A Short History on SAT Solver Technology and What is Next?

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A. Biere, FMV, JKU Linz

- actually "... short **personal, recent** history ..."

- recent:
  - improvement of SAT solvers since Chaff (2000)
  - almost same time span as the existence of the SAT competitions
  - for previous history see

    [L. Zhang, S. Malik, *The Quest for Efficient SAT Solvers*, CAV'03]

- personal:
  - development of the technology related to my implementations:

    Limmat, CompSAT, FunEx, NanoSAT, BooleForce, PicoSAT

Disclaimer

- focus on **industrial** applications
  - combinatorial and random benchmarks / solvers provide new challenges, new ideas
- definition of a “fast” solver:
  - ranked higher in the “industrial” track of the SAT competition
- actually, we use the **SAT-Race 2006** setup
  - number solved instances from 100 selected industrial examples
  - 43 SAT, 57 UNSAT, time limit 900 seconds, memory limit 1.5 GB

solver	count	solved	unsolved	time	mb	memout
picosat	100	78	22	38240	5793	0
booleforce	100	56	44	51645	17651	1
compsat	100	38	62	62639	37042	0
funex	100	31	69	68791	16197	0
nanosat	100	30	70	69666	19738	0
limmat	100	20	80	74880	34533	0

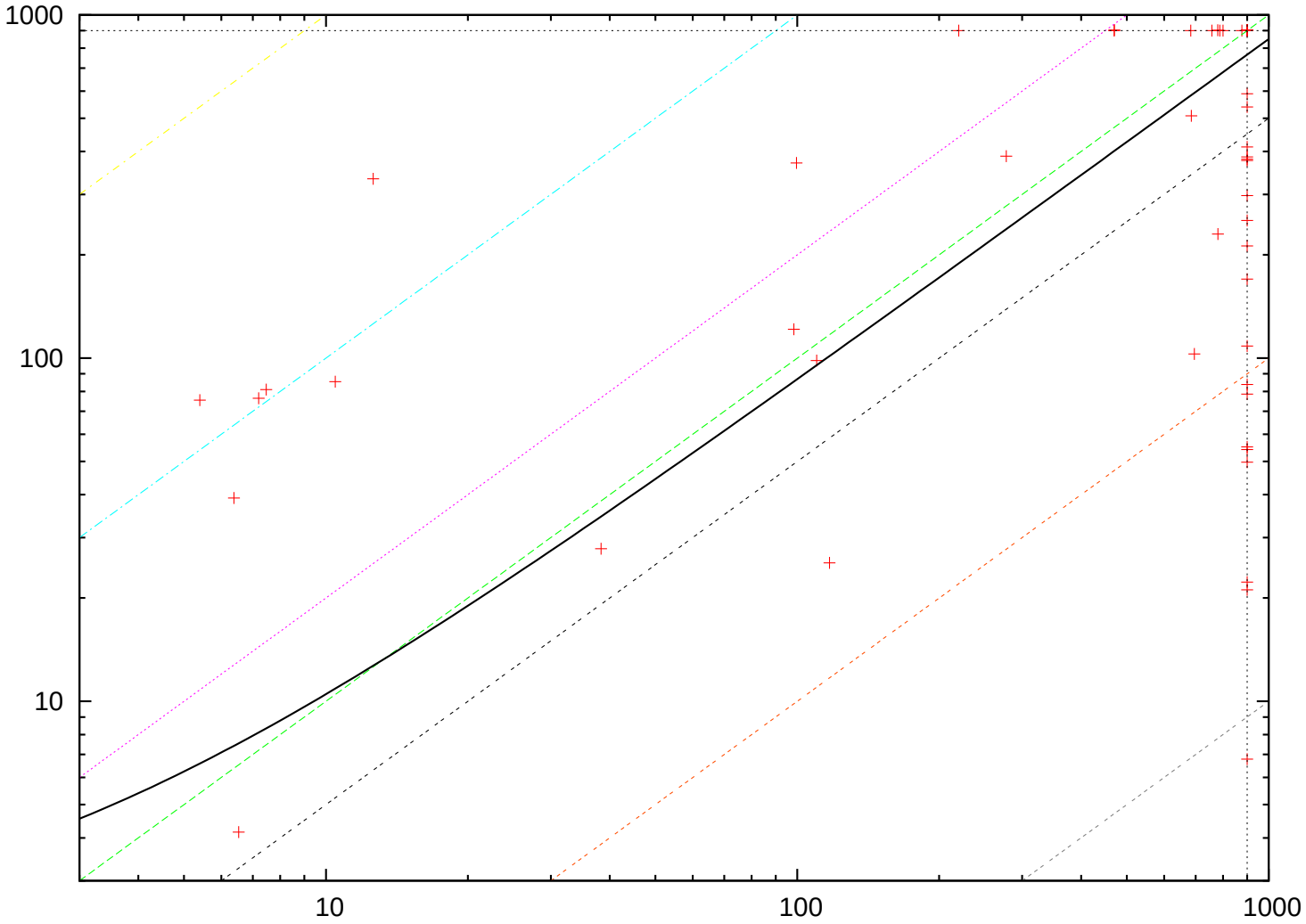
	limmat	compsat	funex	nanosat	booleforce	picosat
ibm-2002-05r-k90	99.61	370.45	---	507.86	162.22	**27.54**
ibm-2002-07r-k100	---	54.14	726.33	15.97	14.50	**7.31**
ibm-2002-11r1-k45	---	---	---	---	409.21	**129.40**
ibm-2002-19r-k100	---	---	---	---	---	**410.01**
ibm-2002-21r-k95	---	---	---	---	---	**281.74**
ibm-2002-26r-k45	6.53	**4.16**	24.38	302.93	368.93	6.34
ibm-2002-27r-k95	98.32	121.42	---	---	178.95	**21.66**
ibm-2004-03-k70	277.60	387.64	852.74	---	150.25	**38.43**
ibm-2004-04-k100	---	---	---	---	---	**172.50**
ibm-2004-06-k90	---	---	---	---	320.65	**74.48**
ibm-2004-19-k90	---	---	---	---	---	**293.49**
ibm-2004-1_11-k25	109.91	98.43	108.27	66.07	22.16	**10.86**
ibm-2004-1_31_2-k25	---	---	---	---	224.75	**139.24**
ibm-2004-26-k25	**2.12**	68.08	445.86	5.77	24.67	3.54
ibm-2004-2_02_1-k100	117.01	25.32	182.28	---	37.30	**16.62**
ibm-2004-2_14-k45	---	108.50	286.52	---	55.67	**22.73**
ibm-2004-3_02_1-k95	8.36	**1.48**	125.07	31.30	20.15	2.19
ibm-2004-3_02_3-k95	**1.99**	108.18	5.43	20.19	45.90	6.91
ibm-2004-3_11-k60	---	---	---	---	---	**794.18**
ibm-2004-6_02_3-k100	12.60	333.13	91.46	197.83	20.40	**6.80**
manol-pipe-c10id_s	---	22.24	130.07	122.20	37.86	**6.29**
manol-pipe-c10nidw_s	---	**78.59**	---	---	460.10	202.31
manol-pipe-c6nidw_i	---	---	---	---	---	**752.67**
manol-pipe-c7b	---	---	164.37	338.03	127.91	**45.79**
manol-pipe-c7b_i	---	---	174.96	246.76	93.01	**55.91**
manol-pipe-c7bidw_i	---	---	---	---	---	---
manol-pipe-c7nidw	---	---	---	---	---	---
manol-pipe-c9	---	212.27	20.86	29.77	17.60	**6.96**
manol-pipe-c9nidw_s	---	**55.13**	---	---	372.85	110.43
manol-pipe-f10ni	---	---	---	---	---	---
manol-pipe-f6bi	---	49.74	29.50	17.88	16.44	**4.76**
manol-pipe-f7idw	---	---	---	---	---	**586.18**
manol-pipe-f9b	---	---	---	---	---	---
manol-pipe-f9n	---	---	---	---	---	---
manol-pipe-g10b	---	---	---	---	228.93	**88.82**
manol-pipe-g10bidw	---	---	---	---	---	**642.67**
manol-pipe-g10id	---	---	327.93	---	185.53	**135.33**
manol-pipe-g10nid	---	---	---	---	---	**592.59**
manol-pipe-g6bi	---	6.78	7.94	6.41	5.13	**1.84**
manol-pipe-g7nidw	---	170.01	91.12	225.00	70.20	**22.71**
aloul-chnl11-13	**220.04**	---	---	---	---	---
een-pico-prop01-75	6.38	39.10	8.41	13.24	19.58	**2.52**
een-pico-prop05-50	---	---	---	---	126.75	**36.96**
een-tip-sat-nusmv-t5.B	**7.47**	81.00	31.49	19.29	29.96	14.96
een-tip-sat-nusmv-tt5.B	**7.20**	76.40	31.56	16.16	30.69	15.40
een-tip-uns-nusmv-t5.B	**5.40**	75.46	11.44	5.96	8.37	7.18
goldb-heqc-alu4mul	---	---	---	---	---	**800.56**
goldb-heqc-dalumul	---	---	---	---	---	---
goldb-heqc-desmul	---	297.59	373.39	---	135.20	**67.27**
goldb-heqc-frg2mul	---	---	---	---	538.71	**164.30**
goldb-heqc-i10mul	---	---	---	---	---	**753.49**
goldb-heqc-i8mul	---	---	---	---	---	---
goldb-heqc-term1mul	---	---	---	---	---	**213.41**
grieu-vmpc-s05-25	---	412.29	---	212.22	799.56	**12.38**
grieu-vmpc-s05-27	470.28	---	**44.58**	---	---	48.10
grieu-vmpc-s05-28	---	---	---	---	---	**329.56**
grieu-vmpc-s05-34	---	---	---	---	---	---
hoons-vbmc-lucky7	---	---	---	---	161.63	**8.02**
maris-s03-gripper11	---	---	---	---	---	**43.85**
narain-vpn-clauses-6	---	---	---	---	---	**753.68**
schup-l2s-guid-1-k56	---	---	---	---	---	**699.22**
schup-l2s-motst-2-k315	---	---	---	---	---	**885.23**
simon-s02-w08-18	---	---	---	---	**422.23**	448.21
simon-s02b-dp11u10	---	---	---	642.53	**445.20**	---
simon-s02b-k2f-gr-rcs-w8	---	---	**21.56**	---	---	---
simon-s02b-r4b1k1.1	---	---	---	---	672.81	**21.11**
simon-s03-fifo8-300	---	---	---	---	248.84	**247.99**
simon-s03-fifo8-400	---	---	---	---	878.35	**409.51**
vange-col-abb313GPIA-9-c	---	---	---	---	---	---
vange-col-inithx.i.1-cn-54	**10.47**	85.43	536.45	385.09	42.08	17.08
mizh-md5-47-3	---	---	---	---	**432.36**	---
mizh-md5-47-4	---	---	---	---	---	**703.03**
mizh-md5-47-5	---	---	---	---	---	**747.32**
mizh-md5-48-2	---	---	---	---	---	---
mizh-md5-48-5	---	---	---	---	**389.84**	---
mizh-sha0-35-2	---	---	---	---	514.28	**221.90**
mizh-sha0-35-3	---	539.47	---	861.69	---	**339.62**
mizh-sha0-35-4	---	385.72	---	848.40	220.59	**187.10**
mizh-sha0-35-5	---	---	---	---	---	**280.16**
mizh-sha0-36-2	---	---	---	---	---	**388.62**
velev-engi-uns-1.0-4nd	685.22	507.97	361.34	272.51	**84.70**	127.01
velev-engi-uns-1.0-5c1	38.34	27.85	35.00	20.89	14.17	**7.84**
velev-fvp-sat-3.0-b18	---	379.89	---	---	---	**102.62**
velev-live-uns-2.0-ebuf	---	589.51	116.98	80.98	**68.10**	518.45
velev-npe-1.0-9dlx-b71	---	---	---	---	---	**510.05**
velev-pipe-o-uns-1.0-7	---	---	---	---	---	---
velev-pipe-o-uns-1.1-6	---	---	**884.27**	---	---	---
velev-pipe-sat-1.0-b10	---	229.92	---	483.01	**75.56**	319.61
velev-pipe-sat-1.0-b7	---	---	---	503.48	590.91	**218.38**
velev-pipe-sat-1.0-b9	---	83.77	---	---	73.65	**55.59**
velev-pipe-sat-1.1-b7	---	---	---	---	231.01	**34.41**
velev-pipe-uns-1.0-8	---	---	---	---	---	---
velev-pipe-uns-1.0-9	---	---	---	---	**185.97**	---
velev-pipe-uns-1.1-7	---	---	---	---	---	---
velev-vliw-sat-2.0-b6	---	**21.12**	439.47	---	158.95	246.47
velev-vliw-sat-4.0-b1	---	**251.93**	---	---	---	730.80
velev-vliw-sat-4.0-b3	695.53	**102.87**	---	166.16	608.80	112.91
velev-vliw-sat-4.0-b4	---	376.49	---	---	**164.77**	867.02
velev-vliw-uns-2.0-iq4	---	---	---	---	---	---
velev-vliw-uns-4.0-9C1	---	---	---	---	---	---

Limmat vs CompSAT

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **Limmat** faster

below diagonal $\Rightarrow$ **CompSAT** faster

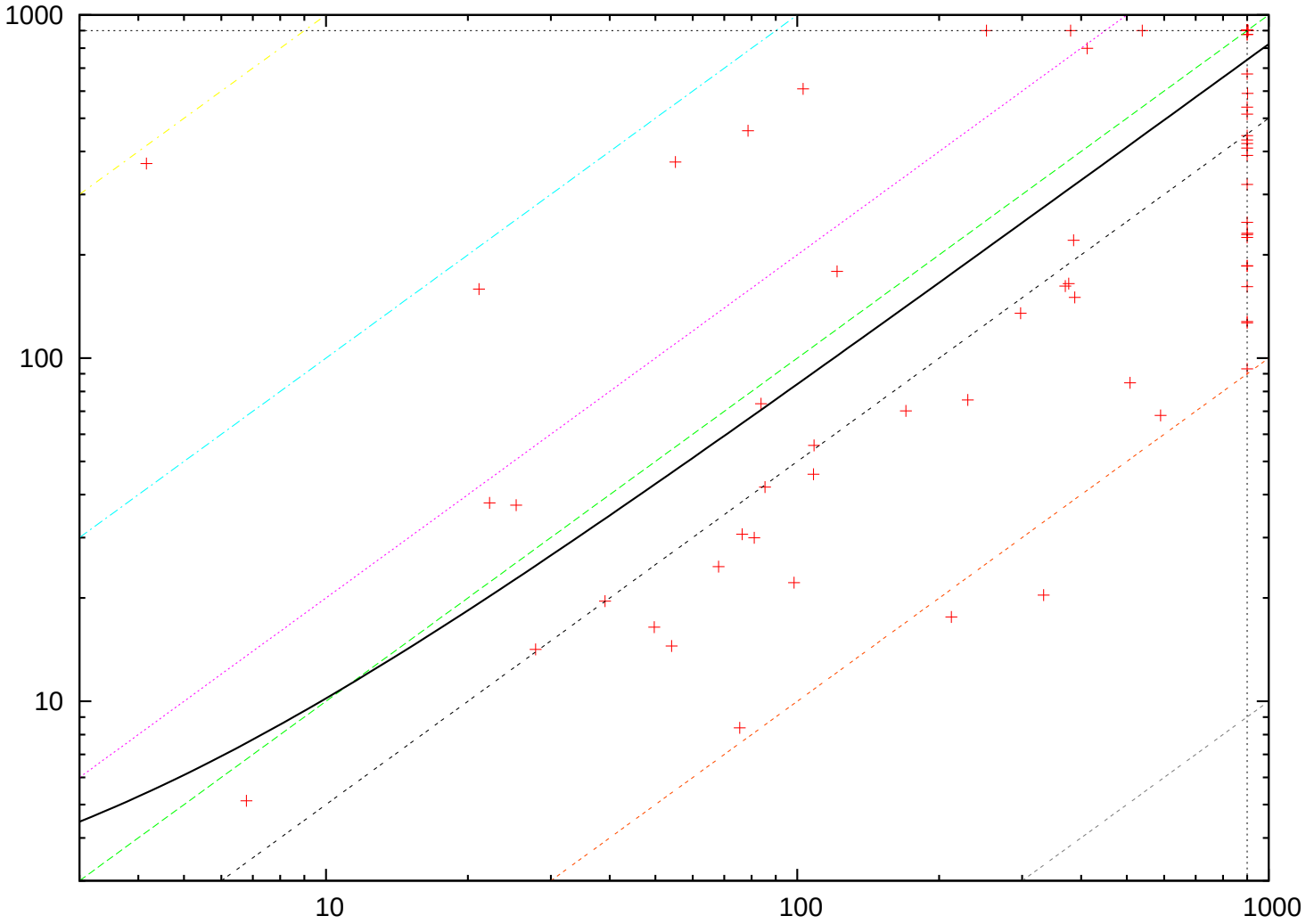


CompSAT vs BooleForce

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **CompSAT** faster

below diagonal $\Rightarrow$ **BooleForce** faster

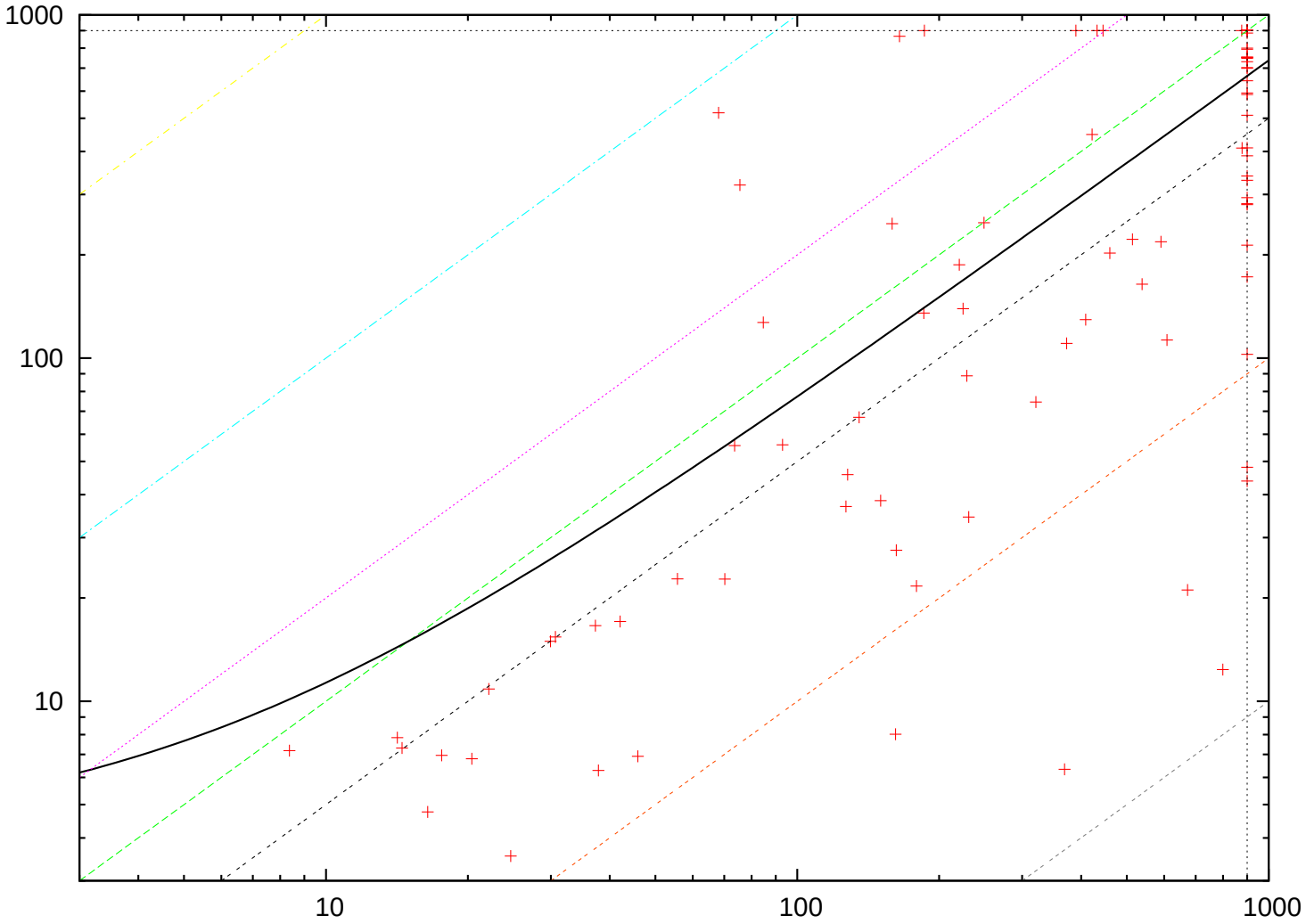


BooleForce vs PicoSAT

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **BooleForce** faster

below diagonal $\Rightarrow$ **PicoSAT** faster

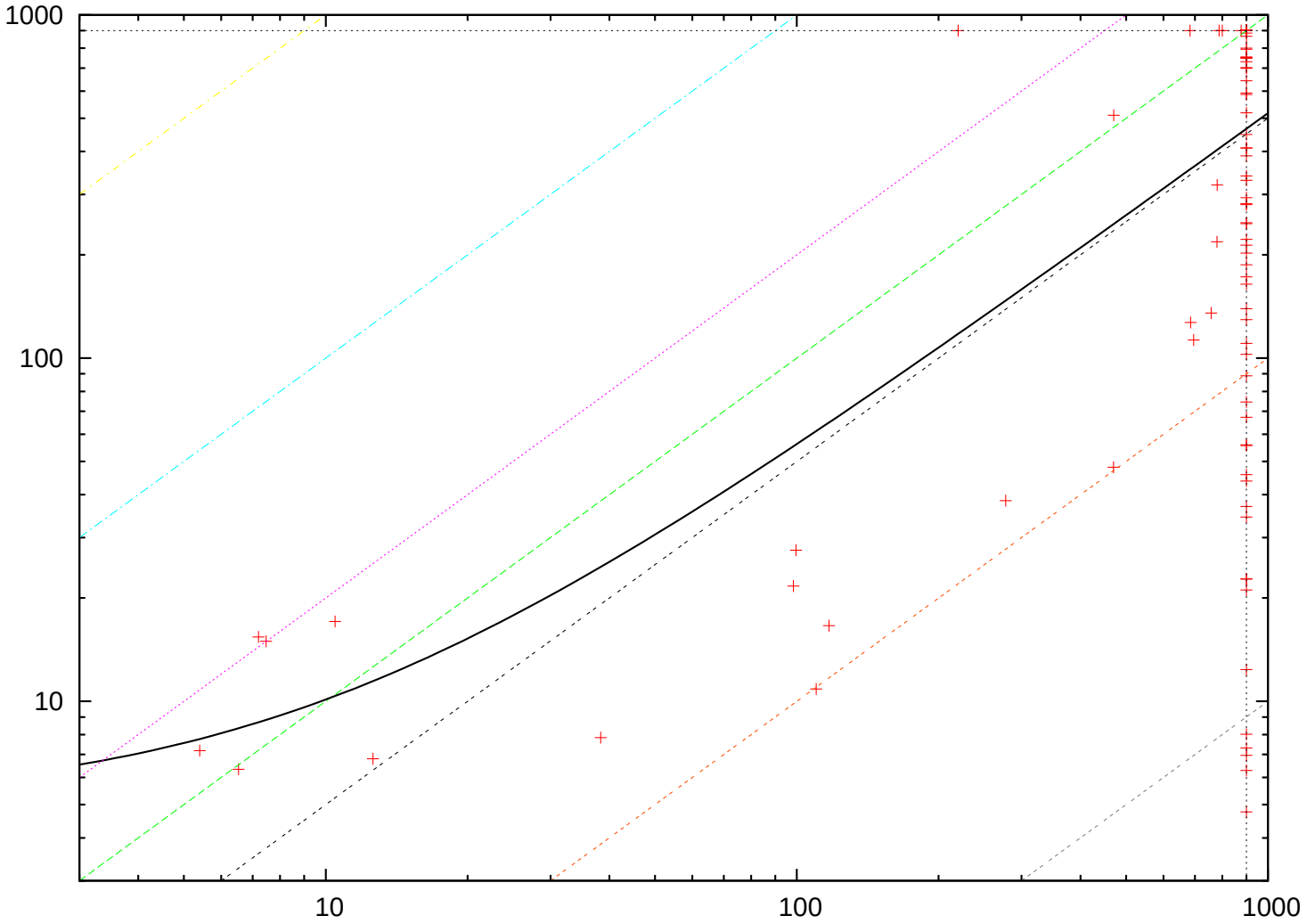


Limmat vs PicoSAT

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **Limmat** faster

below diagonal $\Rightarrow$ **PicoSAT** faster

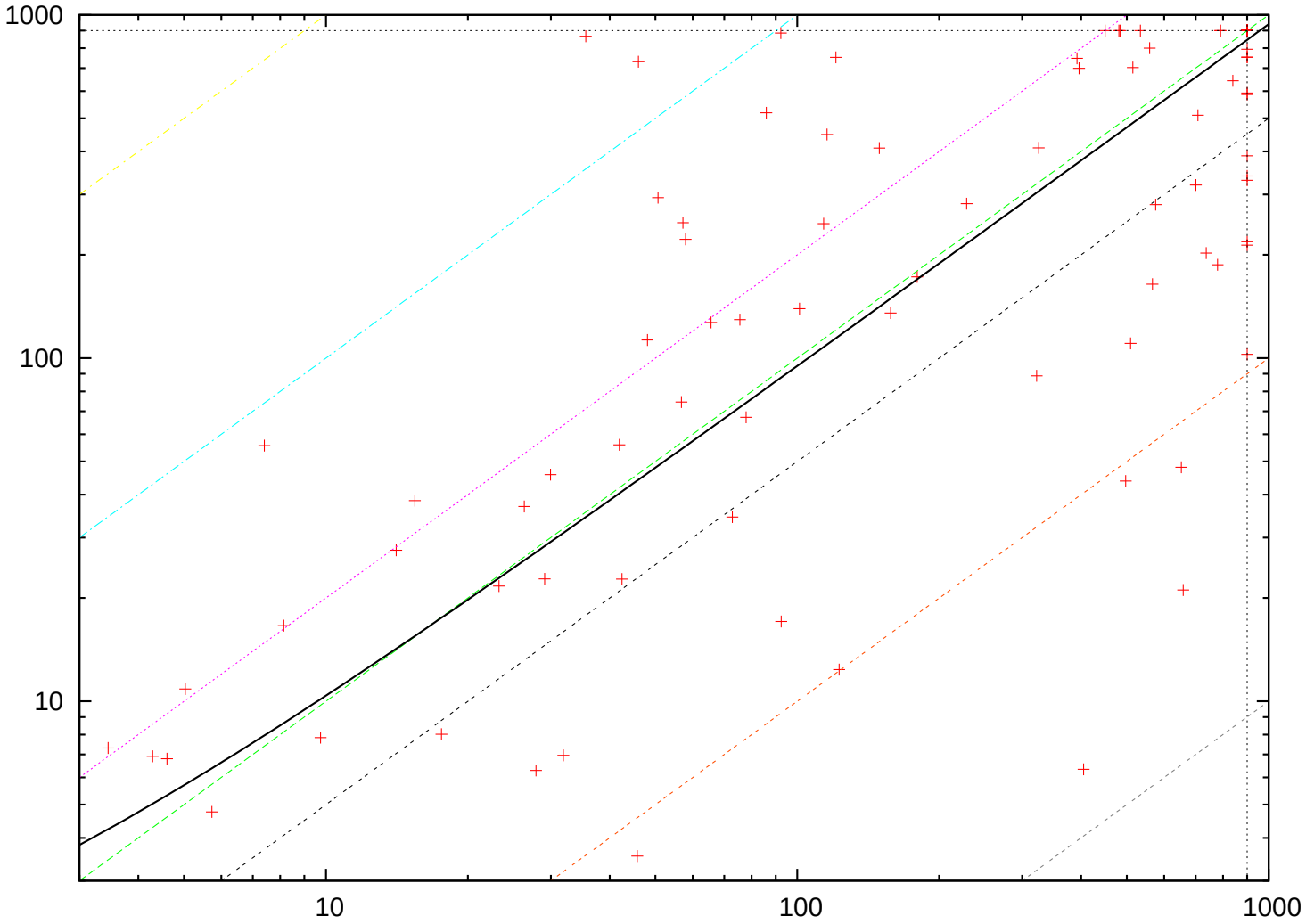


MiniSAT vs PicoSAT

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **MiniSAT** faster

below diagonal $\Rightarrow$ **PicoSAT** faster

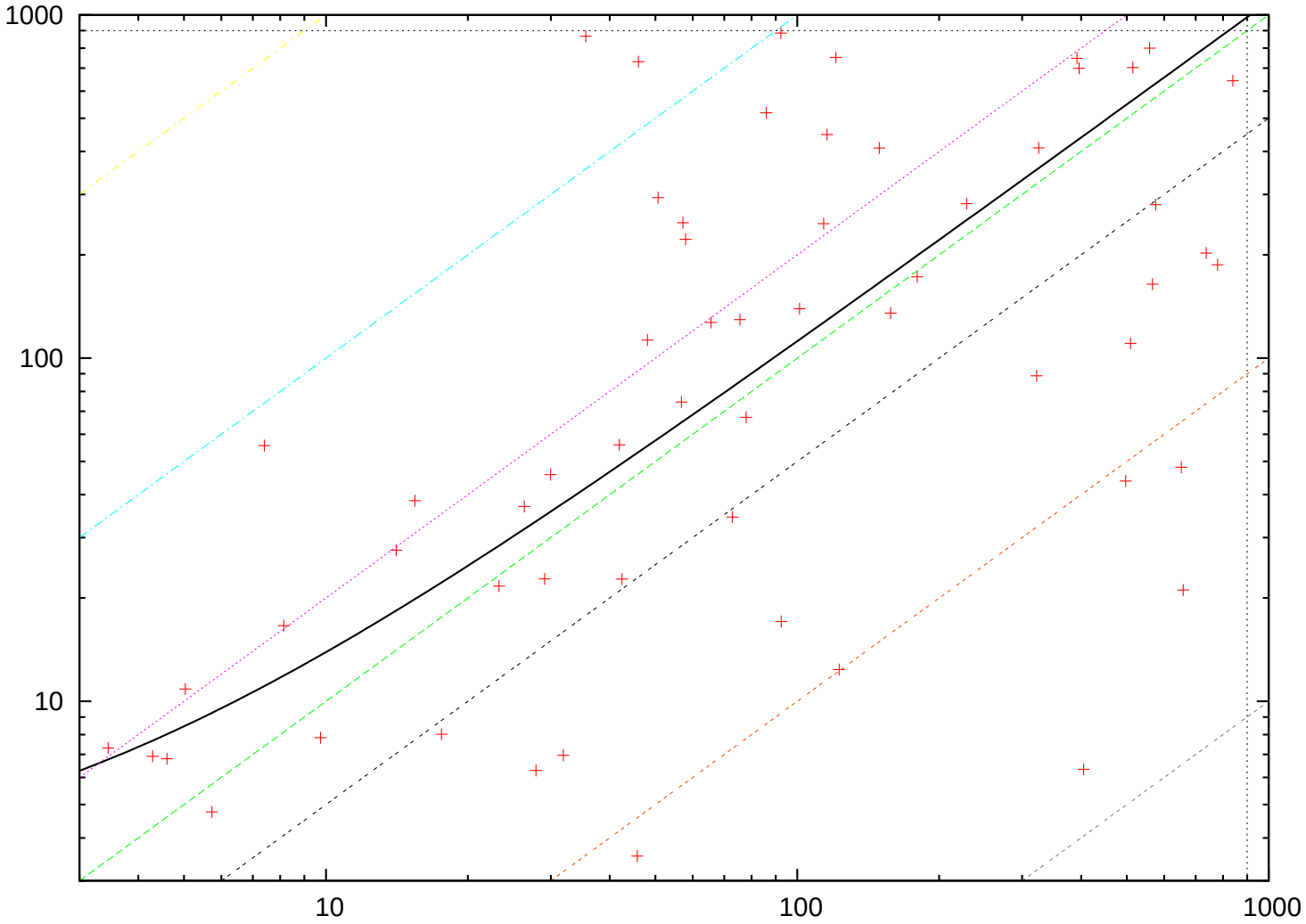


MiniSAT vs PicoSAT on Commonly Solved Instances Only

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **MiniSAT** faster

below diagonal $\Rightarrow$ **PicoSAT** faster



Decide

- VSIDS heuristics from Chaff
  - **high pass filter** on DLIS (DLIS from Grasp: max. occurrences)
  - ignores satisfied clauses ($\Rightarrow$ efficient to implement)
  - very effective (my intuition: localize search)
  - original implementation:
    - halve occurrence count every 256th conflict
    - and (at that point) sort variables with respect to this score
    - for then 256 conflicts pick first variable in this order (without sorting)
- BerkMin style heuristics empirically not as effective as MiniSAT's VSIDS

VSIDS in MiniSAT (since 2005)

A. Biere, FMV, JKU Linz

- new implementation of VSIDs in MiniSAT
  - always pick variable with largest score $\Rightarrow$ priority queue

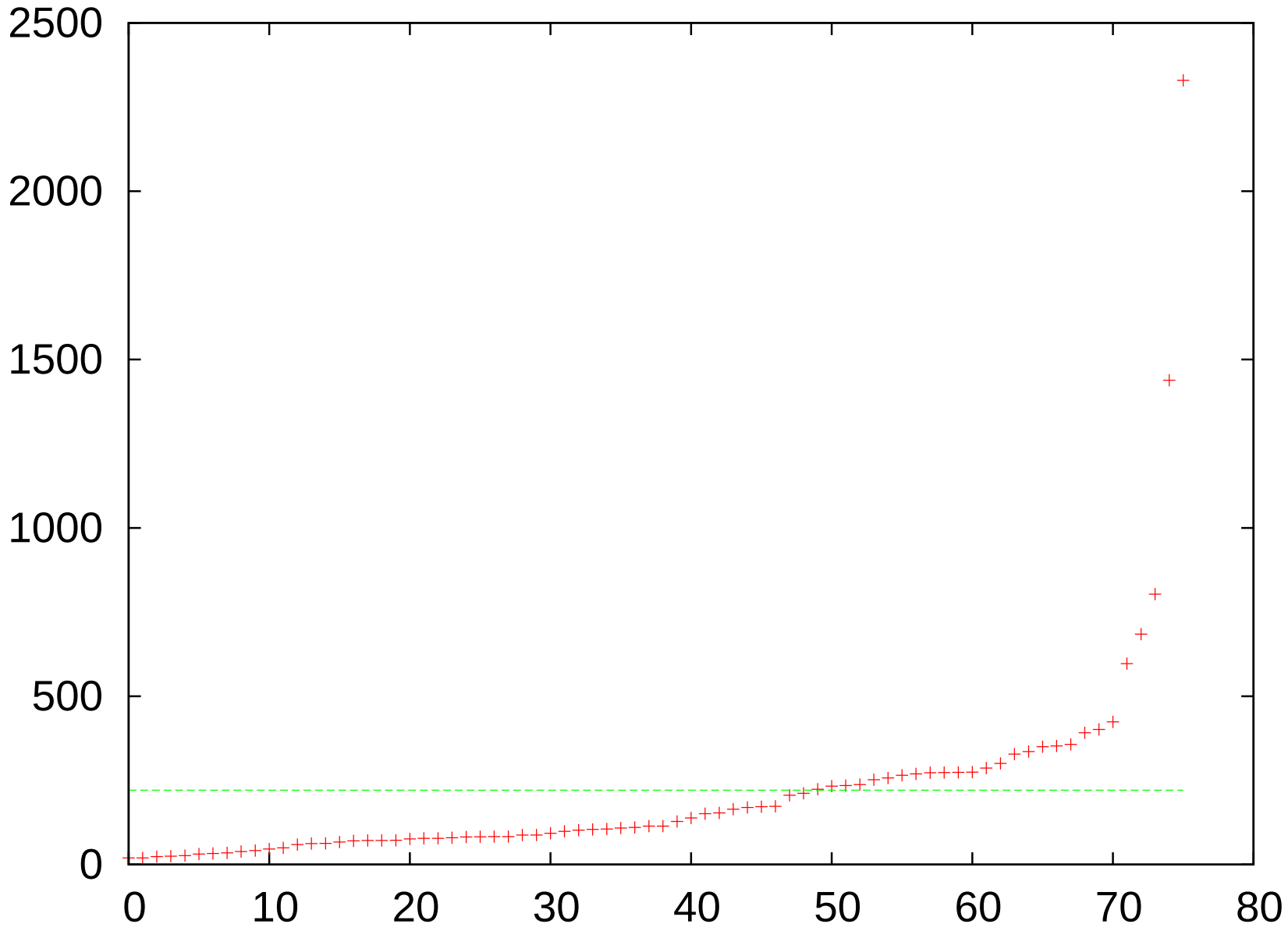
    (JeruSAT / NanoSAT also have *imprecise* but O(1) priority queue)
  - **1st key insight**: remove assigned variables lazily from priority queue

    (allows to use *precise* O(log n) priority queue)
  - **2nd key insight**: exponentially decrease **all** scores at each conflict

    (simulated by increasing score increment exponentially)
  - use **floating point numbers** for scores (long term memory)
- "non deterministic" behavior due to floating point numbers
  - BooleForce / PicoSAT uses platform independent SW floats

Average Number Assignments per Decision

A. Biere, FMV, JKU Linz



Score Initialization

A. Biere, FMV, JKU Linz

- originally in Chaff: use statically computed LIS (max. occurrence)
  - easy to implement:

    increase score for original and learned clauses in the same way
- empirically worse than simple max. variable index order
  - scrambled instances harder to solve than unscrambled in competition
- MiniSAT uses static order (implicitly) for initialization
  - variables are pushed on to the priority queue as they occur
  - more like a DFS static order (similar to variable index order)
- PicoSAT explicilty orders variables by their index initially

Phase Assignment

A. Biere, FMV, JKU Linz

- for satisfiable instances the only thing you need

  [courtesy H. van Maaren]

- originally in Chaff: count occurrences of literals not variables

- MiniSAT simply always assigns to FALSE

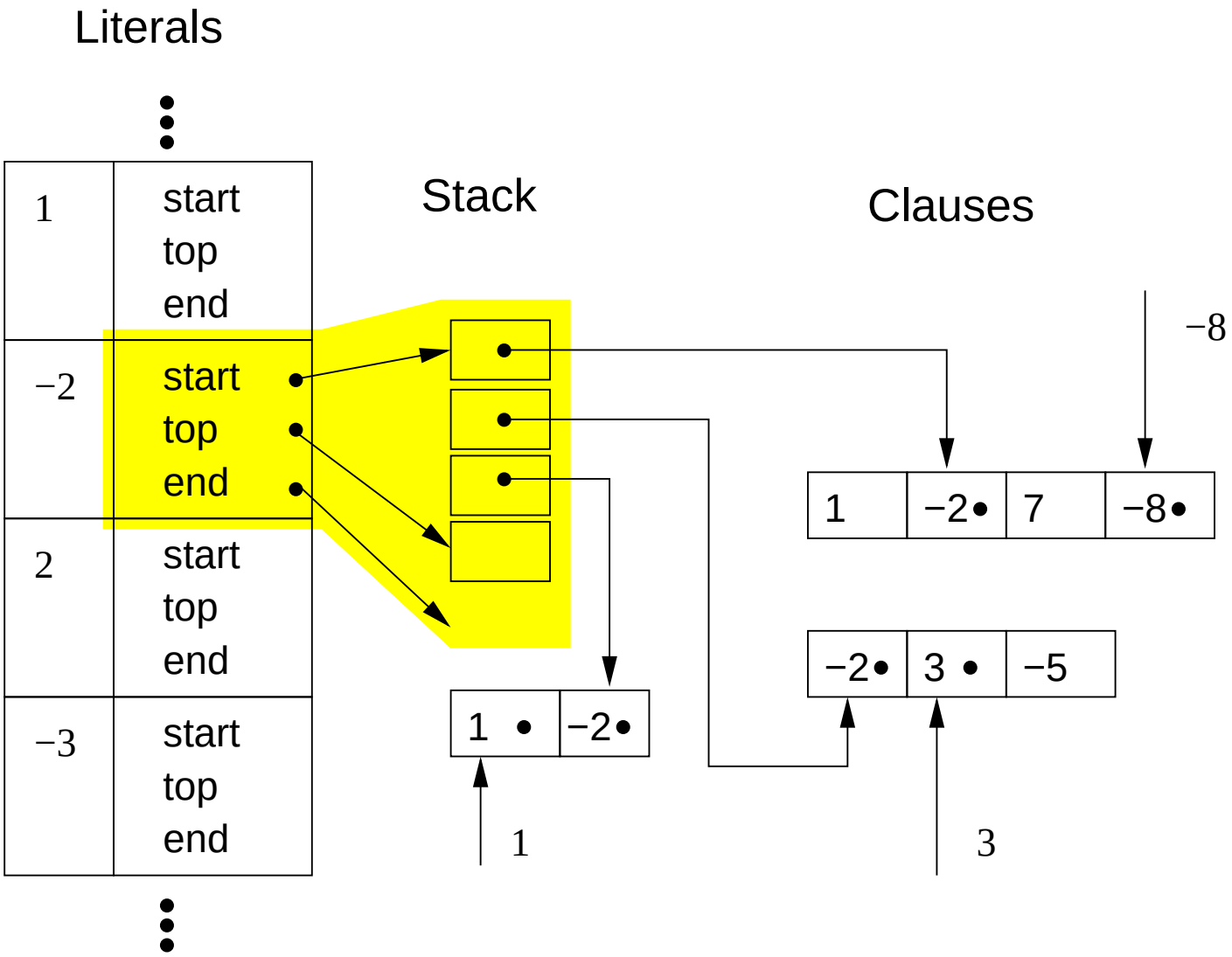
- initially: LIS for RSat, PicoSAT Jeroslow-Wang

- dynamically: PicoSAT and RSat use last phase

  - no problem switching different disconnected components
  - supports rapid restarts ("other watched" often true)

ZChaff Occurrence Stacks

A. Biere, FMV, JKU Linz



Average Number Clauses Visited Per Propagation

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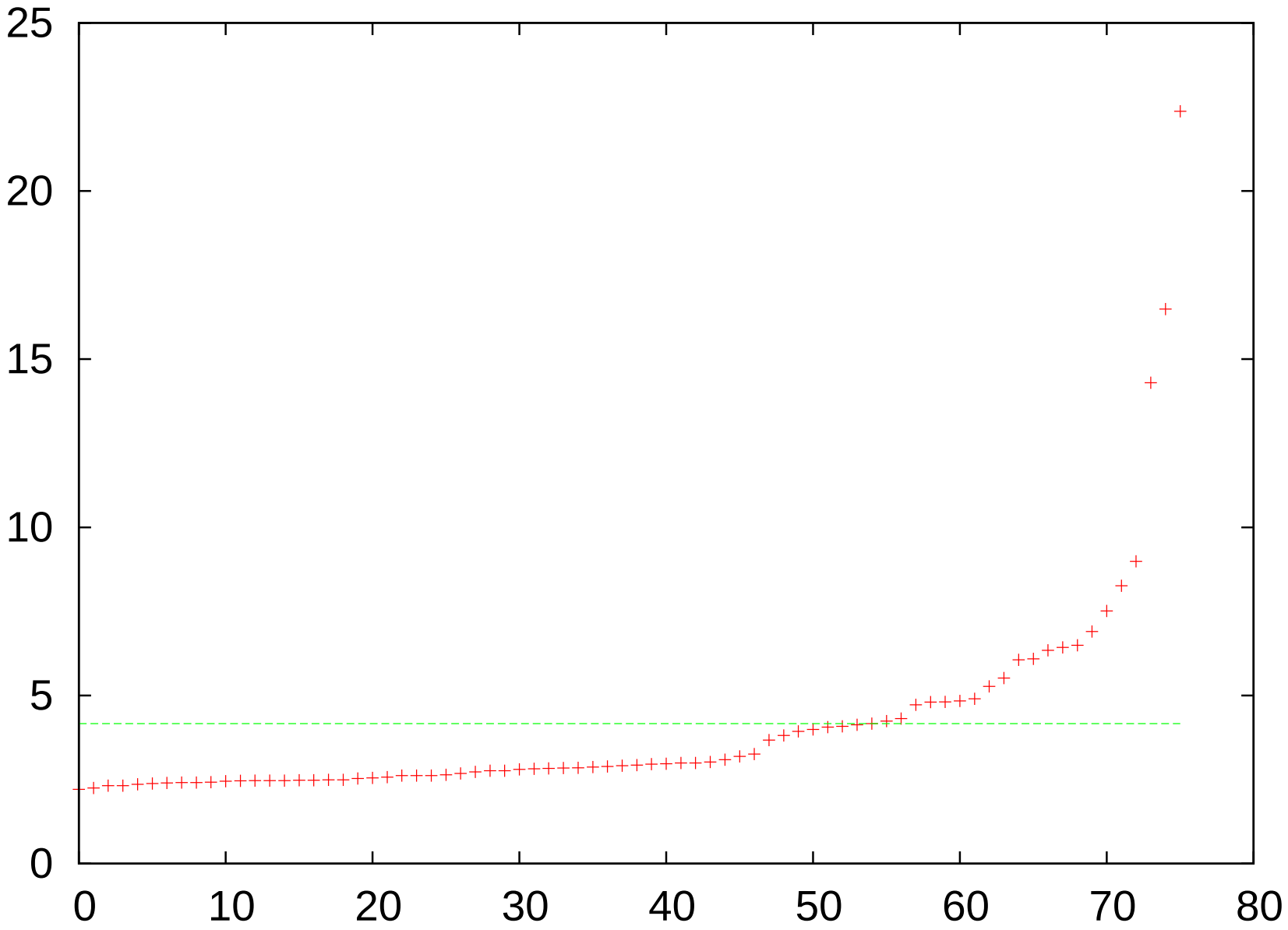

Average Learned Clause Length

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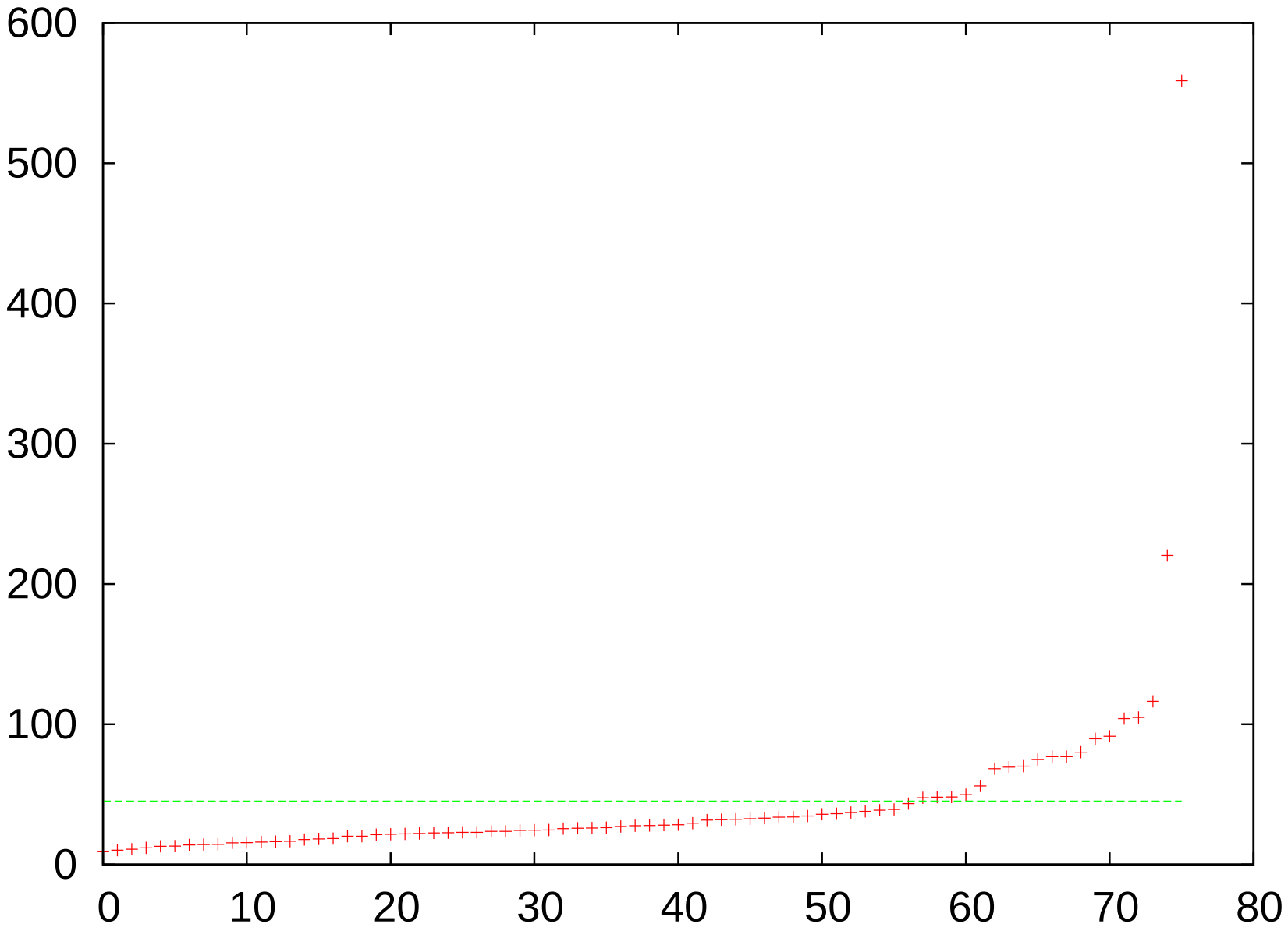

Percentage Visited Clauses With Other Watched Literal True

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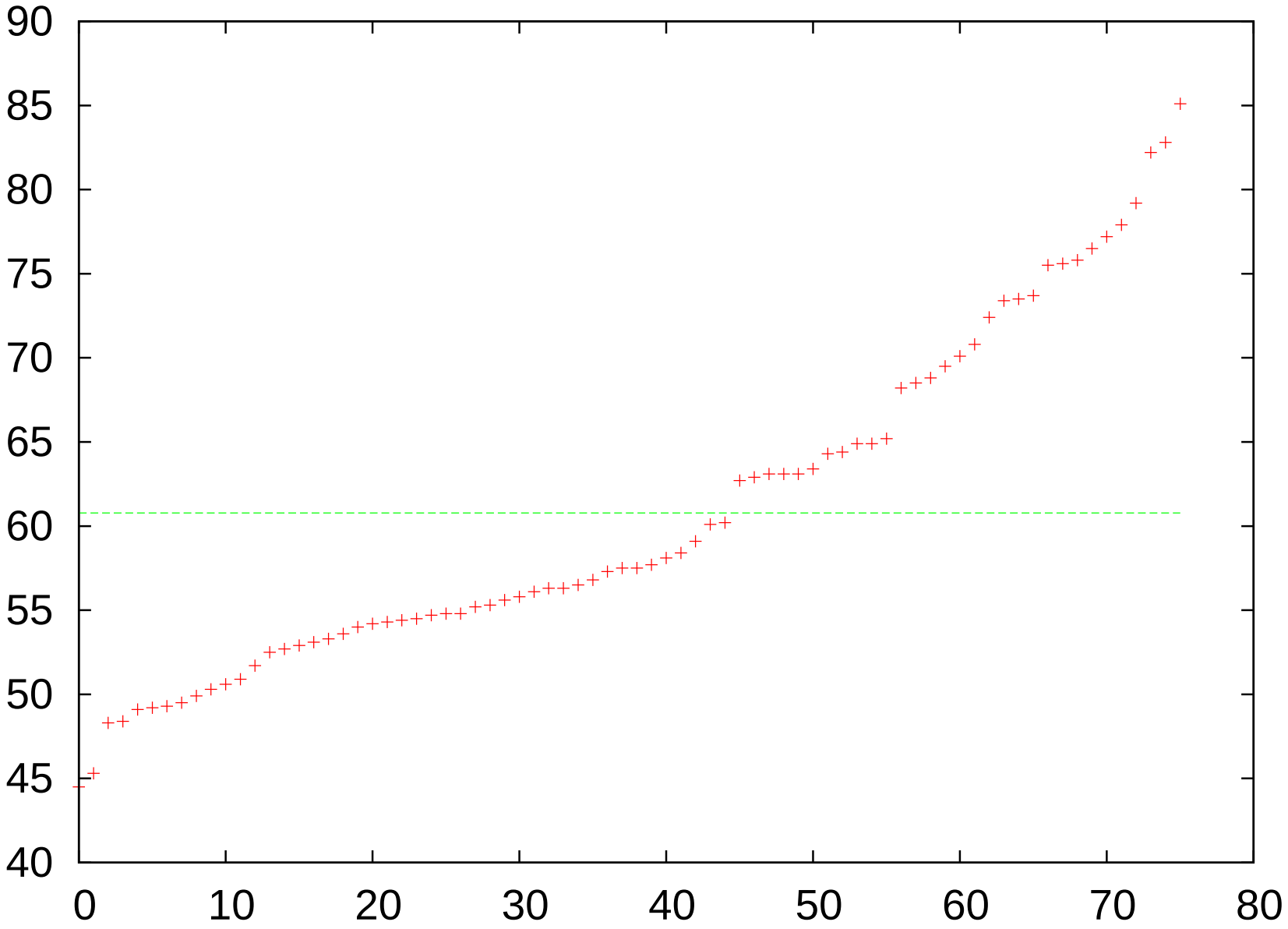
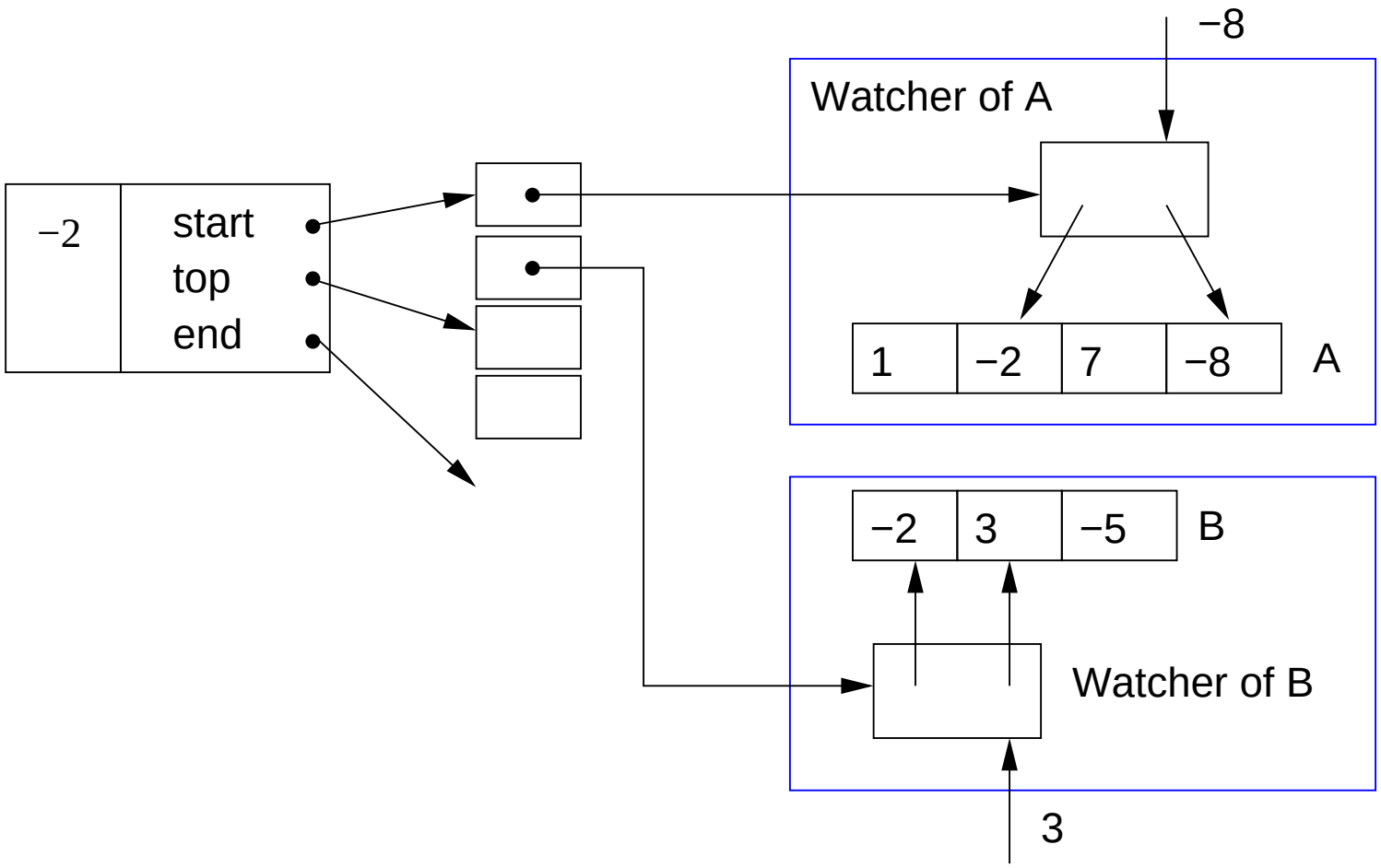
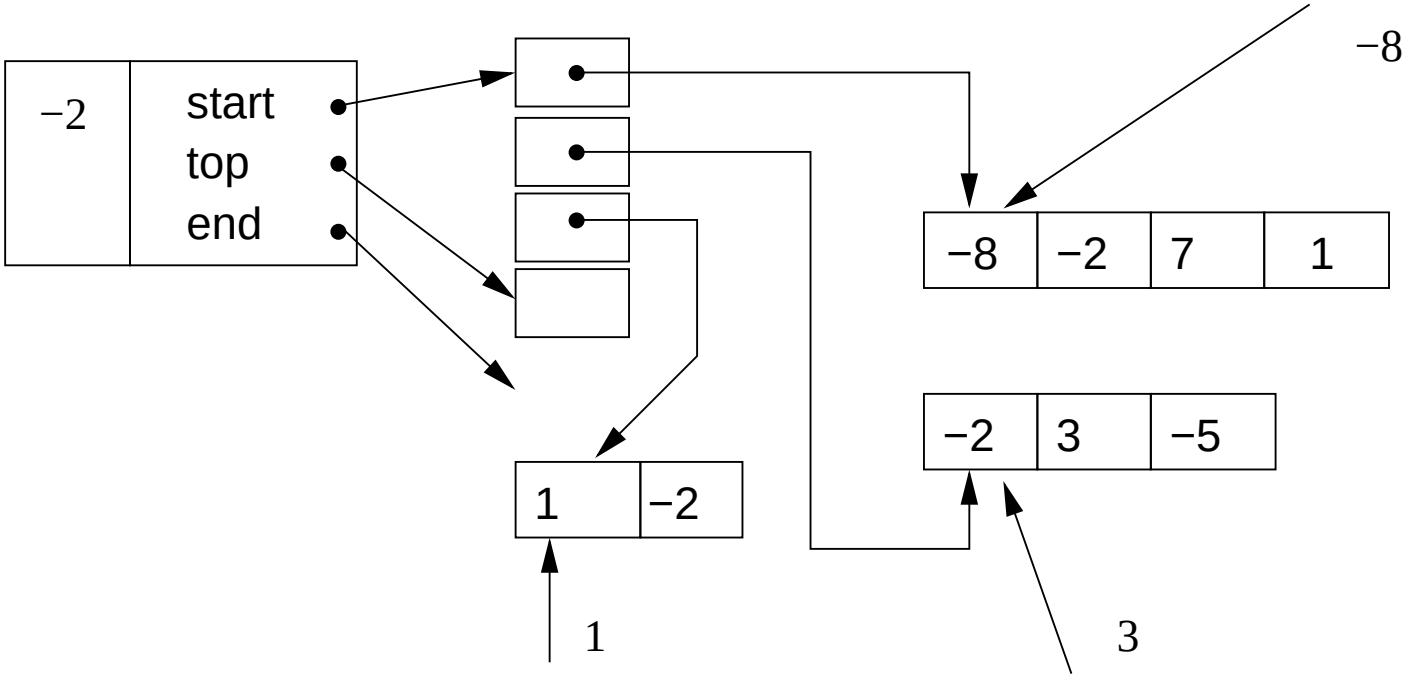


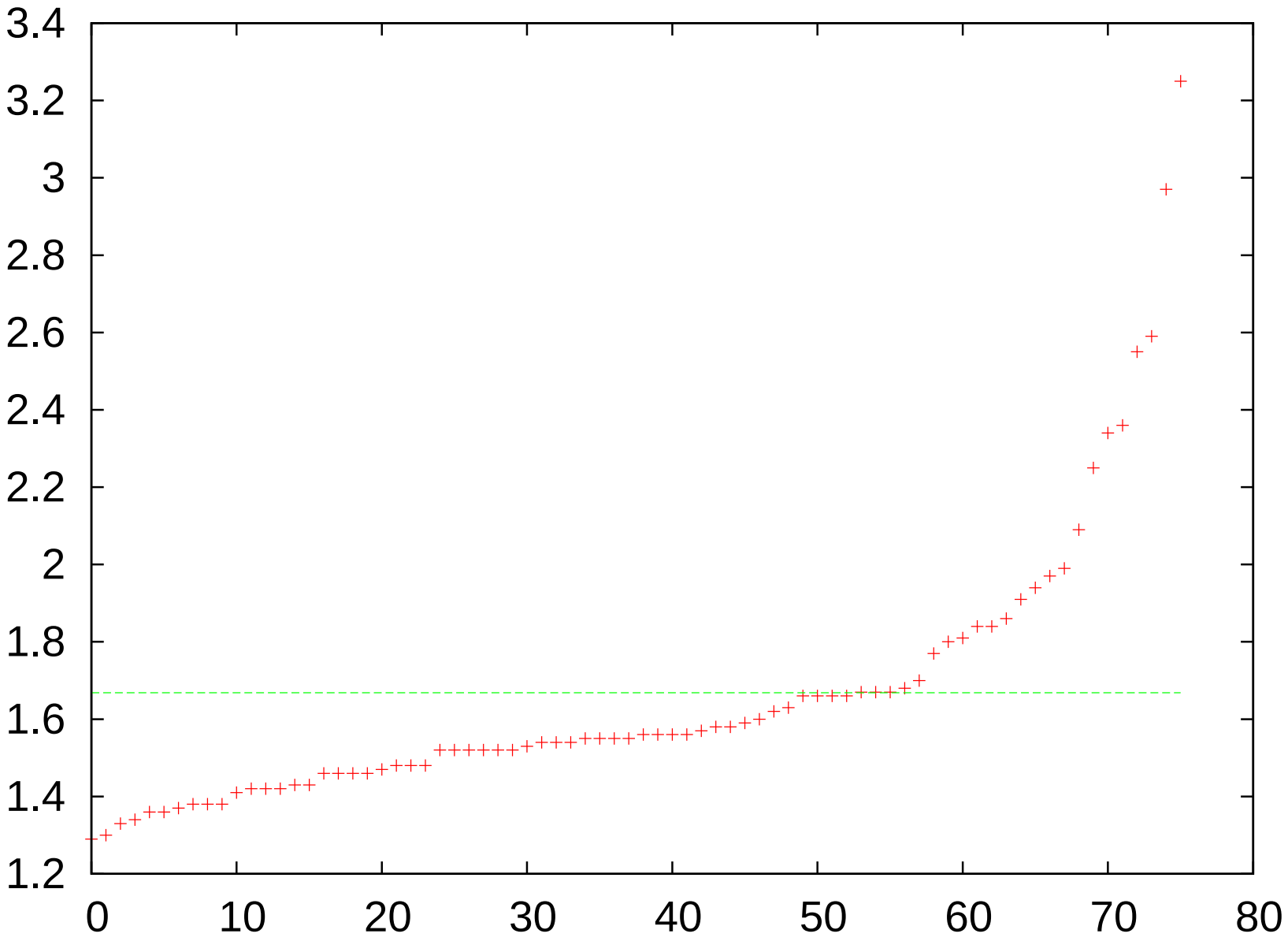

−8
Watcher of A
−2
start
top
end
1
−2
7
−8
A
−2
3
−5
B
Watcher of B
3

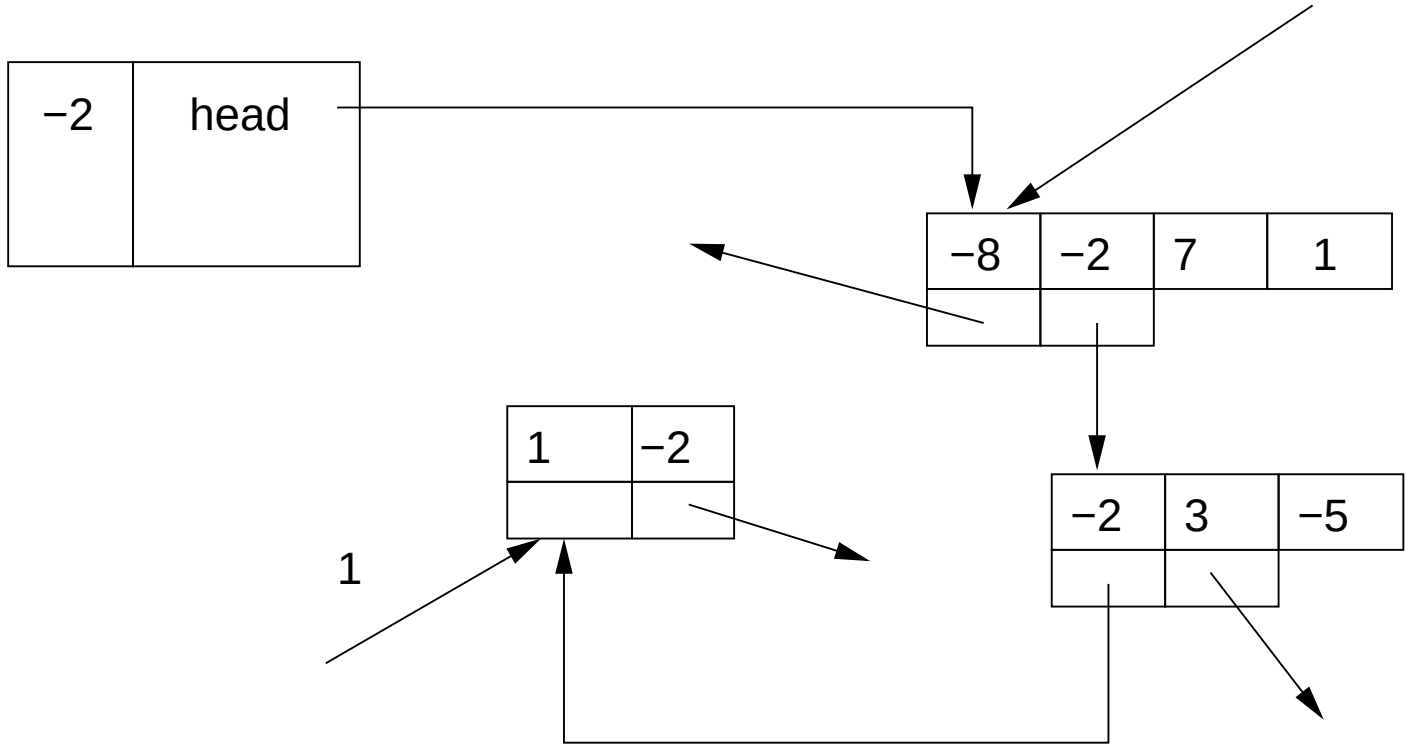


invariant: first two literals are watched

Average Number Literals Traversed Per Visited Clause

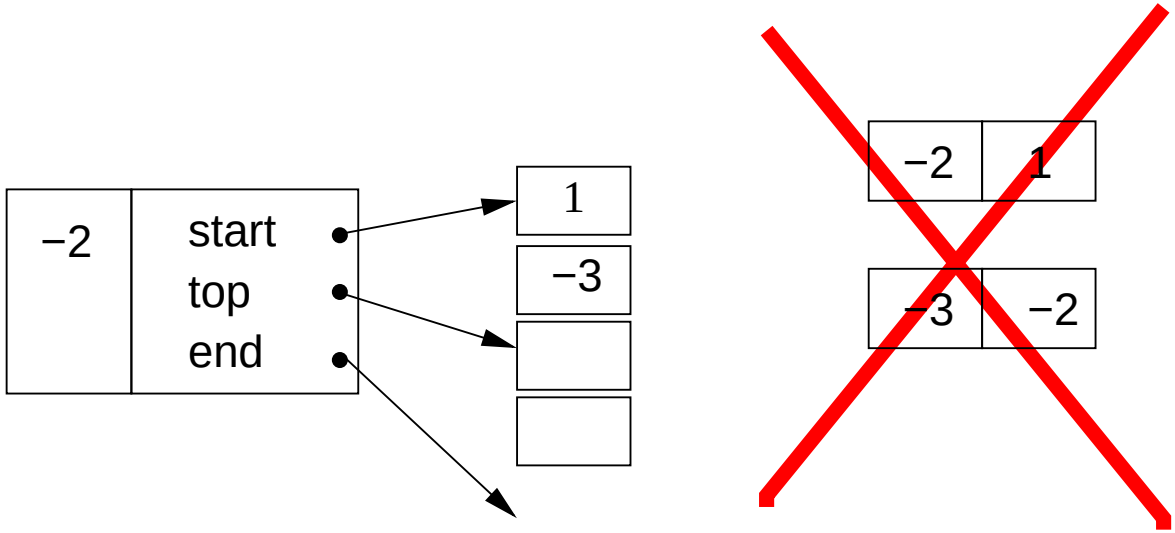
A. Biere, FMV, JKU Linz





invariant: first two literals are watched

Additional Binary Clause Watcher Stack



List vs Stack based Occurrence Lists

A. Biere, FMV, JKU Linz

solver	count	solved	unsolved	time	mb	memout
list2	100	78	22	38240	5793	0
stack2	100	76	24	40334	6768	0
list	100	72	28	41345	6917	0
stack	100	67	33	43510	8677	0

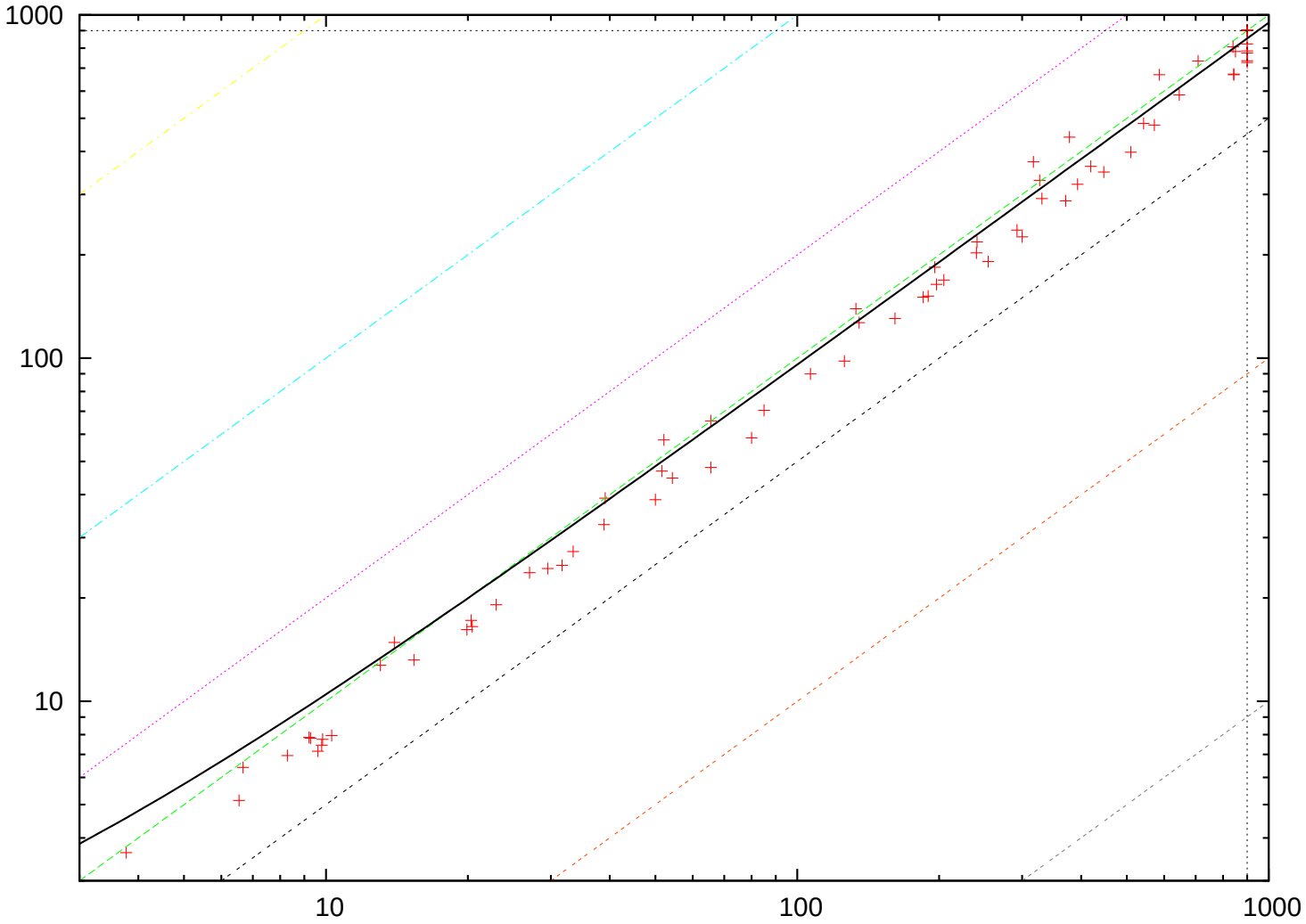
	stack	stack2	list	list2
ibm-2002-05r-k90	38.93	30.82	32.74	**27.54**
ibm-2002-07r-k100	9.79	8.56	7.45	**7.31**
ibm-2002-11r1-k45	185.10	150.40	150.55	**129.40**
ibm-2002-19r-k100	572.24	468.00	477.96	**410.01**
ibm-2002-21r-k95	393.35	325.04	321.27	**281.74**
ibm-2002-26r-k45	6.67	6.66	6.42	**6.34**
ibm-2002-27r-k95	29.54	24.75	24.36	**21.66**
ibm-2004-03-k70	54.32	45.18	44.74	**38.43**
ibm-2004-04-k100	239.96	195.40	202.50	**172.50**
ibm-2004-06-k90	106.61	87.36	89.89	**74.48**
ibm-2004-19-k90	419.27	335.11	362.31	**293.49**
ibm-2004-1_11-k25	15.37	12.47	13.20	**10.86**
ibm-2004-1_31_2-k25	197.39	158.66	164.07	**139.24**
ibm-2004-26-k25	3.77	3.72	3.62	**3.54**
ibm-2004-2_02_1-k100	22.98	19.09	19.12	**16.62**
ibm-2004-2_14-k45	33.46	26.84	27.31	**22.73**
ibm-2004-3_02_1-k95	2.79	2.43	2.42	**2.19**
ibm-2004-3_02_3-k95	9.21	7.86	7.85	**6.91**
ibm-2004-3_11-k60	---	887.29	---	**794.18**
ibm-2004-6_02_3-k100	9.28	7.86	7.81	**6.80**
manol-pipe-c10id_s	8.28	7.20	6.95	**6.29**
manol-pipe-c10nidw_s	292.62	236.14	236.05	**202.31**
manol-pipe-c6nidw_i	---	897.06	822.80	**752.67**
manol-pipe-c7b	65.58	56.86	47.99	**45.79**
manol-pipe-c7b_i	80.01	69.89	58.57	**55.91**
manol-pipe-c7bidw_i	---	---	---	---
manol-pipe-c7nidw	---	---	---	---
manol-pipe-c9	9.62	8.70	7.15	**6.96**
manol-pipe-c9nidw_s	161.21	128.85	130.44	**110.43**
manol-pipe-f10ni	---	---	---	---
manol-pipe-f6bi	6.54	5.62	5.14	**4.76**
manol-pipe-f7idw	843.60	690.68	672.09	**586.18**
manol-pipe-f9b	---	---	---	---
manol-pipe-f9n	---	---	---	---
manol-pipe-g10b	125.93	105.64	98.02	**88.82**
manol-pipe-g10bidw	---	758.79	727.39	**642.67**
manol-pipe-g10id	189.55	156.87	151.60	**135.33**
manol-pipe-g10nid	843.51	696.59	669.31	**592.59**
manol-pipe-g6bi	2.36	2.13	1.89	**1.84**
manol-pipe-g7nidw	31.67	26.92	24.89	**22.71**
aloul-chnl11-13	---	---	---	---
een-pico-prop01-75	3.09	2.94	2.53	**2.52**
een-pico-prop05-50	49.99	44.71	38.67	**36.96**
een-tip-sat-nusmv-t5.B	19.92	17.22	16.18	**14.96**
een-tip-sat-nusmv-tt5.B	20.44	17.66	16.51	**15.40**
een-tip-uns-nusmv-t5.B	9.84	8.44	7.75	**7.18**
goldb-heqc-alu4mul	840.46	**795.29**	807.84	800.56
goldb-heqc-dalumul	---	---	---	---
goldb-heqc-desmul	85.04	77.55	70.44	**67.27**
goldb-heqc-frg2mul	204.57	188.78	168.86	**164.30**
goldb-heqc-i10mul	850.51	784.76	781.94	**753.49**
goldb-heqc-i8mul	---	---	---	---
goldb-heqc-term1mul	240.57	226.77	218.11	**213.41**
grieu-vmpc-s05-25	13.97	**12.25**	14.85	12.38
grieu-vmpc-s05-27	52.10	**46.26**	57.79	48.10
grieu-vmpc-s05-28	316.88	**288.98**	373.18	329.56
grieu-vmpc-s05-34	---	---	---	---
hoons-vbmc-lucky7	10.28	9.48	**7.95**	8.02
maris-s03-gripper11	51.61	47.26	46.89	**43.85**
narain-vpn-clauses-6	---	854.12	---	**753.68**
schup-l2s-guid-1-k56	---	814.37	774.41	**699.22**
schup-l2s-motst-2-k315	---	---	---	**885.23**
simon-s02-w08-18	646.22	496.08	584.89	**448.21**
simon-s02b-dp11u10	---	---	---	---
simon-s02b-k2f-gr-rcs-w8	---	---	---	---
simon-s02b-r4b1k1.1	27.03	23.17	23.71	**21.11**
simon-s03-fifo8-300	330.42	271.20	291.54	**247.99**
simon-s03-fifo8-400	543.01	446.35	483.26	**409.51**
vange-col-abb313GPIA-9-c	---	---	---	---
vange-col-inithx.i.1-cn-54	20.32	20.01	17.22	**17.08**
mizh-md5-47-3	---	---	---	---
mizh-md5-47-4	---	849.87	734.97	**703.03**
mizh-md5-47-5	---	---	785.55	**747.32**
mizh-md5-48-2	---	---	---	---
mizh-md5-48-5	---	---	---	---
mizh-sha0-35-2	299.80	272.94	225.70	**221.90**
mizh-sha0-35-3	447.09	406.48	348.67	**339.62**
mizh-sha0-35-4	253.97	230.44	191.24	**187.10**
mizh-sha0-35-5	371.02	339.75	287.28	**280.16**
mizh-sha0-36-2	509.72	463.50	398.25	**388.62**
velev-engi-uns-1.0-4nd	195.81	143.33	183.93	**127.01**
velev-engi-uns-1.0-5c1	13.04	9.04	12.74	**7.84**
velev-fvp-sat-3.0-b18	135.24	112.67	126.94	**102.62**
velev-live-uns-2.0-ebuf	708.71	539.14	734.76	**518.45**
velev-npe-1.0-9dlx-b71	---	526.42	---	**510.05**
velev-pipe-o-uns-1.0-7	---	---	---	---
velev-pipe-o-uns-1.1-6	---	---	---	---
velev-pipe-sat-1.0-b10	585.93	337.18	669.79	**319.61**
velev-pipe-sat-1.0-b7	378.05	230.08	440.44	**218.38**
velev-pipe-sat-1.0-b9	65.55	56.62	65.67	**55.59**
velev-pipe-sat-1.1-b7	39.13	35.81	39.05	**34.41**
velev-pipe-uns-1.0-8	---	---	---	---
velev-pipe-uns-1.0-9	---	---	---	---
velev-pipe-uns-1.1-7	---	---	---	---
velev-vliw-sat-2.0-b6	326.62	260.00	329.90	**246.47**
velev-vliw-sat-4.0-b1	---	764.64	---	**730.80**
velev-vliw-sat-4.0-b3	133.14	117.92	139.36	**112.91**
velev-vliw-sat-4.0-b4	---	893.40	---	**867.02**
velev-vliw-uns-2.0-iq4	---	---	---	---
velev-vliw-uns-4.0-9C1	---	---	---	---

Stacks vs Lists

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **stack** faster

below diagonal $\Rightarrow$ **list** faster

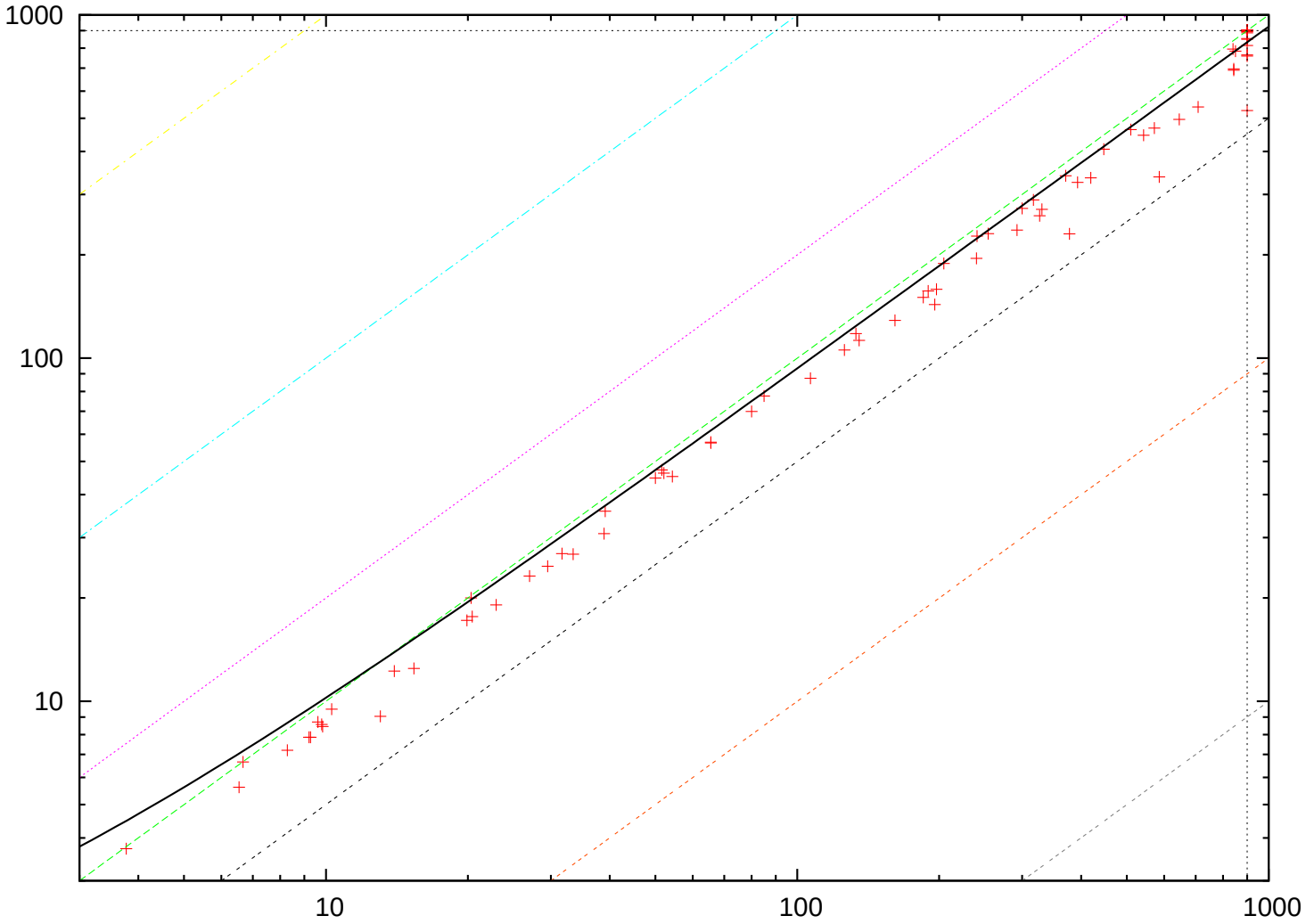


Stacks vs Stacks2

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **stack** faster

below diagonal $\Rightarrow$ **stack2** faster

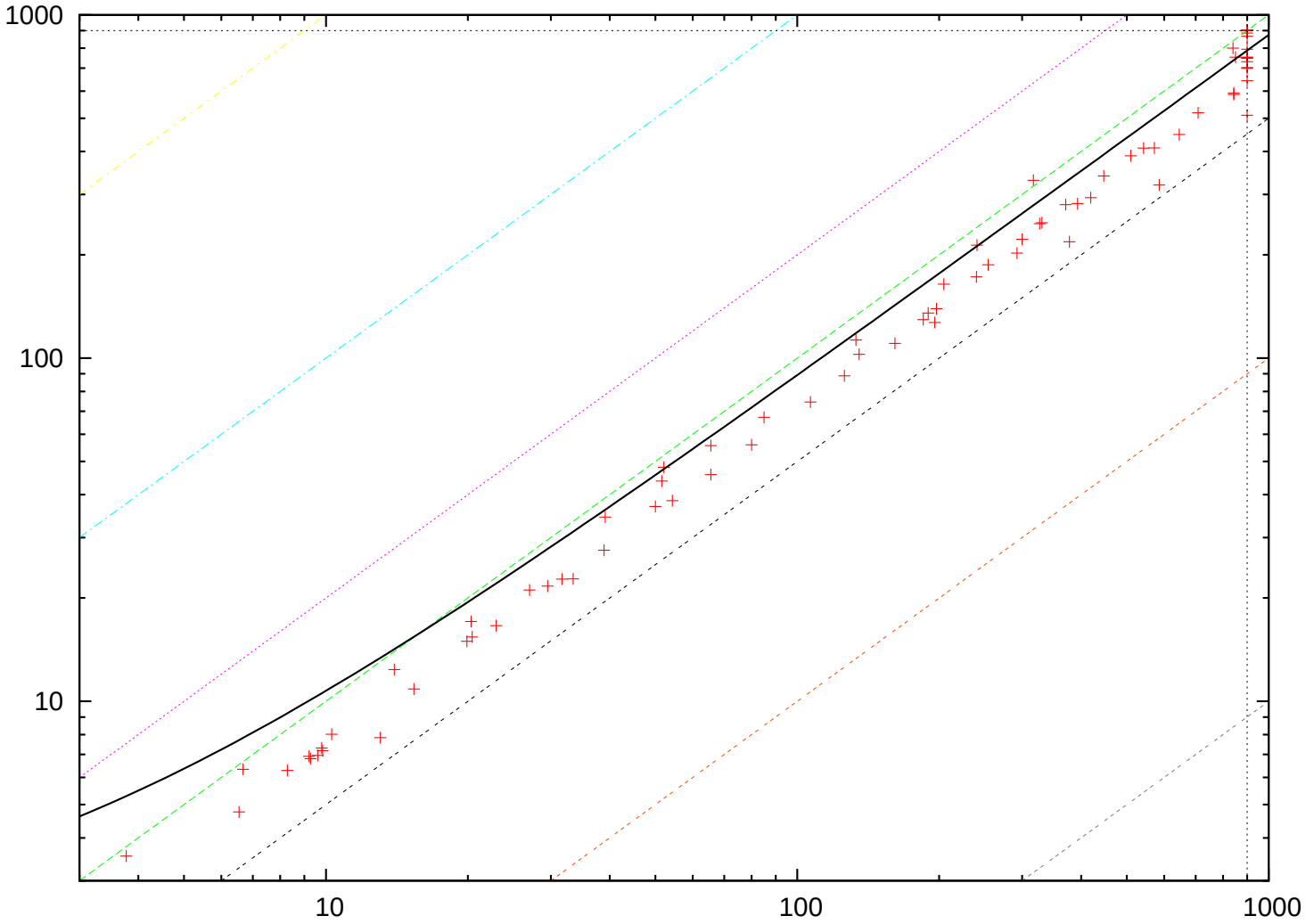


Stacks vs Lists2

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **stack** faster

below diagonal $\Rightarrow$ **list2** faster



Restart

- *really important* (more than I thought)
  - combine **rapid restarts** with **saving phases** (TinySAT + RSat)
- originally in ZChaff every 10000 conflicts (increased by 50%)
- MiniSAT every 100 conflicts (increased by 50%)
- PicoSAT also roughly every 100 conflicts:
  - outer interval increased by 10%, if reached resets inner interval to 100
  - inner interval starts at 100, increased by 10% until outer is reached
  - restart triggered at end of inner interval

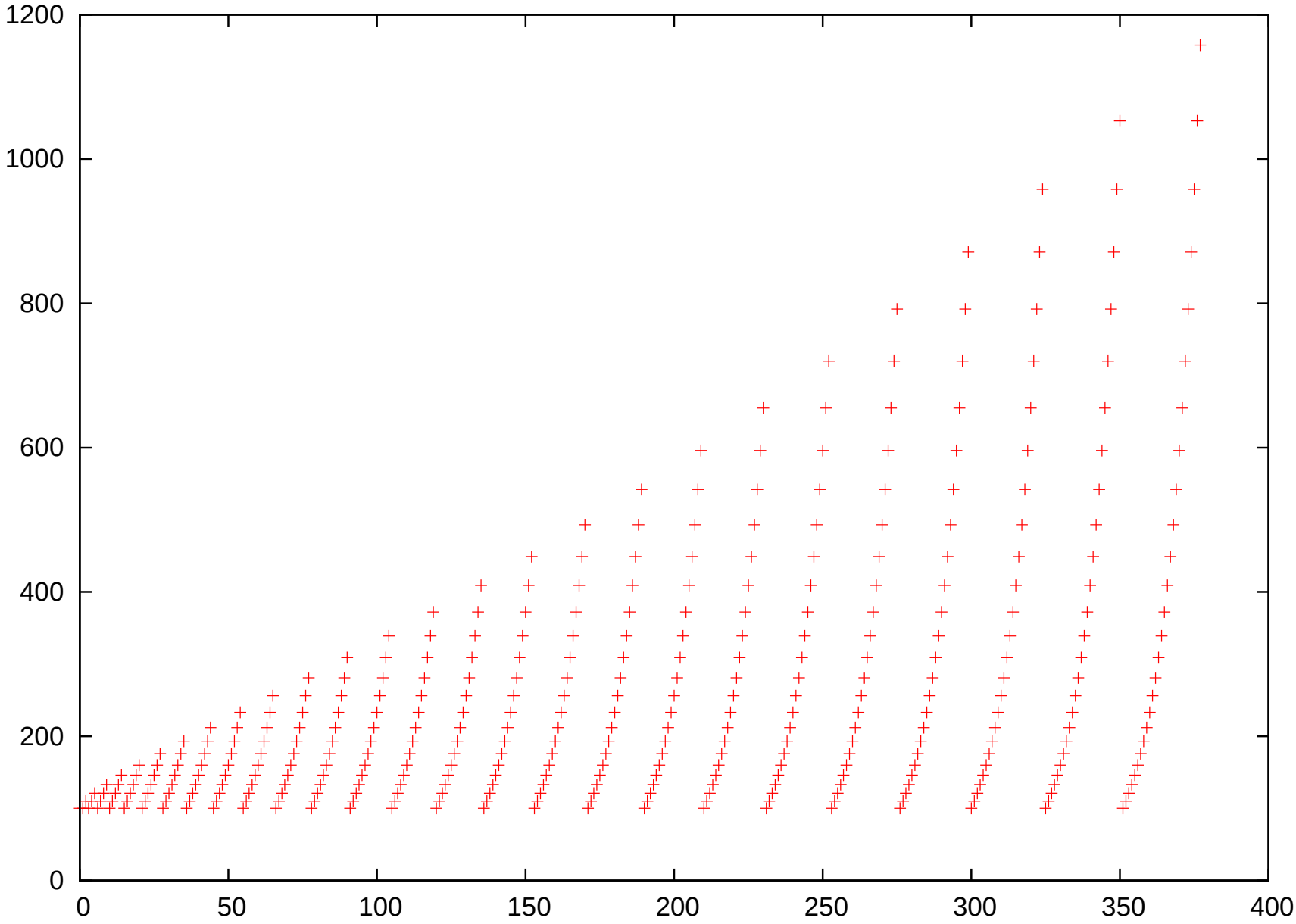
Restart Policy / Schedule in PicoSAT

A. Biere, FMV, JKU Linz

```
int inner = 100, outer = 100;
int restarts = 0, conflicts = 0;

for (;;)
  {
    ... // run SAT core loop for 'inner' conflicts

    restarts++;
    conflicts += inner;

    if (inner >= outer)
      {
        outer *= 1.1;
        inner = 100;
      }
    else
      inner *= 1.1;
  }
```

Restarts Intervals

A. Biere, FMV, JKU Linz



solver	count	solved	unsolved	time	mb	memout
base	100	78	22	38240	5793	0
seed	100	73	27	42931	6273	0
norandom	100	73	27	40717	6036	0
norestart	100	49	51	56250	7012	0

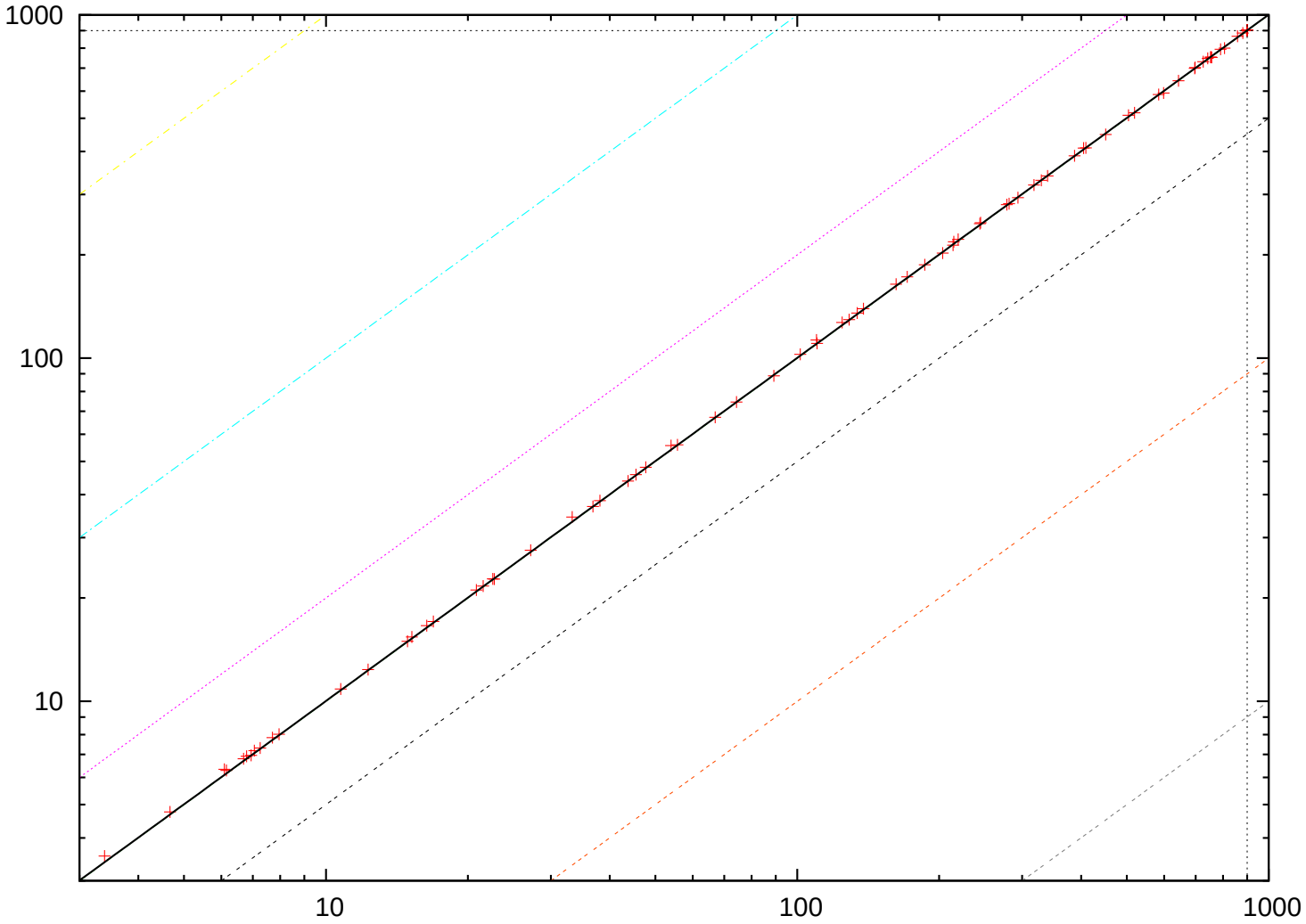
	base	seed	norandom	norestart					
ibm-2002-05r-k90	27.54	27.59	22.84	**18.49**	goldb-heqc-i10mul	753.49	**663.64**	789.31	---
ibm-2002-07r-k100	7.31	**6.68**	7.48	---	goldb-heqc-i8mul	---	---	---	---
ibm-2002-11r1-k45	129.40	**96.63**	104.76	273.50	goldb-heqc-term1mul	213.41	**136.73**	428.72	311.29
ibm-2002-19r-k100	410.01	532.76	626.19	**306.16**	grieu-vmpc-s05-25	12.38	135.86	**1.81**	121.49
ibm-2002-21r-k95	281.74	512.23	459.57	**145.10**	grieu-vmpc-s05-27	48.10	174.25	184.25	**1.52**
ibm-2002-26r-k45	6.34	**6.00**	6.11	6.23	grieu-vmpc-s05-28	**329.56**	744.25	---	521.70
ibm-2002-27r-k95	21.66	24.43	14.71	**10.60**	grieu-vmpc-s05-34	---	---	---	---
ibm-2004-03-k70	38.43	43.80	**24.19**	44.99	hoons-vbmc-lucky7	8.02	**6.47**	7.40	21.73
ibm-2004-04-k100	**172.50**	256.18	288.87	591.18	maris-s03-gripper11	43.85	37.83	**31.39**	---
ibm-2004-06-k90	74.48	53.62	31.27	**23.86**	narain-vpn-clauses-6	753.68	**385.94**	457.96	---
ibm-2004-19-k90	293.49	**97.64**	369.22	127.28	schup-l2s-guid-1-k56	**699.22**	772.26	749.08	---
ibm-2004-1_11-k25	10.86	7.39	7.70	**7.33**	schup-l2s-motst-2-k315	885.23	**721.62**	871.97	804.53
ibm-2004-1_31_2-k25	**139.24**	158.98	172.37	---	simon-s02-w08-18	448.21	498.61	**377.50**	636.65
ibm-2004-26-k25	3.54	3.37	**3.34**	3.52	simon-s02b-dp11u10	---	---	**572.63**	---
ibm-2004-2_02_1-k100	16.62	17.17	**13.22**	15.75	simon-s02b-k2f-gr-rcs-w8	---	---	---	---
ibm-2004-2_14-k45	**22.73**	27.21	29.62	38.91	simon-s02b-r4b1k1.1	**21.11**	---	---	---
ibm-2004-3_02_1-k95	**2.19**	6.56	8.47	12.45	simon-s03-fifo8-300	247.99	286.09	**233.94**	805.22
ibm-2004-3_02_3-k95	6.91	7.00	8.38	**4.37**	simon-s03-fifo8-400	**409.51**	454.42	495.64	---
ibm-2004-3_11-k60	794.18	846.18	**724.47**	---	vange-col-abb313GPIA-9-c	---	---	---	---
ibm-2004-6_02_3-k100	6.80	**4.98**	9.67	5.20	vange-col-inithx.i.1-cn-54	17.08	**16.09**	26.76	676.64
manol-pipe-c10id_s	6.29	6.13	**5.76**	6.04	mizh-md5-47-3	---	**537.35**	---	---
manol-pipe-c10nidw_s	202.31	188.49	**155.20**	---	mizh-md5-47-4	703.03	867.49	**578.73**	748.90
manol-pipe-c6nidw_i	752.67	**653.43**	673.55	---	mizh-md5-47-5	**747.32**	---	---	---
manol-pipe-c7b	**45.79**	47.47	63.51	267.24	mizh-md5-48-2	---	**493.02**	---	658.26
manol-pipe-c7b_i	**55.91**	61.17	60.58	326.76	mizh-md5-48-5	---	**391.71**	812.82	393.35
manol-pipe-c7bidw_i	---	---	---	---	mizh-sha0-35-2	**221.90**	422.29	363.07	---
manol-pipe-c7nidw	---	---	---	---	mizh-sha0-35-3	339.62	679.47	**229.42**	686.43
manol-pipe-c9	6.96	**6.91**	7.96	23.83	mizh-sha0-35-4	**187.10**	379.92	524.00	---
manol-pipe-c9nidw_s	110.43	**84.64**	95.27	93.63	mizh-sha0-35-5	**280.16**	---	---	---
manol-pipe-f10ni	---	---	---	---	mizh-sha0-36-2	**388.62**	---	---	---
manol-pipe-f6bi	**4.76**	5.40	5.70	9.22					
manol-pipe-f7idw	586.18	363.25	**351.63**	---	velev-engi-uns-1.0-4nd	127.01	131.49	120.32	**40.78**
manol-pipe-f9b	---	---	---	---	velev-engi-uns-1.0-5c1	7.84	7.83	**7.75**	9.11
manol-pipe-f9n	---	---	---	---	velev-fvp-sat-3.0-b18	102.62	859.24	**70.47**	---
manol-pipe-g10b	88.82	**85.02**	104.70	---	velev-live-uns-2.0-ebuf	518.45	406.93	**204.90**	---
manol-pipe-g10bidw	**642.67**	883.92	718.07	---	velev-npe-1.0-9dlx-b71	**510.05**	---	---	---
manol-pipe-g10id	135.33	124.22	**101.71**	---	velev-pipe-o-uns-1.0-7	---	---	---	---
manol-pipe-g10nid	**592.59**	691.86	779.63	---	velev-pipe-o-uns-1.1-6	---	---	---	---
manol-pipe-g6bi	**1.84**	2.27	1.96	2.27	velev-pipe-sat-1.0-b10	319.61	117.05	**56.45**	---
manol-pipe-g7nidw	**22.71**	25.51	25.62	---	velev-pipe-sat-1.0-b7	218.38	---	**50.53**	---
					velev-pipe-sat-1.0-b9	55.59	255.46	60.51	**49.76**
aloul-chnl11-13	---	---	---	---	velev-pipe-sat-1.1-b7	**34.41**	576.36	58.01	---
een-pico-prop01-75	2.52	3.27	**2.05**	2.80	velev-pipe-uns-1.0-8	---	---	---	---
een-pico-prop05-50	**36.96**	47.81	45.97	171.62	velev-pipe-uns-1.0-9	---	---	---	---
een-tip-sat-nusmv-t5.B	14.96	**12.55**	17.79	12.95	velev-pipe-uns-1.1-7	---	---	---	---
een-tip-sat-nusmv-tt5.B	15.40	**13.32**	13.83	14.89	velev-vliw-sat-2.0-b6	246.47	**239.09**	298.95	---
een-tip-uns-nusmv-t5.B	7.18	7.56	11.28	**7.17**	velev-vliw-sat-4.0-b1	730.80	---	741.75	**520.21**
goldb-heqc-alu4mul	800.56	734.20	---	**592.21**	velev-vliw-sat-4.0-b3	112.91	207.32	125.96	**97.16**
goldb-heqc-dalumul	---	---	---	---	velev-vliw-sat-4.0-b4	867.02	---	**455.97**	---
goldb-heqc-desmul	67.27	**67.18**	72.01	80.13	velev-vliw-uns-2.0-iq4	---	---	---	---
goldb-heqc-frg2mul	**164.30**	172.45	183.24	---	velev-vliw-uns-4.0-9C1	---	---	---	---

Check vs Base (Precision of Measurement)

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **check** faster

below diagonal $\Rightarrow$ **base** faster

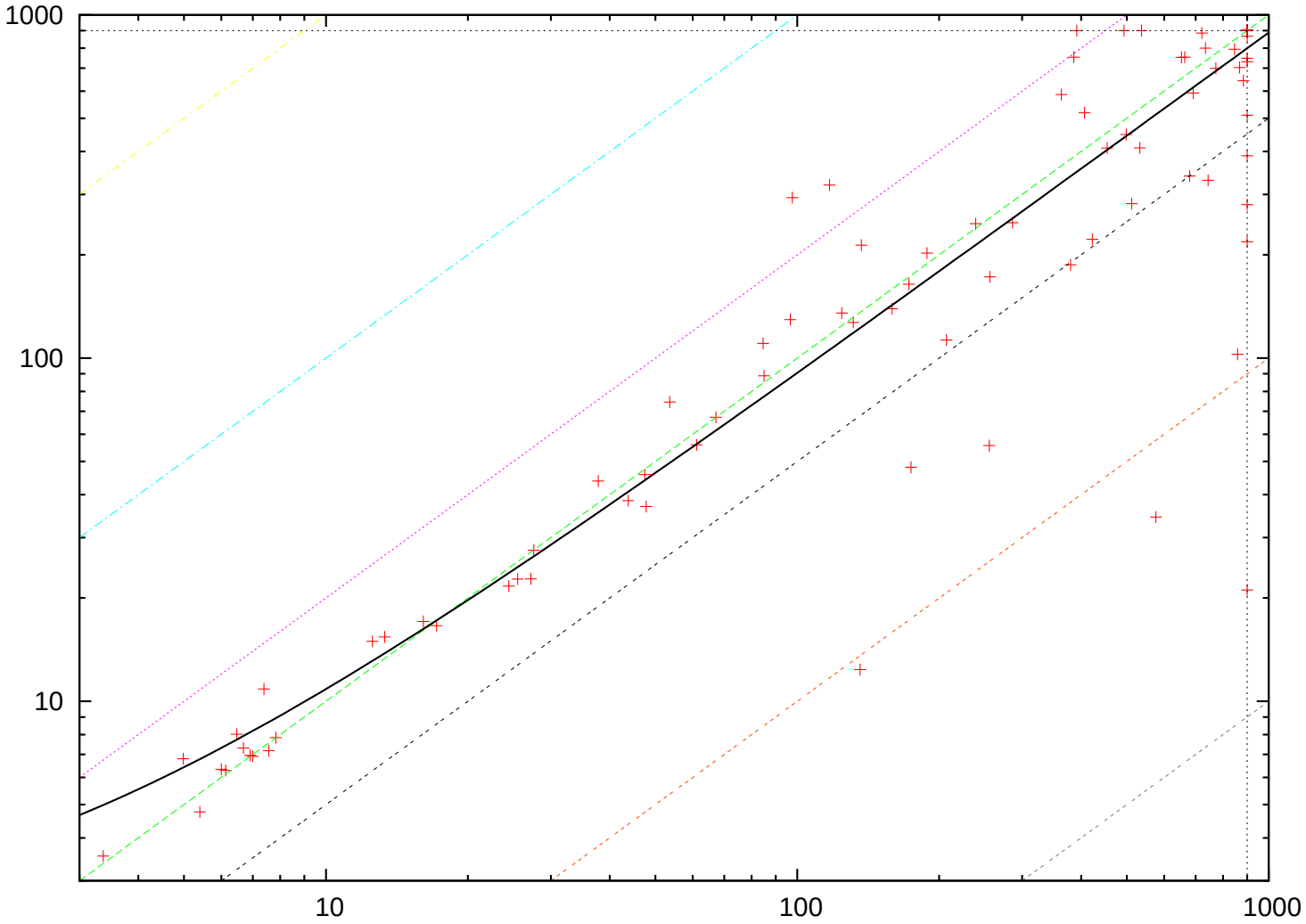


Different Seed vs Base

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **seed** faster

below diagonal $\Rightarrow$ **base** faster

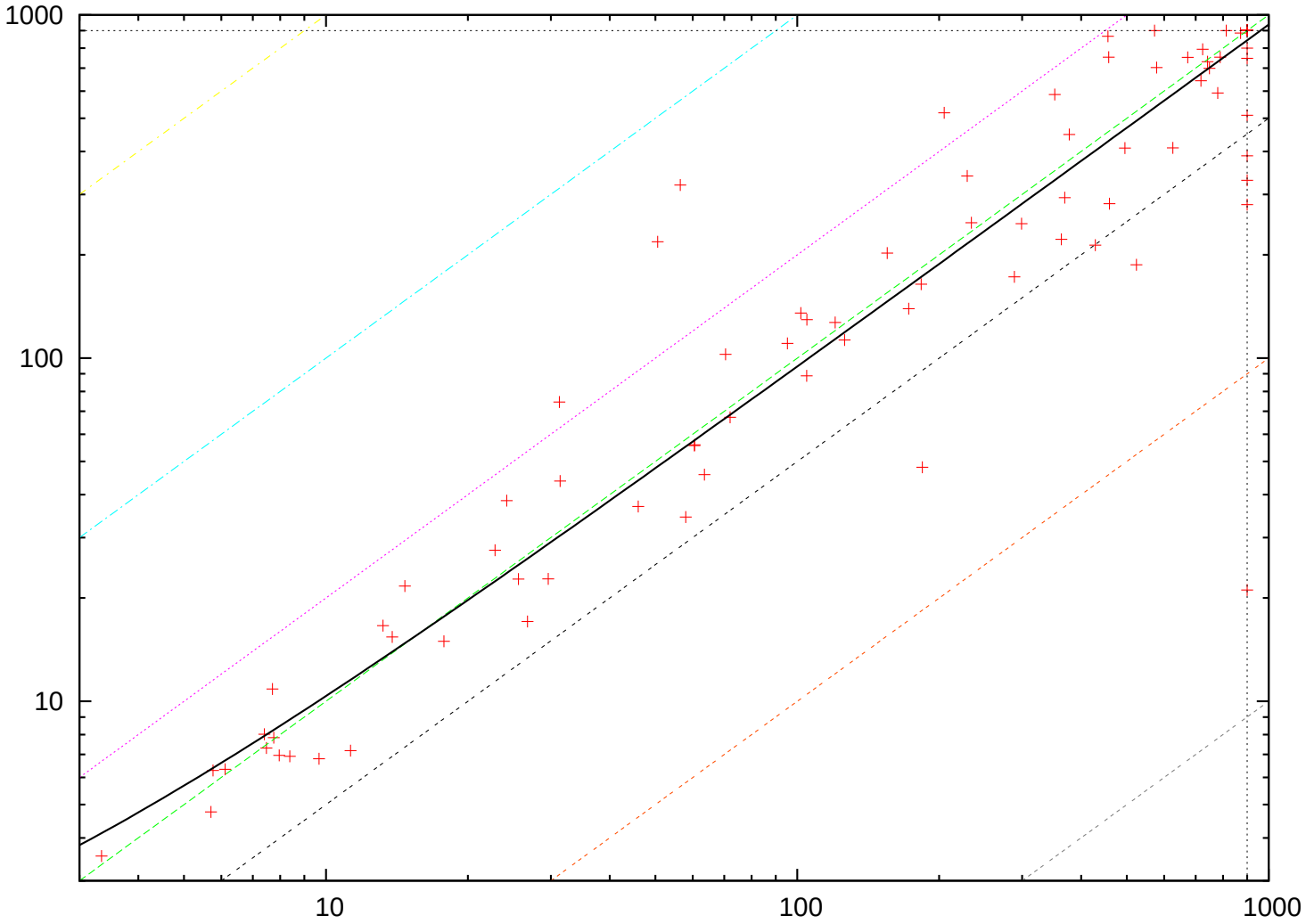


No Random Decisions vs Base

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **norandom** faster

below diagonal $\Rightarrow$ **base** faster

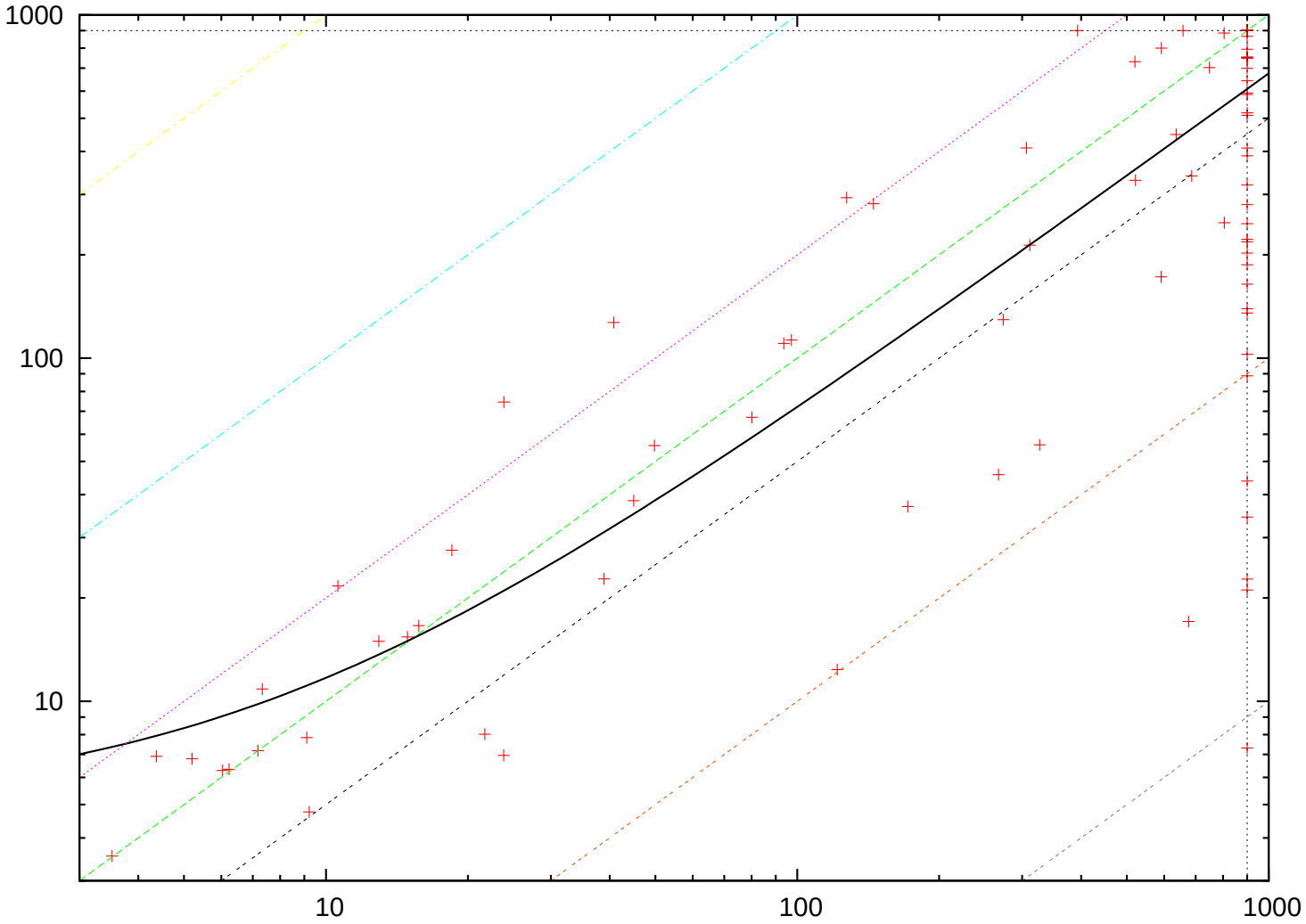


No Restarts vs Base

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **norestart** faster

below diagonal $\Rightarrow$ **base** faster

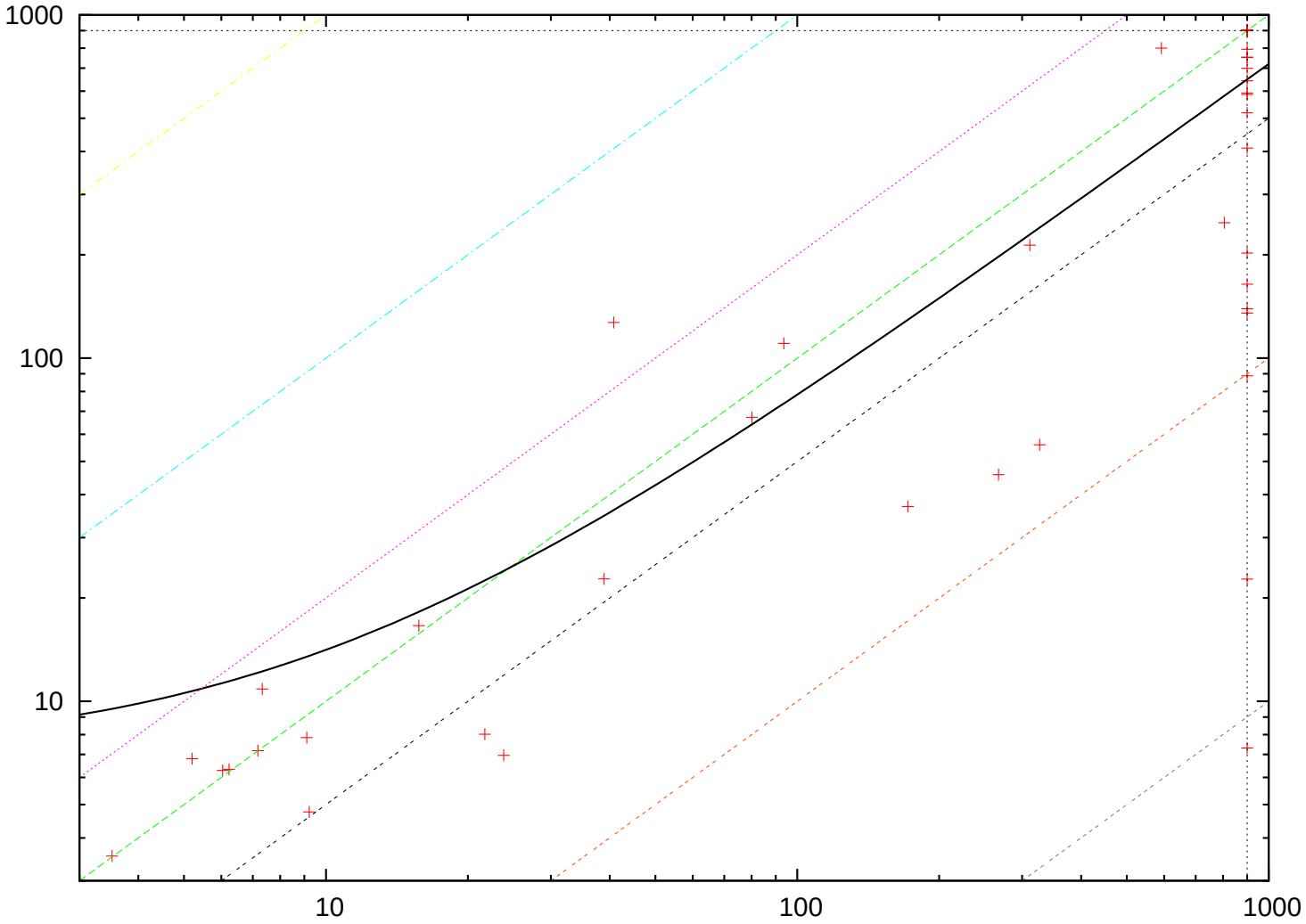


No Restarts vs Base on Satisfiable Instances

A. Biere, FMV, JKU Linz

above diagonal $\Rightarrow$ **norestart** faster

below diagonal $\Rightarrow$ **base** faster

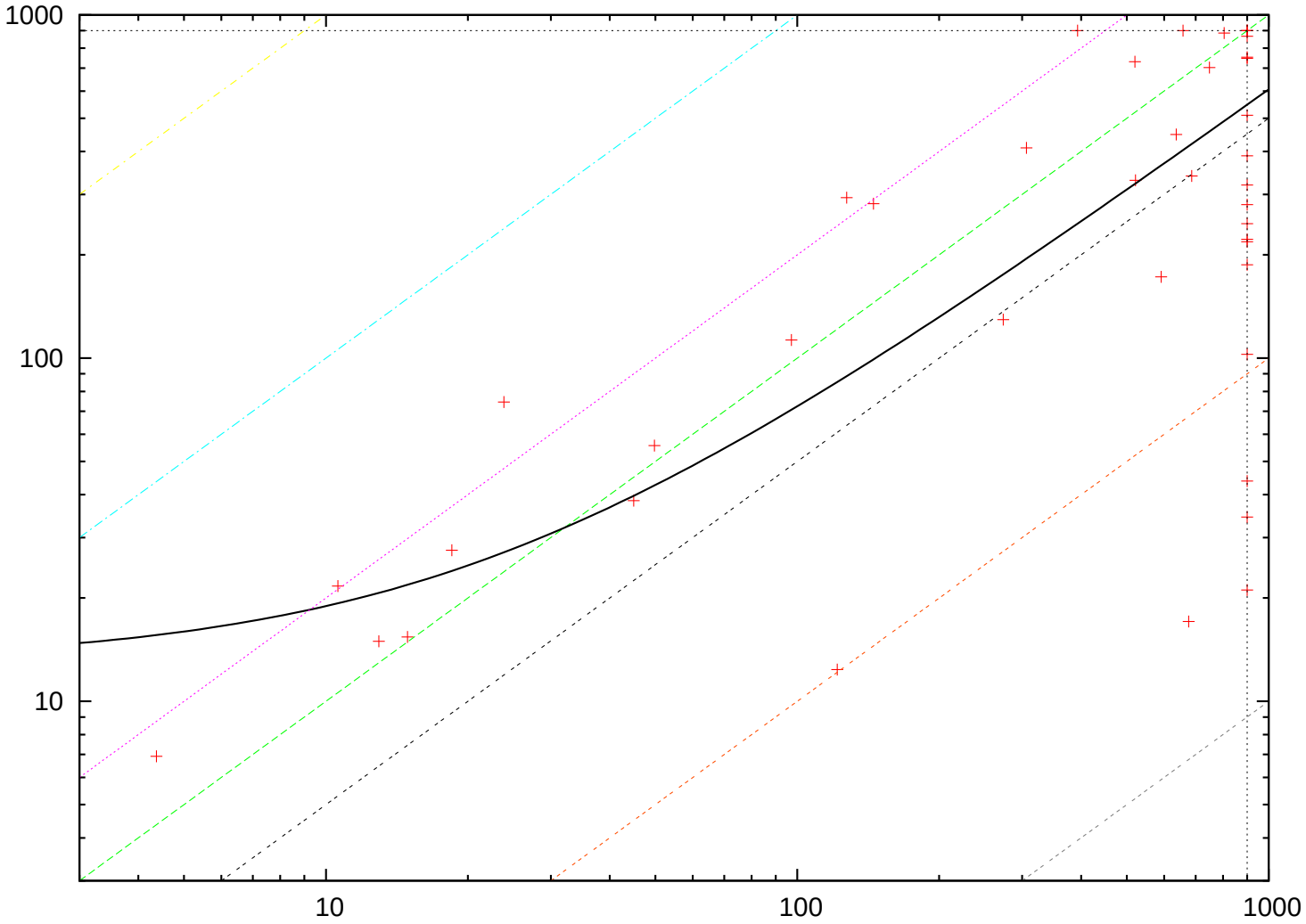


No Restarts vs Base on Unsatisfiable Instances

A. Biere, FMV, JKU Linz

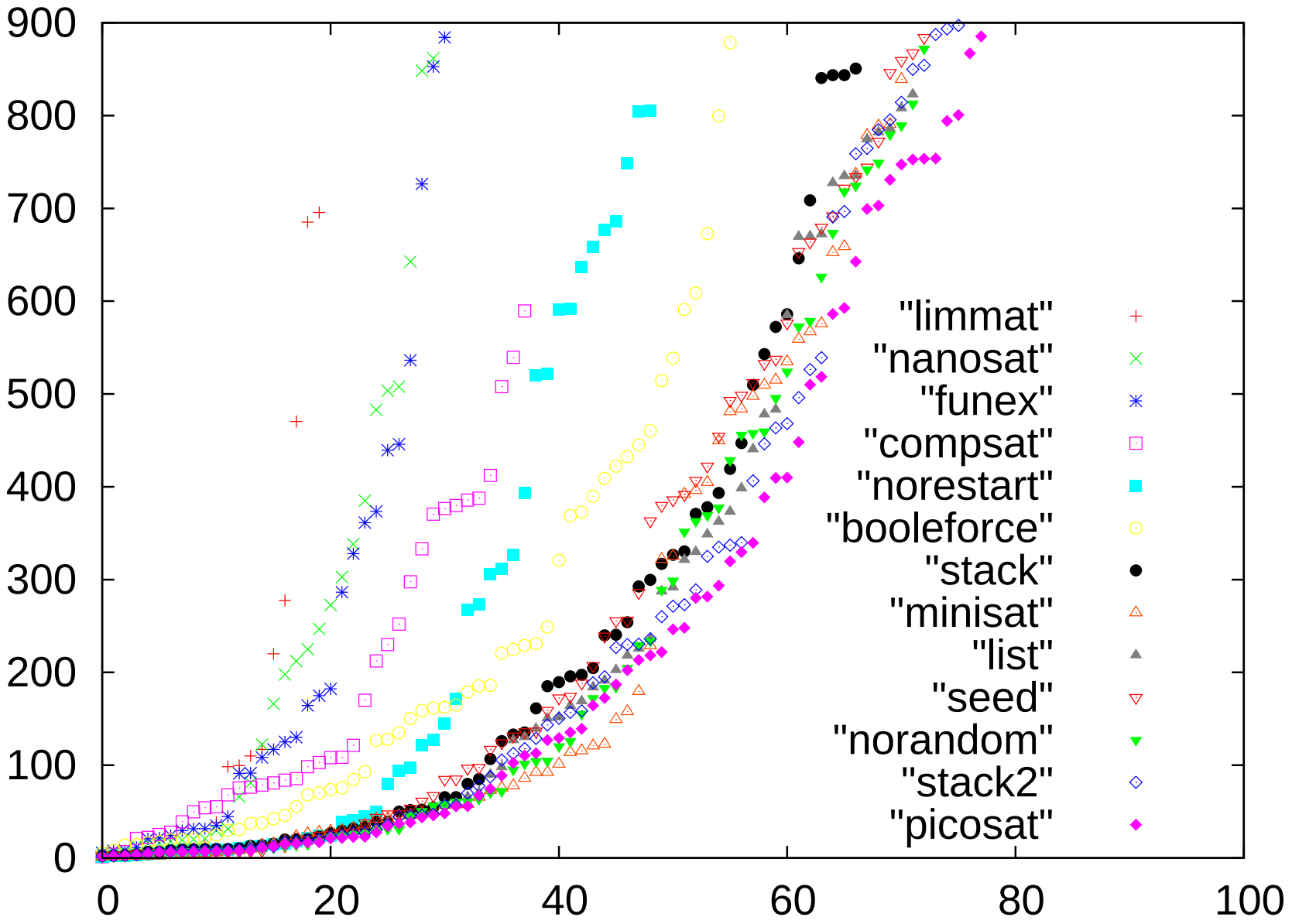
above diagonal $\Rightarrow$ **norestart** faster

below diagonal $\Rightarrow$ **base** faster



Cactus

A. Biere, FMV, JKU Linz



Three More Important Features of MiniSAT

A. Biere, FMV, JKU Linz

- preprocessing ala SATeLite
  - has been integrated into MiniSAT 2.0 but **not** in PicoSAT

    (all numbers in this talk with MiniSAT 2.0)

- clause shrinking (also in BooleForce and PicoSAT)
  - removes literals from (first UIP) learned clauses
  - conflict analysis simply resolves clauses as long variables go away

- aggressive reduction of learned clauses
  - half of the learned clauses with lower activity are removed frequently

What is Next?

A. Biere, FMV, JKU Linz

- more **effective** and **efficient** (accumulated linear time) preprocessors
- (efficient) integration of (effective) preprocessing into search
- more usage of toplogical information (see structural SAT track)
- replace **magic constants** by instance specific or even dynamic metrics
  - score increment increment (increased by 10% at every conflict)
  - restart schedule (more dynamic, e.g. restart if stuck)
  - reduce schedule

    (MiniSAT and PicoSAT increase reduce interval by 5% at restart)

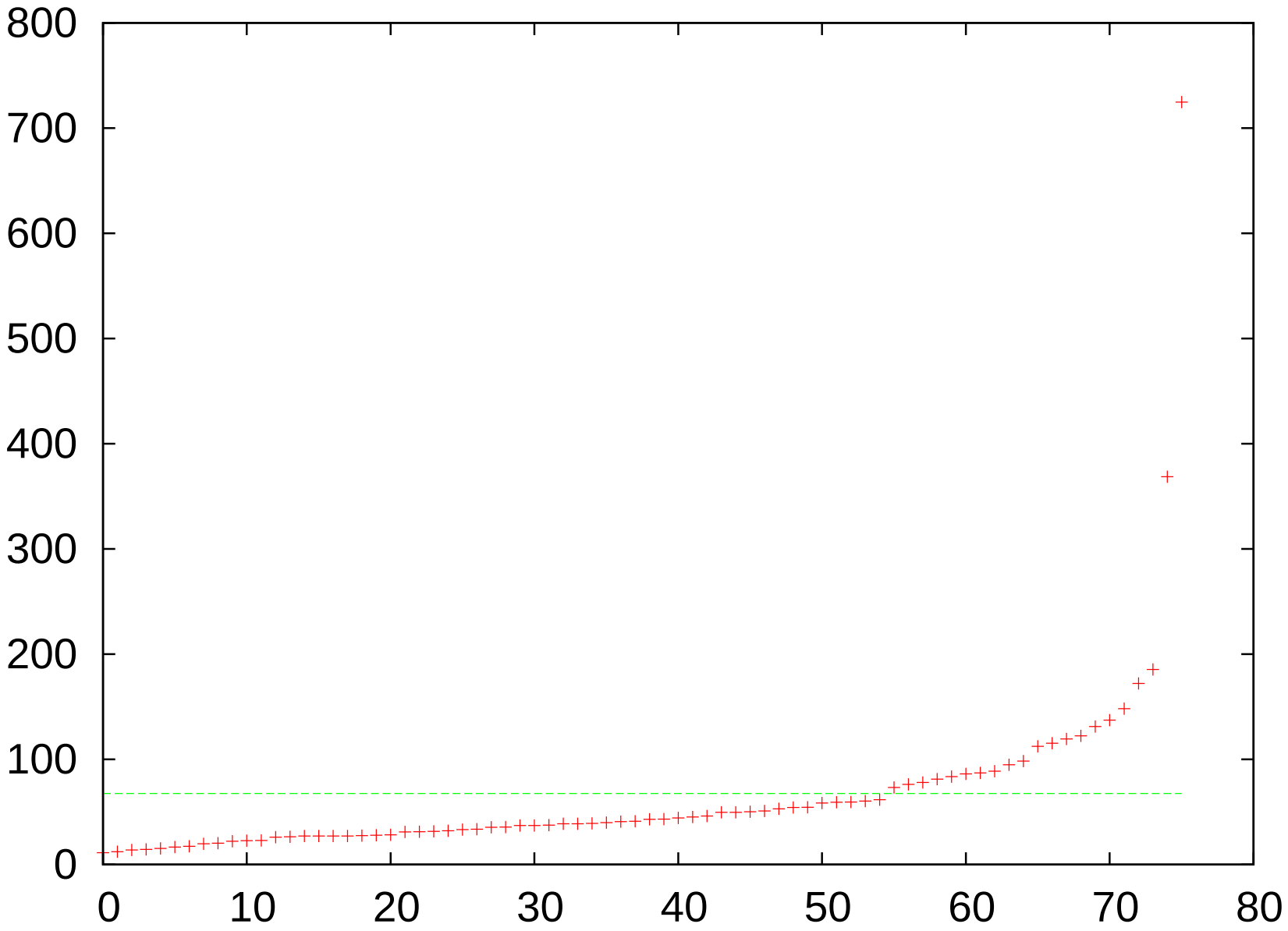
How To Do SAT Solver Research?

A. Biere, FMV, JKU Linz

- "hacking"
  - not really: algorithms need to be redesigned
  - we need efficient (accumulated linear) incremental algorithms
- emphasis on **empirical** and **systems** work
  - there are lot of papers without proper benchmarking
  - engineering (aka "hacking") takes time but also is necessary
- how to fit this kind of research into the **academic systems**:
  - empirical work on SAT solvers should be rewarded
  - systems work on SAT solvers should be rewarded

Average Learned Not Shrunken Clause Length

A. Biere, FMV, JKU Linz



Average Number of Antecedents of Learned Clauses

A. Biere, FMV, JKU Linz