# Evaluating LTL Satisfiability Solvers

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# LTL Satisfiability – (Our) Motivation



Verification gains momentum $\Rightarrow$ specifications become object of interest

Investigation of specifications

Property Simulation (e.g., RAT [PSC+06])

- Example traces, possibly with constraints
- Makes properties executable

Property Assurance (e.g., RAT [PSC+06])

- Possibilities, assertions

Sanity Checks (e.g., RAT [PSC+06]; [RV10]; [FKSFV08])

- Satisfiability, non-validity, non-redundancy

Boil down to LTL satisfiability.

(Note: checks beyond satisfiability are important, too.)

# LTL Satisfiability – (Our) Motivation



## Some specific triggers

Antichains for LTL satisfiability ([WDMR08])

- Claims advantage of **`ALASKA`** over **`NuSMV-BDD`**

LTL satisfiability solver comparison by Rozier and Vardi ([RV10])

- Focus on LTL satisfiability via explicit and BDD-based symbolic model checking, i.e., no SAT-based, temporal-resolution, tableaux-based tools.

Interest in Temporal Resolution and its potential for extraction of unsatisfiable cores ([Sch10])

No recent evaluation of LTL satisfiability solvers using a broad range of algorithms, a broad range of benchmarks, and comprehensive criteria available.

# Objective



Objective: compare performance of
off-the-shelf solvers for propositional LTL satisfiability.

This is a comparison of tools (as opposed to one of algorithms).

- Different features (e.g., preprocessing/simplification).
- Different maturity.
- Different programming languages.

# Outline



1. Introduction
2. LTL Solvers
3. Benchmarks
4. Methodology
5. Findings
6. Conclusions

# Selection of LTL Solvers



## Reduction to Model Checking

- Selected: **ALASKA**, **NuSMV-BDD**, **NuSMV-SBMC**
- Ruled out: explicit state model checkers [RV10], **Cadence SMV** (BDDs) [RV10], **SAL** [RV10], **VIS** (BDDs)
- Last hardware model checking competition [HWMCC10] focuses on safety

## Tableau-Based Algorithms

- Selected: **LWB**, **pltl**
- Ruled out: **TWB**, **LTL Tableau** [GKS09]

## Temporal Resolution

- Selected: **TRP++**, **TSPASS**
- Ruled out: **TeMP** [HKR+04,LH10]

# Selection of Benchmarks



Use families from previous comparisons [WDMR08,RV10,HS02].

- But: restrict number of instances in random category.

Add families not used for LTL satisfiability before: **acacia**, **amba**, **forobots**.

Create new families: **O1formula**, **O2formula**, **phltl**.

Scale up families.

Add variants that enforce non-trivial behavior.

To my knowledge this is the most comprehensive set of benchmarks in comparing propositional LTL satisfiability solvers to date.

# Benchmarks



| Family | Description | #Inst./uns. | Max. $\|\phi\|$ | Source |
|---|---|---|---|---|
| | Category **application** | | | |
| **acacia** | Arbiters and traffic light controllers | 71/- | 426 | [FJR09] |
| **alaska_lift** | Elevator specifications | 136/34 | 4450 | [WDMR08] |
| **alaska_szymanski** | Mutual exclusion protocol | 4/- | 183 | [WDMR08] |
| **anzu_amba** | Microcontroller buffer architecture | 51/- | 6173 | [BGJ+07a] |
| **anzu_genbuf** | Generalized buffer | 60/- | 5805 | [BGJ+07b] |
| **forobots** | Model of a robot with properties | 39/25 | 636 | [BDF09] |
| | Category **crafted** | | | |
| **rozier_counter** | 4 variants of a serial counter | 78/- | 751 | [RV10] |
| **rozier_pattern** | 8 scalable patterns to trigger difficulties in LTL to Büchi translators | 244/- | 7992 | [RV10] |
| **schup._O1/2form.** | Expon. behavior in some solvers | 54/42 | 6001 | |
| **schuppan_phltl** | Temporal variant of pigeonhole | 18/10 | 40501 | |
| | Category **random** | | | |
| **rozier_formulas** | Obtained by generating a syntax tree [DGV99] | 2000/57 | 185 | [RV10] |
| **trp** | Obtained by lifting propositional CNF into fixed temporal structure | 970/397 | 1422 | [HS02] |

# Setup, Flow



## Flow

Preliminary Stage

- Purpose: reduce number of configurations for **TRP++** and **TSPASS**
- 10 second time out

Main Stage

- All remaining configurations for all solvers
- 60 second time out

Graphical Evaluation

- Choose one winning configuration per solver based on highest score

## Setup

Hardware/Software

- Intel Xeon 3.0 GHz
- 4 GB memory
- Red Had Linux 5.4, 64 bit kernel 2.6.18
- Measure time, memory with **run** [BJ]

No shuffling of benchmarks

One run per instance and solver configuration

Memory out: 2 GB

# Scoring



Objective:

- Score by highest number of solved instances; break ties by lower time taken on solved instances. (Frequently used.)

Problem:

- Benchmark families with very different numbers of instances.
- Smallest family has 4 instances; largest has $> 2000$.

Solution:

- Arrange benchmark families in tree.
- Assign equal weight to the (immediate) children of each node.

Caveat:

- The weight of an instance may change between different scores, e.g., share of solved instances (all instances count) and run time on solved instances (only solved instances count).
- The weight of an instance may change between different solvers for the same score, e.g., run time on solved instances (only instances solved by particular solver count).

# Cactus Plots vs. Contour/Discrete Raw Data Plots



## Cactus Plots

- are standard;
- easily allow to identify the winner when ranking by highest number of solved instances with ties broken by time spent on solved instances;
- break the correlation between different solvers on the same instance.

## Contour/Discrete Raw Data Plots

- retain the correlation between different solvers on the same instance;
- easily allow to identify similar and complementary behavior;
- easily allow to see performance of a solver on subfamilies;
- easily allow to see difficulty of instances and subfamilies.

# Correctness



We found 1 or 2 bugs each in **ALASKA**, **NuSMV**, **TRP++**, and **TSPASS**.

- Kindly fixed quickly by tool authors.

We also found bugs in **LWB**.

- We contacted the developers.
- We received no response.
- 187 out of 7446 instances (known) buggy.
- 13 wrong results.
- Others abnormal termination.
- Hors concours.

# Winning Configurations per Tool



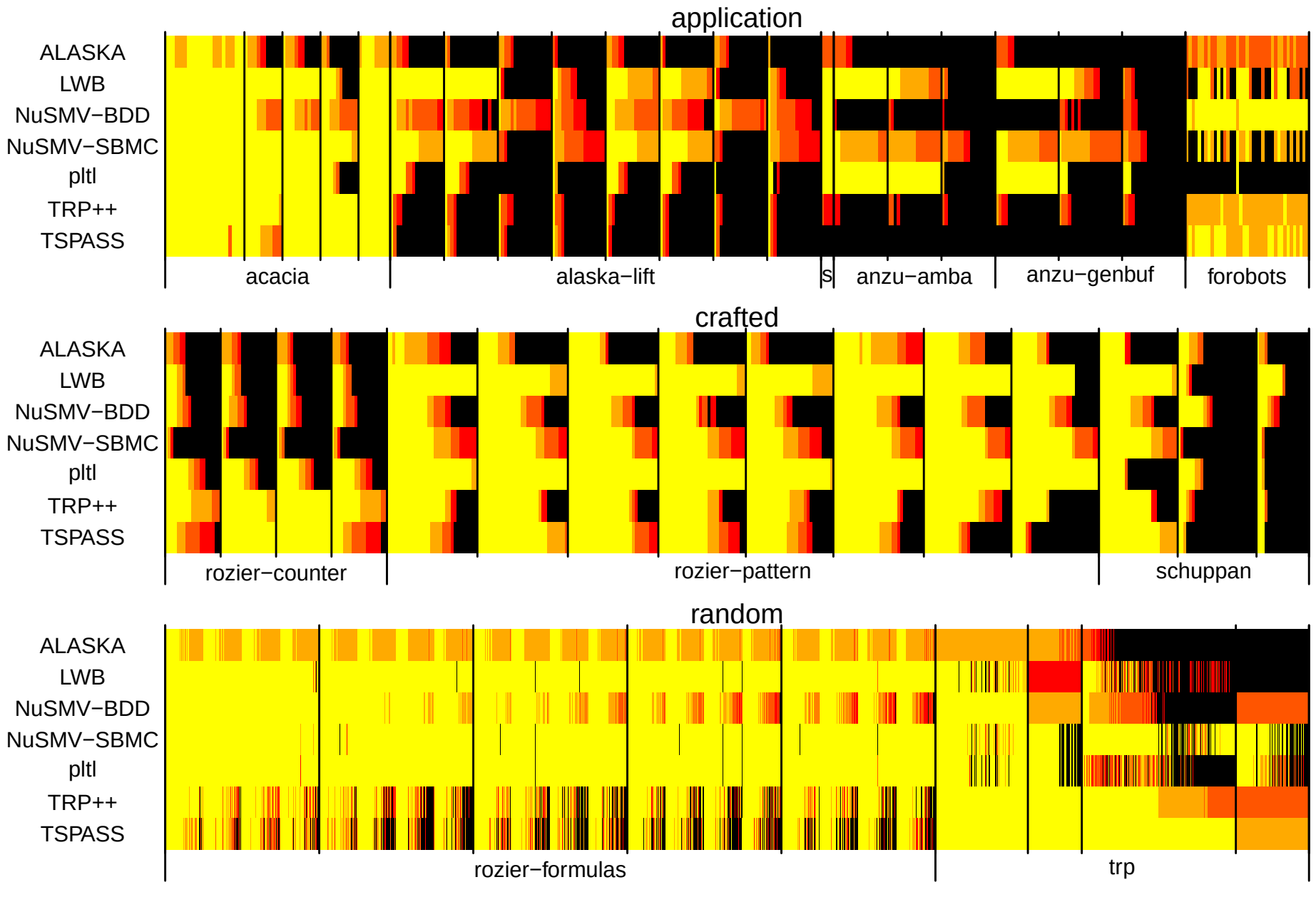
We select one winning configuration (column max) per tool.

| | model construction disabled (*sat* and *unsat* instances) | | | |
|---|---|---|---|---|
| tool | winning configuration | max | min | vbs |
| **ALASKA** | `noc_nos_nob` | 0.581 | 0.322 | 0.595 |
| **LWB** | `mod` | 0.740 | 0.656 | 0.800 |
| **NuSMV-BDD** | `dcx_fflt_dyn_elbwd` | 0.743 | 0.607 | 0.823 |
| **NuSMV-SBMC** | `nodcx_c` | 0.723 | 0.651 | 0.726 |
| **pltl** | `tree` | 0.694 | 0.687 | 0.702 |
| **TRP++** | `s_r_noal_bfs_nop_fsr` | 0.752 | 0.593 | 0.776 |
| **TSPASS** | `ext_nogrp_nosev_sub_nosls_rfmrr-_norbmrr_nomod_mor` | 0.667 | 0.479 | 0.670 |

Numbers: weighted share of solved instances. vbs: virtual best solver.

# Run Times (Contour/Discrete Raw Data Plots)

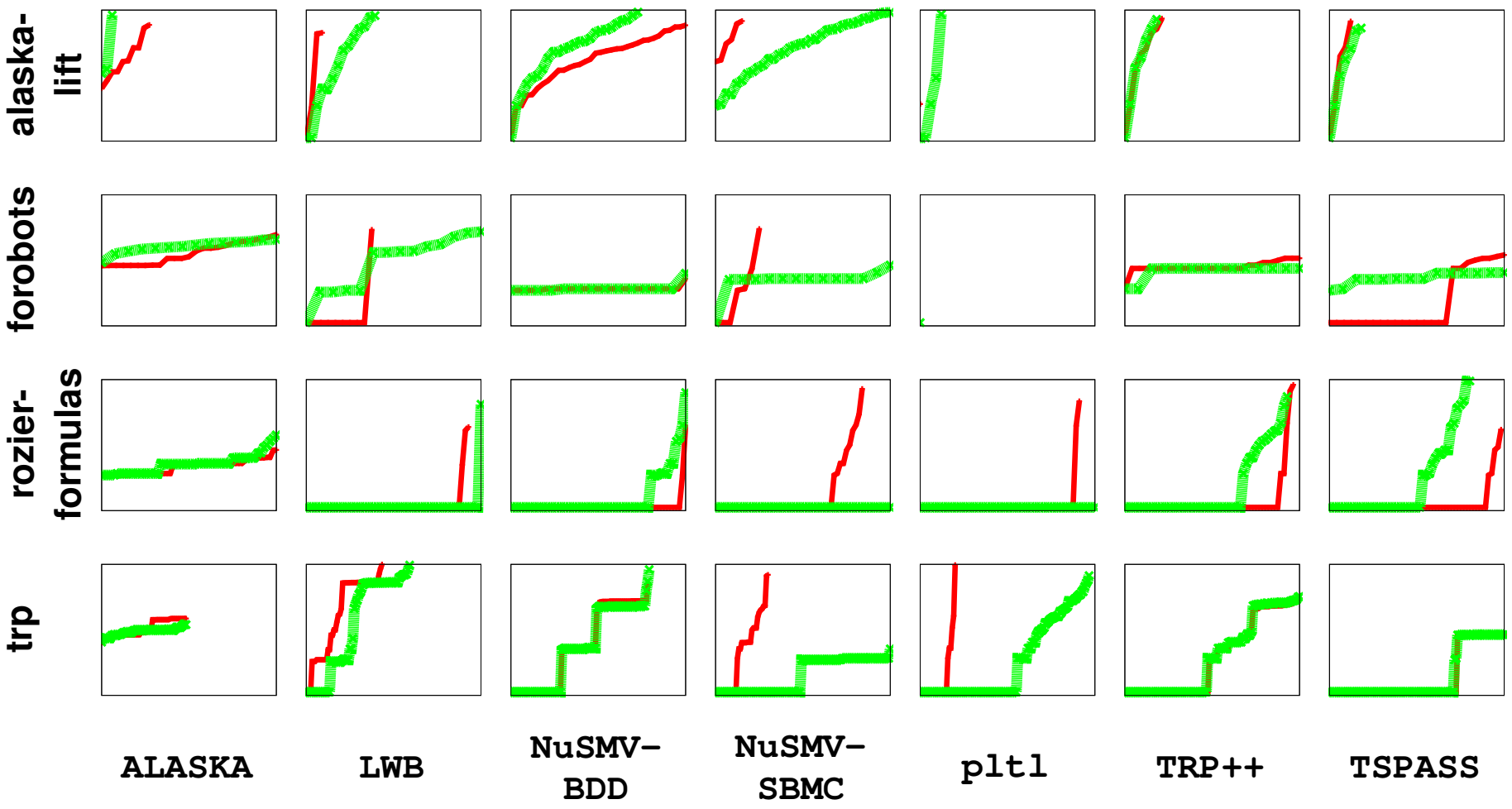





Author: V. Schuppan

# Run Times *Sat* vs. *Unsat* Instances






key: *sat* *unsat*

x-axes: number of solved instances

y-axes: run time

Instances selected to “equalize” features.

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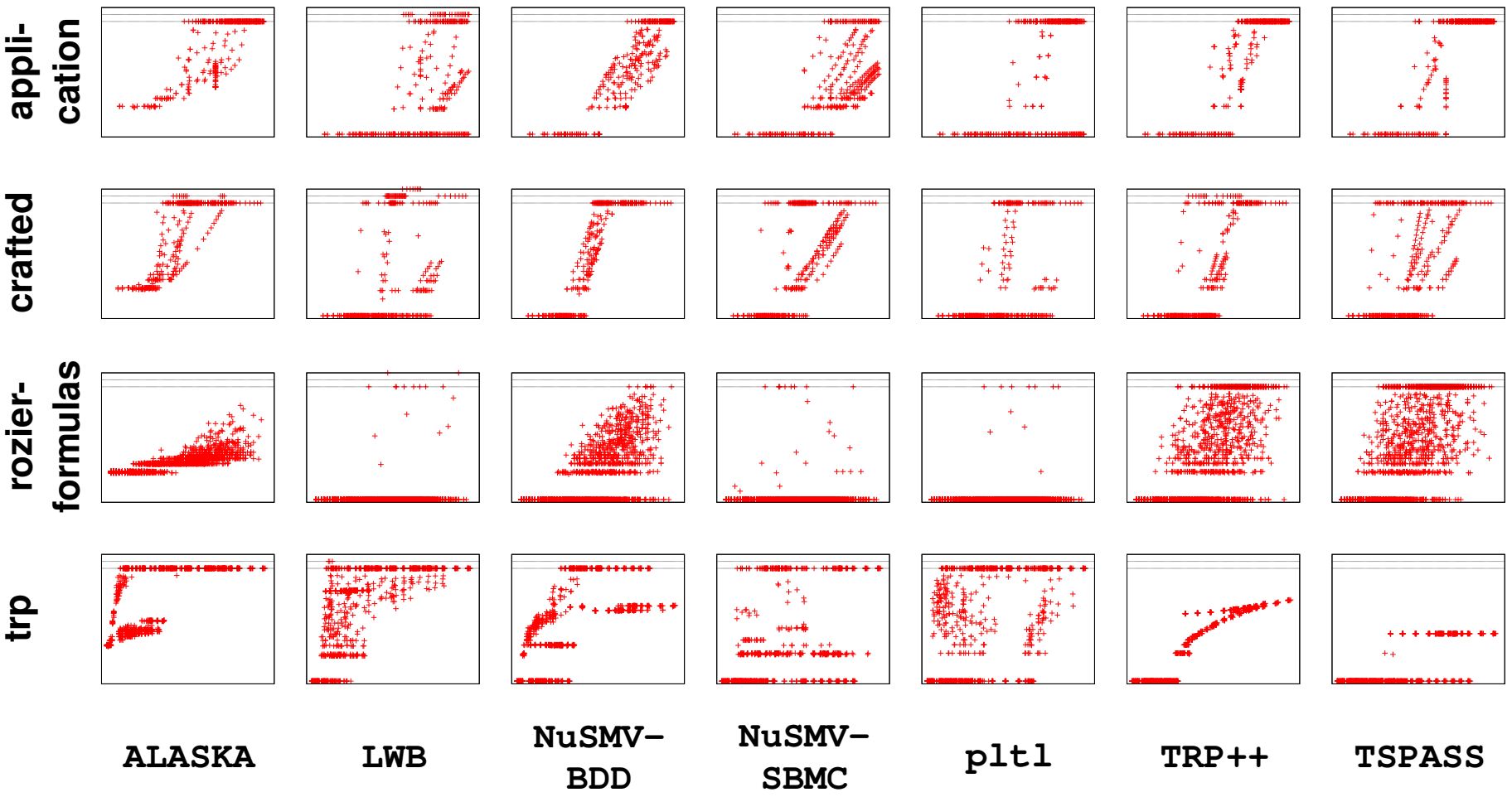
# Run Times by Instance Size

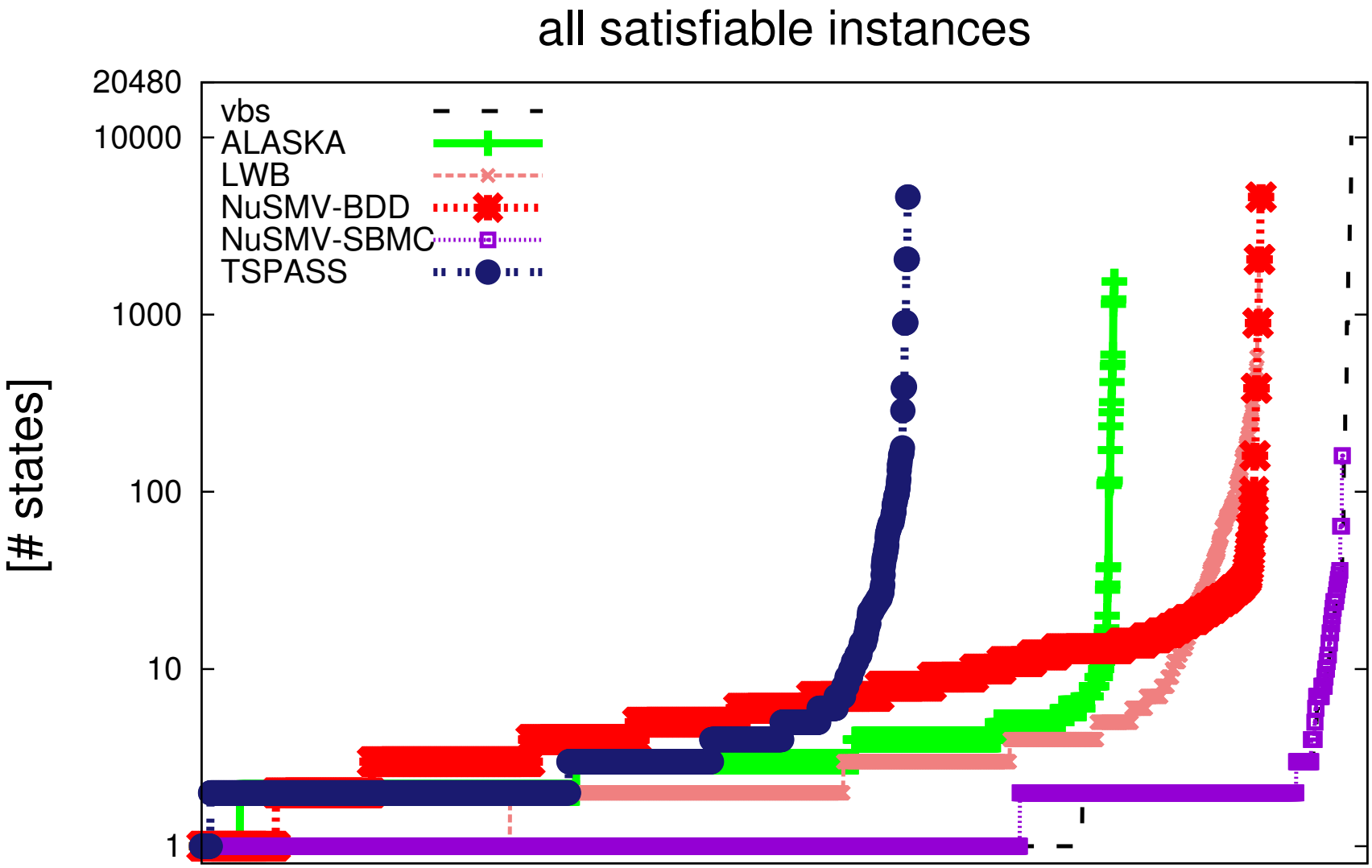





x-axes: instance size
y-axes: run time

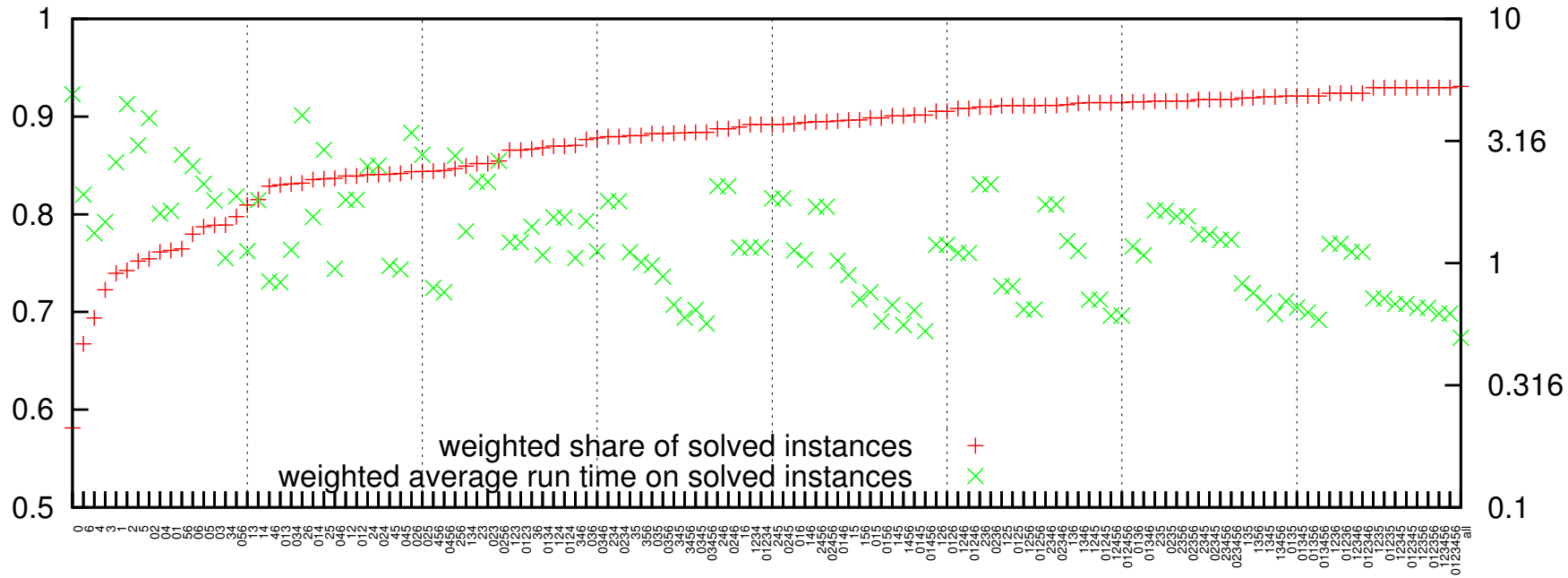
# Model Sizes




all satisfiable instances
20480
10000
1000
100
10
1
[# states]
vbs
ALASKA
LWB
NuSMV-BDD
NuSMV-SBMC
TSPASS

# Potential of a Portfolio Solver (Perfect Oracle)





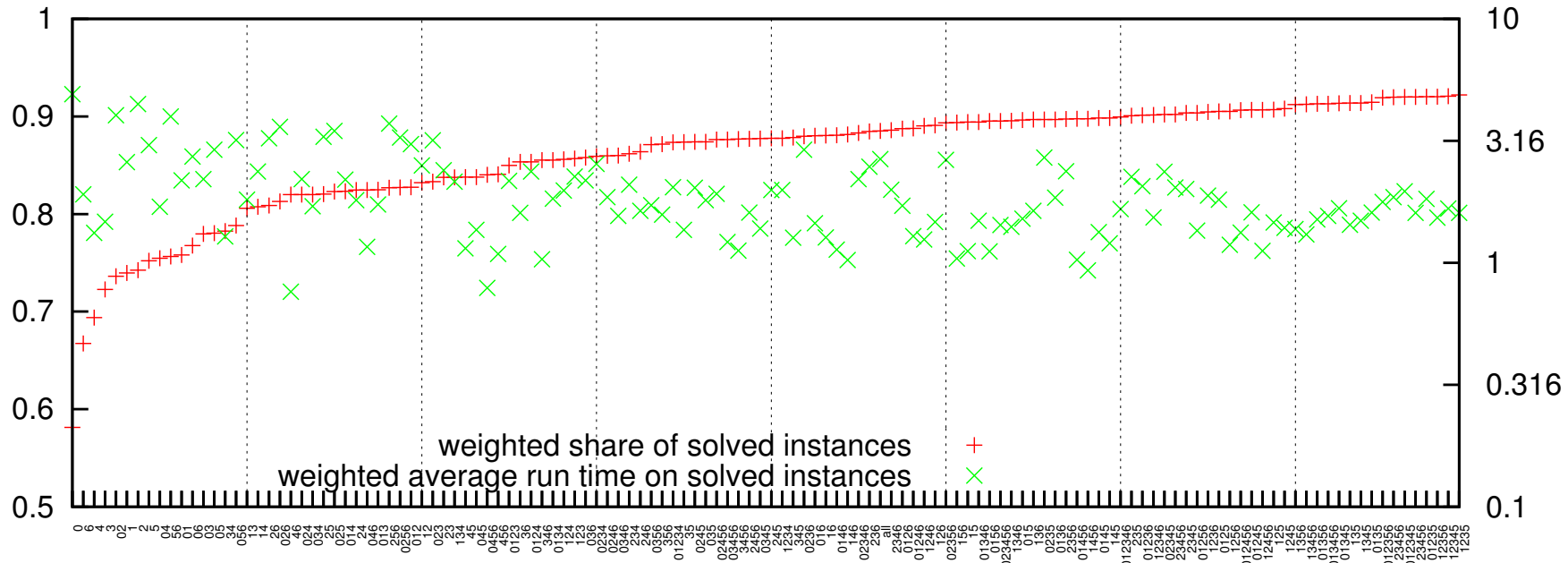

Mode: perfect oracle selects best portfolio member for any given instance. Best case scenario for portfolio solvers without communication between portfolio members. Unrealistic.

Left y-axis: weighted share of solved instances.

Right y-axis: weighted average run time on solved instances [seconds].

# Potential of a Portfolio Solver (Perfect Task Switcher)






Mode: task switching with no overhead and infinitely small time slices between portfolio members. Reference case scenario for portfolio solvers without communication between portfolio members. Should be beaten.

Left y-axis: weighted share of solved instances.

Right y-axis: weighted average run time on solved instances [seconds].

# Potential of a Portfolio Solver (Fast Presolver)



Even a simplistic portfolio solver can yield considerable benefits.

Pick 4 best 2-configuration portfolios.

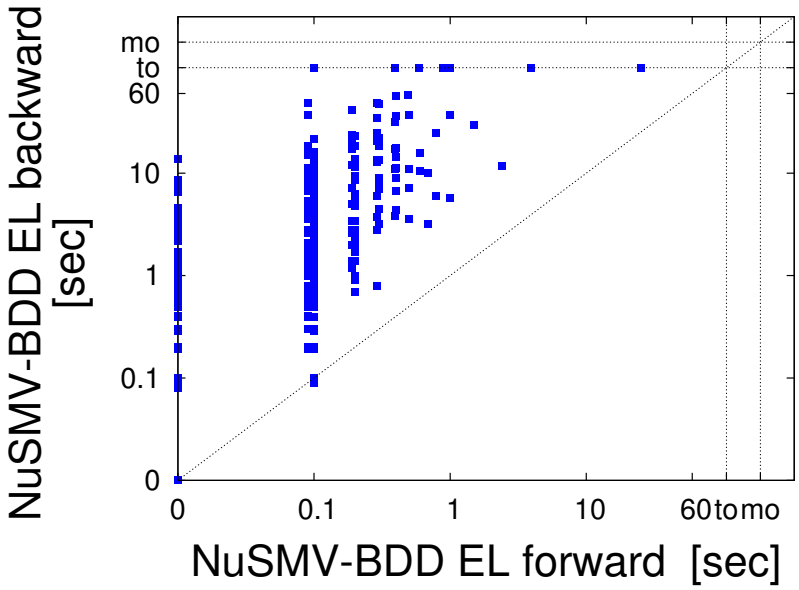
Run one as fast presolver [XHH+08] for a short time. If that fails, run the other solver for the remaining time.

| Results | 1st as fast presolver | | | | 2nd as fast presolver | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 second | | 2 seconds | | 1 second | | 2 seconds | |
| | share | time | share | time | share | time | share | time |
| (**LWB**, **TRP++**) | 0.880 | 1.09 | 0.885 | 1.30 | 0.841 | 1.26 | 0.850 | 1.45 |
| (**LWB**, **TSPASS**) | 0.868 | 0.88 | 0.874 | 1.10 | 0.850 | 1.20 | 0.858 | 1.48 |
| (**NuSMV-SBMC**, **TRP++**) | 0.823 | 1.03 | 0.841 | 1.18 | 0.860 | 0.97 | 0.862 | 1.31 |
| (**NuSMV-SBMC**, **TSPASS**) | 0.813 | 1.00 | 0.831 | 1.21 | 0.837 | 1.17 | 0.840 | 1.42 |

| Reference | 1st in isolation | | 2nd in isolation | | perfect oracle | | perf. task switcher | |
|---|---|---|---|---|---|---|---|---|
| | share | time | share | time | share | time | share | time |
| (**LWB**, **TRP++**) | 0.740 | 2.59 | 0.752 | 3.03 | 0.896 | 0.89 | 0.894 | 1.12 |
| (**LWB**, **TSPASS**) | 0.740 | 2.59 | 0.667 | 1.91 | 0.889 | 1.16 | 0.881 | 1.27 |
| (**NuSMV-SBMC**, **TRP++**) | 0.723 | 1.47 | 0.752 | 3.03 | 0.880 | 1.11 | 0.874 | 1.37 |
| (**NuSMV-SBMC**, **TSPASS**) | 0.723 | 1.47 | 0.667 | 1.91 | 0.867 | 1.41 | 0.853 | 1.60 |

# A Performance Advantage of ALASKA over NuSMV-BDD?






[WDMR08] claims an advantage of **ALASKA** over **NuSMV-BDD**.

A difference beyond representation (antichains vs. BDDs) was direction of fixed point computations. (Forward fixed point computation was not available in **NuSMV-BDD** when [WDMR08] was done.)

Using appropriate options in **NuSMV** and forward rather than backward fixed point computation **ALASKA** does not outperform **NuSMV-BDD**.

# The End



## Summary

Identification of reference solvers with options at instance level.

No solver dominates. Rather, complementary behavior.

We don't declare any single solver to be the winner.

A portfolio approach seems worth trying.

Benchmarks, data, more plots available:
`http://www.schuppan.de/viktor/atva11/`.

## Future Work

Check out participants of HWMCC'11.

Consider explicit state model checkers that handle the property on-the-fly.

Have a proper competition?

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# Questions?

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