth compatible with the prefix p
(Empirical measure of a QBF's hardness)



Hardware

- Intel Xeon E31245 PCs @ 3.30 GHz
- 600 s CPU time
- 4 GB RAM
- Ubuntu 12.04 64 bit

? Memory available at QBF Gallery 2014

→ Florian, Martina?



3 Pools of Problems

- **QBF Gallery 2014 Track 1** 276 instances
- **QBF Gallery 2014 Track 2.** 735 instances
- **Challenging** instances from QBFEVAL events from 2004 to 2010 — between 96 and 961 instances per year (those classified as “Hard” and “Medium-Hard” in the respective assessment)



QBF-G-T2 Suite

- bomb and dungeon** conformant planning problems with optimal length and uncertainty of the initial state.
- complexity** automatic reduction between decision problems: original problem undecidable in general, reducible to Σ_2^P if the dimension of the reduction is fixed and given, and the size of the inputs is bounded.
- hardness** Black-Box BMC of incomplete parametrized arbiter of a bus system.
- planning** planning problems encoded into QBF using iterative squaring formulation and tree-like encoding.
- testing** test patterns for sequential circuits coming from ISCAS 89 and ITC 99 benchmarks having a maximum amount of inputs set to don't care.



Legacy Solvers

AIGSOLVE AIG-based operation, with preliminary phases for simplification, structure extraction and early quantification.

Unique AIG-based solver

AQME multi-engine (2CLSQ, QUANTOR, QuBE, sKIZZO, and sSOLVE) solver using Machine Learning techniques. Its reasoning engines are a subset from QBFEVAL'06.

Unique multi-engine, represents SOTA'06

QUANTOR based on Q-resolution and Shannon expansion, plus equivalence reasoning, subsumption checking, simplification.

Key technique: Resolution and Expansion



Legacy Solvers (cont'd)

QuBE based on preprocessing and CSDCL-based decision procedure.

Key technique: QDLL-based

sKizzo reasoning engine for QBF featuring among others search, resolution and skolemization.

Key technique: Skolemization-based

STRUQS dynamic switch between search and variable-elimination driven by graph abstractions of the QBF.

Key technique: First dynamic alternation of different techniques



New Solvers

- DEPQBF** CSDCL-based solver leveraging dependencies among variable to loosen branching order constraints.
- GHOSTQ** non-prenex DPLL-based solver making use of auxiliary variables to force necessary assignments, and featuring an additional CEGAR-based learning.
- RAREQS** CEGAR-based solver performing a kind of resolution and expansion procedure in a depth-first way to compute a global solution step-by-step.



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BLOQQER preprocessor coupled with these solvers after submission review



Solver Abstractions

$$\text{SOTA-LEGACY} = \{\text{AIGSOLVE} + \text{QUANTOR} + \text{QUBE} + \text{sKIZZO} + \text{STRUQS}\}$$

$$\text{SOTA-NEW} = \{\text{B+DEPQBF} + \text{B+GHOSTQ} + \text{B+RAREQS}\}$$

$$\text{SOTA} = \text{SOTA-LEGACY} \cup \text{SOTA-NEW}$$

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$$\{\text{DEPQBF}, \text{GHOSTQ}, \text{RAREQS}\} \notin \text{SOTA-NEW}$$

$$\text{SOTA} = \text{SOTA-LEGACY} \cup \text{SOTA-NEW}$$

QBF Gallery 2014 formulas – Track 1 (276)

Solver	Total		True		False		Unique	
	#	Time	#	Time	#	Time	#	Time
B+RAREQS	128	6389.60	66	1441.13	62	4948.47	12	3622.20
B+DEPQBF	127	5241.49	66	2392.48	61	2849.01	8	750.79
AIGSOLVE	116	5333.01	56	2177.45	60	3155.56	22	1058.86
QuBE	106	8764.73	53	3997.78	53	4766.95	5	1455.38
GHOSTQ	91	4814.73	48	2912.38	43	1902.17	4	158.97
DEPQBF	88	2388.32	39	1163.15	49	1225.17	5	454.77
RAREQS	79	2588.64	32	1593.25	47	995.39	6	787.33
B+GHOSTQ	63	4429.57	34	2415.86	29	2013.71	–	–
sKIZZO	51	948.81	18	556.76	33	392.06	2	35.15
QUANTOR	50	1498.37	28	911.72	22	586.65	4	270.33
STRUQS	43	6092.64	31	4052.98	12	2039.66	2	942.89



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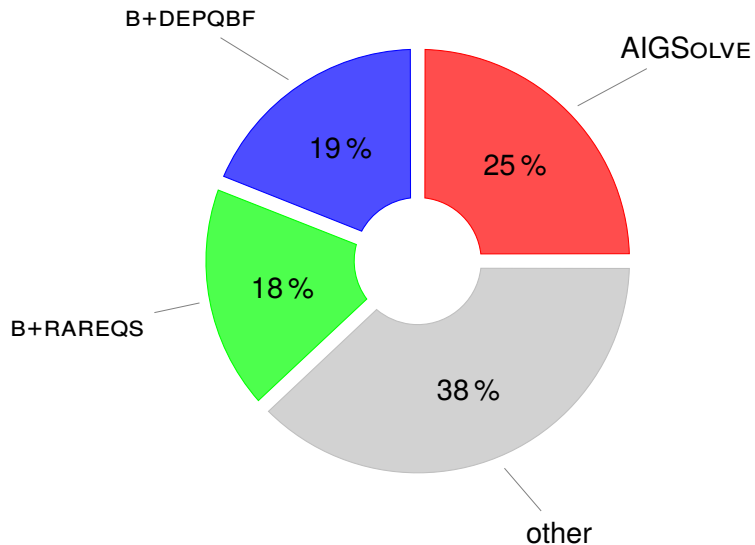
SOTA solves 207 formulas

SOTA-NEW 159

SOTA-LEGACY 184



SOTA Composition



QBF Gallery 2014 Track 1 – Hardness

Solved Instances

 \hat{c} 15226 \hat{v} 3652 $t\hat{w}_p$ 495

Unsolved Instances

 \hat{c} 69238 \hat{v} 7251 $t\hat{w}_p$ 927

SOTA-LEGACY

Solved

 $t\hat{w}_p$ 464

Unsolved

 $t\hat{w}_p$ 952

SOTA-NEW

Solved

 $t\hat{w}_p$ 545

Unsolved

 $t\hat{w}_p$ 581

QBF Gallery 2014 formulas – Track 2 (Summary)

Solver	Total Solved #						
	bomb	complexity	dungeon	hardness	planning	testing	sum
B+RAREQS	82	91	62	68	137	91	531
RAREQS	83	75	57	14	137	34	400
B+DEPQBF	80	58	59	81	44	77	399
AlGSOLVE	83	15	87	12	147	51	395
QUANTOR	82	26	104	0	131	26	369
DEPQBF	67	49	44	8	57	57	282
QUBE	47	39	34	76	14	41	251
B+GHOSTQ	50	46	11	46	12	52	217
STRUQS	36	21	1	88	4	65	215
GHOSTQ	56	42	7	51	11	32	199
sKIZZO	57	9	2	0	74	1	143
AQME	80	33	104	50	123	71	461
SOTA-LEGACY	96	44	106	90	147	76	559
SOTA-NEW	82	91	67	81	137	95	553
SOTA	96	91	106	93	147	105	638
features	high $\frac{c}{v}$ and tw_p	small, few ∇ variables	high c , c_1, c_h, v ; few l and v_∇	small, max v_∇ (5%) and Q-alt.	sim. bomb, max $\frac{c}{v}$ and VG	dim. \rightarrow bomb, 2% v_∇ (hard- ness)	



Past QBFEVAL Challenging Formulas

Year	Solver	Total		True		False		Unique	
		#	Time	#	Time	#	Time	#	Time
2004 (167)	B+RAREQS	68	4210.31	47	1041.52	21	3168.79	9	2097.87
	AIGSOLVE	62	2658.96	46	1781.89	16	877.07	8	862.23
	B+DEPQBF	57	2167.21	43	1415.99	14	751.224	–	–
	GHOSTQ	51	541.62	36	370.74	15	170.88	18	194.05
	B+GHOSTQ	53	1683.57	44	1432.53	9	251.04	1	96.40
	QuBE	28	4783.92	23	3566.83	5	1217.09	–	–
	sKIZZO	23	749.18	16	691.76	7	57.42	–	–
	STRUQS	14	1081.04	9	885.70	5	195.34	–	–
	QUANTOR	13	916.32	11	905.49	2	10.83	–	–
	DEPQBF	2	192.64	–	–	2	192.64	–	–
RAREQS	1	0.24	–	–	1	0.24	1	0.24	
2005 (168)	AIGSOLVE	43	3386.36	32	2119.95	11	1266.41	18	1861.10
	B+RAREQS	35	1765.19	23	825.95	12	939.24	5	222.89
	B+DEPQBF	30	2439.47	23	896.37	7	1543.10	–	–
	GHOSTQ	27	217.17	17	46.44	10	170.43	13	190.25
	B+GHOSTQ	21	388.26	18	61.18	3	327.07	–	–
	QuBE	19	2653.56	16	2365.20	3	288.37	1	19.08
	RAREQS	8	5.57	–	–	8	5.57	3	0.54
	STRUQS	8	921.27	6	687.03	2	234.24	–	–
	sKIZZO	7	595.39	7	595.39	–	–	–	–
	QUANTOR	5	144.64	4	137.29	1	7.34	–	–
DEPQBF	1	243.79	–	–	1	243.79	–	–	

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	DEPQBF	2	192.64	–	–	2	192.64	–	–
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2006 (103)	GHOSTQ	80	1577.10	80	1577.10	–	–	5	15.33
	AIGSOLVE	71	608.62	63	432.35	8	176.27	7	110.74
	QuBE	61	1108.04	57	506.54	4	601.49	2	65.80
	B+DEPQBF	52	1167.25	41	277.36	11	889.89	4	191.62
	B+RAREQS	46	880.79	41	219.68	5	661.11	–	–
	STRUQS	37	373.31	36	298.82	1	74.48	–	–
	B+GHOSTQ	15	464.27	15	464.27	–	–	–	–
	RAREQS	4	277.89	1	102.27	3	175.62	–	–
	DEPQBF	1	22.85	–	–	1	22.85	–	–
	QUANTOR	–	–	–	–	–	–	–	–
SKIZZO	–	–	–	–	–	–	–	–	
2007 (281)	B+RAREQS	148	1619.72	17	1063.27	131	556.46	59	818.12
	QuBE	88	7239.68	13	2729.53	75	4510.16	2	247.79
	RAREQS	83	2706.28	10	1905.49	73	800.79	31	1741.36
	B+DEPQBF	62	3418.31	10	621.09	52	2797.22	–	–
	AIGSOLVE	61	765.34	36	547.74	25	217.61	43	608.41
	DEPQBF	50	2902.71	6	378.32	44	2524.39	5	264.06
	GHOSTQ	49	1699.99	41	360.23	8	1339.76	19	275.34
	QUANTOR	14	1302.44	11	1225.27	3	77.17	4	132.83
	STRUQS	11	2051.88	11	2051.88	–	–	1	124.88
B+GHOSTQ	5	126.83	2	3.31	3	123.52	–	–	
SKIZZO	5	953.55	1	50.44	4	903.11	–	–	



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	B+GHOSTQ	15	464.27	15	464.27	–	–	–	–
	RAREQS	4	277.89	1	102.27	3	175.62	–	–
	DEPQBF	1	22.85	–	–	1	22.85	–	–
	QUANTOR	–	–	–	–	–	–	–	–
SKIZZO	–	–	–	–	–	–	–	–	
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	STRUQS	11	2051.88	11	2051.88	–	–	1	124.88
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SKIZZO	5	953.55	1	50.44	4	903.11	–	–	



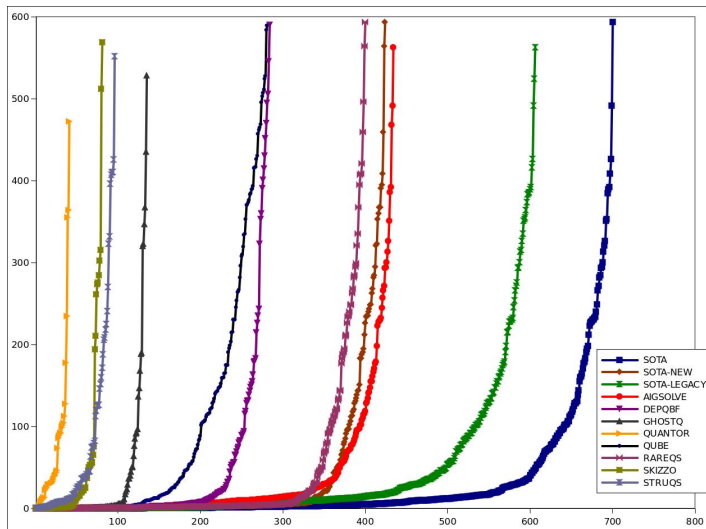
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	B+RAREQS	306	11102.33	94	5309.12	212	5793.20	74	3765.41
	GHOSTQ	304	8299.71	257	5325.55	47	2974.16	49	1493.92
	B+DEPQBF	198	9643.59	73	3754.18	125	5889.41	4	191.62
	QuBE	198	19753.10	71	13501.39	127	6251.71	13	2475.20
	RAREQS	126	4220.58	16	2744.06	110	1476.52	36	2255.13
	DEPQBF	96	4626.18	7	495.77	89	4130.41	4	261.53
	B+GHOSTQ	75	2735.79	61	1352.30	14	1383.49	2	102.44
	sKIZZO	57	3599.21	26	1664.18	31	1935.02	-	-
	STRUQS	50	5458.74	47	4844.87	3	613.87	3	162.84
QUANTOR	19	1646.95	18	1621.94	1	25.02	12	708.57	
2010 (96)	GHOSTQ	29	591.60	25	281.30	4	309.76	10	342.94
	AIGSOLVE	22	282.18	20	262.94	2	19.24	12	270.13
	B+RAREQS	20	912.79	14	304.74	6	608.04	6	255.17
	B+DEPQBF	13	663.84	11	617.63	2	46.21	1	32.49
	B+GHOSTQ	9	2.41	9	2.41	-	-	-	-
	sKIZZO	8	564.39	8	564.39	-	-	-	-
	QuBE	4	210.40	1	19.08	3	191.32	1	19.08
	RAREQS	2	17.41	-	-	2	17.41	1	0.50
	DEPQBF	1	22.85	-	-	1	22.85	-	-
	QUANTOR	-	-	-	-	-	-	-	-
STRUQS	-	-	-	-	-	-	-	-	

Past QBFEVAL Challenging Formulas

Year	Solver	Total		True		False		Unique	
		#	Time	#	Time	#	Time	#	Time
2008 (961)	AIGSOLVE	335	13128.70	237	8439.00	98	4689.70	168	6417.99
	B+RAREQS	306	11102.33	94	5309.12	212	5793.20	74	3765.41
	GHOSTQ	304	8299.71	257	5325.55	47	2974.16	49	1493.92
	B+DEPQBF	198	9643.59	73	3754.18	125	5889.41	4	191.62
	QuBE	198	19753.10	71	13501.39	127	6251.71	13	2475.20
	RAREQS	126	4220.58	16	2744.06	110	1476.52	36	2255.13
	DEPQBF	96	4626.18	7	495.77	89	4130.41	4	261.53
	B+GHOSTQ	75	2735.79	61	1352.30	14	1383.49	2	102.44
	sKizzo	57	3599.21	26	1664.18	31	1935.02	-	-
	STRUQS	50	5458.74	47	4844.87	3	613.87	3	162.84
QUANTOR	19	1646.95	18	1621.94	1	25.02	12	708.57	
2010 (96)	GHOSTQ	29	591.60	25	281.30	4	309.76	10	342.94
	AIGSOLVE	22	282.18	20	262.94	2	19.24	12	270.13
	B+RAREQS	20	912.79	14	304.74	6	608.04	6	255.17
	B+DEPQBF	13	663.84	11	617.63	2	46.21	1	32.49
	B+GHOSTQ	9	2.41	9	2.41	-	-	-	-
	sKizzo	8	564.39	8	564.39	-	-	-	-
	QuBE	4	210.40	1	19.08	3	191.32	1	19.08
	RAREQS	2	17.41	-	-	2	17.41	1	0.50
	DEPQBF	1	22.85	-	-	1	22.85	-	-
	QUANTOR	-	-	-	-	-	-	-	-
STRUQS	-	-	-	-	-	-	-	-	

Past QBFEVAL Challenging Formulas



Past QBFEVAL Challenging Formulas

	2004	2005	2006	2007	2008	2010
SOTA	81	55	82	214	581	34
SOTA-NEW	73	41	55	152	326	21
SOTA-LEGACY	69	49	77	150	492	26

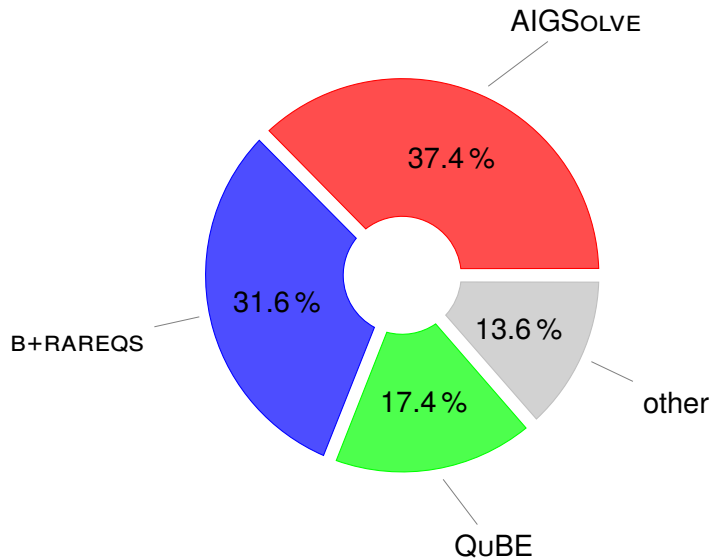
Past QBFEVAL Challenging Formulas

	2004	2005	2006	2007	2008	2010
AIGSOLVE		43			335	
SOTA	81	55	82	214	581	34
SOTA-NEW	73	41	55	152	326	21
SOTA-LEGACY	69	49	77	150	492	26

Past QBFEVAL Challenging Formulas

	2004	2005	2006	2007	2008	2010
AIGSOLVE		43			335	
GHOSTQ			80			29
SOTA	81	55	82	214	581	34
SOTA-NEW	73	41	55	152	326	21
SOTA-LEGACY	69	49	77	150	492	26

CHALLENGING: SOTA Composition



Summary

- Intersection of several solving technologies and historical view of evaluations
- SOTA is mostly composed by new solvers
- Impact of preprocessing on new solvers
- “Old” solving techniques still worth consideration
- Portfolio approaches
- Valid common testbed?

