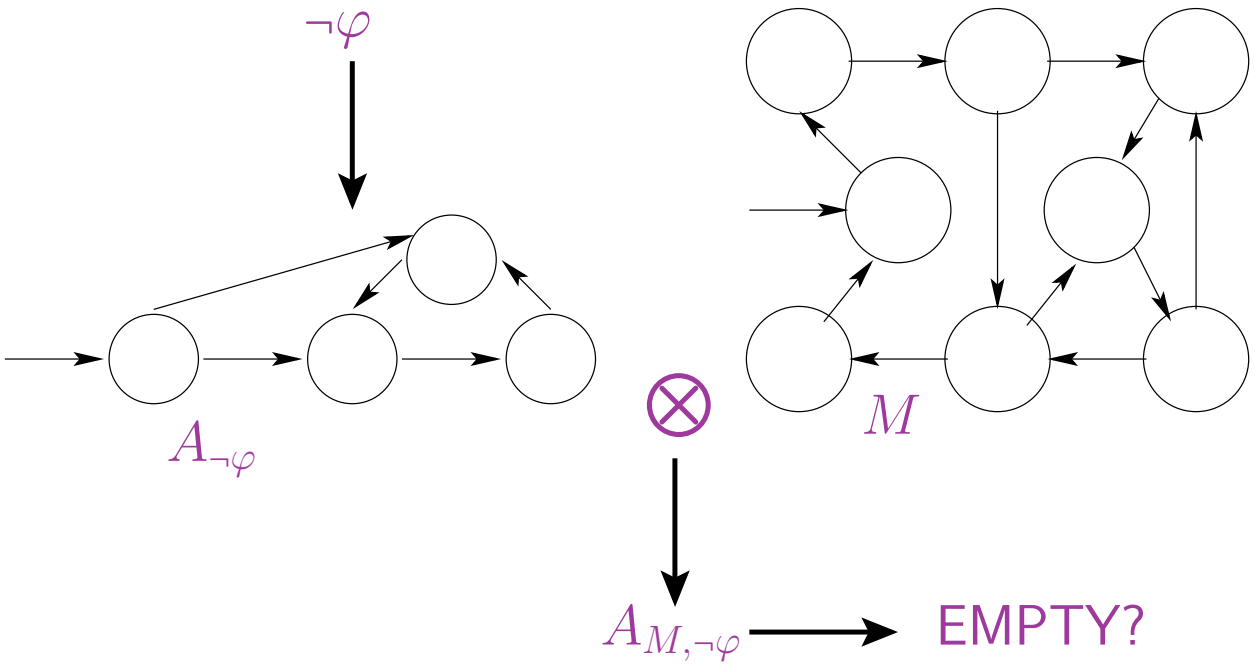
Developing an Open-Source, State-of-the-Art Symbolic Model-Checking Framework for the Model-Checking Research Community

Kristin Yvonne Rozier
Iowa State University

30th International Symposium on Model Checking Software
April 11, 2024

Automata-Theoretic Approach to Model Checking[1]



[1] Vardi, Wolper, LICS, 1986

Small Aircraft Transportation System (SAT)[2]

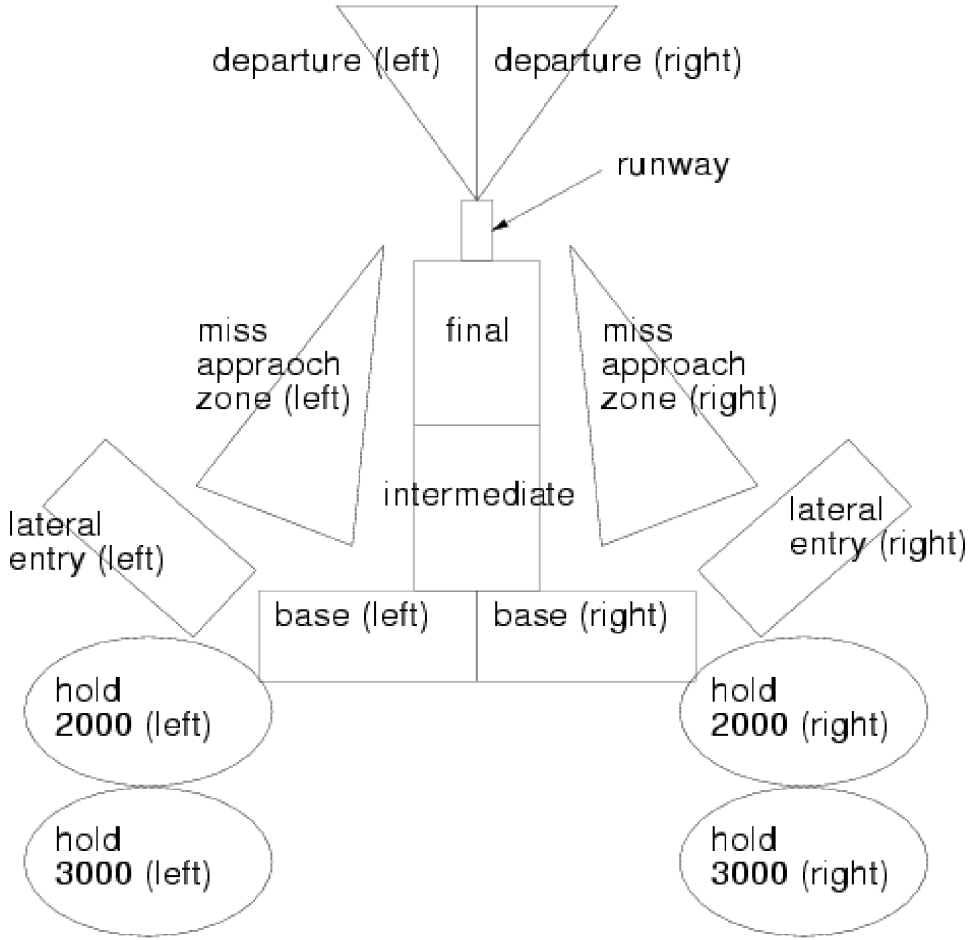


Figure 2. Operational Zones of the SCA.

[2] V. Carreño, C. Muñoz. "Safety Verification of the Small Aircraft Transportation System Concept of Operations."

Symbolic Model Checking[3]

$$\varphi = (p \mathcal{U} q)$$

```
module main() {
  VAR
p: boolean;
q: boolean;
EL_X__p_U_q : boolean;
DEFINE S__p_U_q := q | (p & EL_X__p_U_q);
TRANS  ( EL_X__p_U_q = (next(S__p_U_q) ))
FAIRNESS (!S__p_U_q | q)
SPEC !(S__p_U_q & EG TRUE) }
```

```
module main() {
p: boolean;
q: boolean;
FAIRNESS  TRUE; }
```

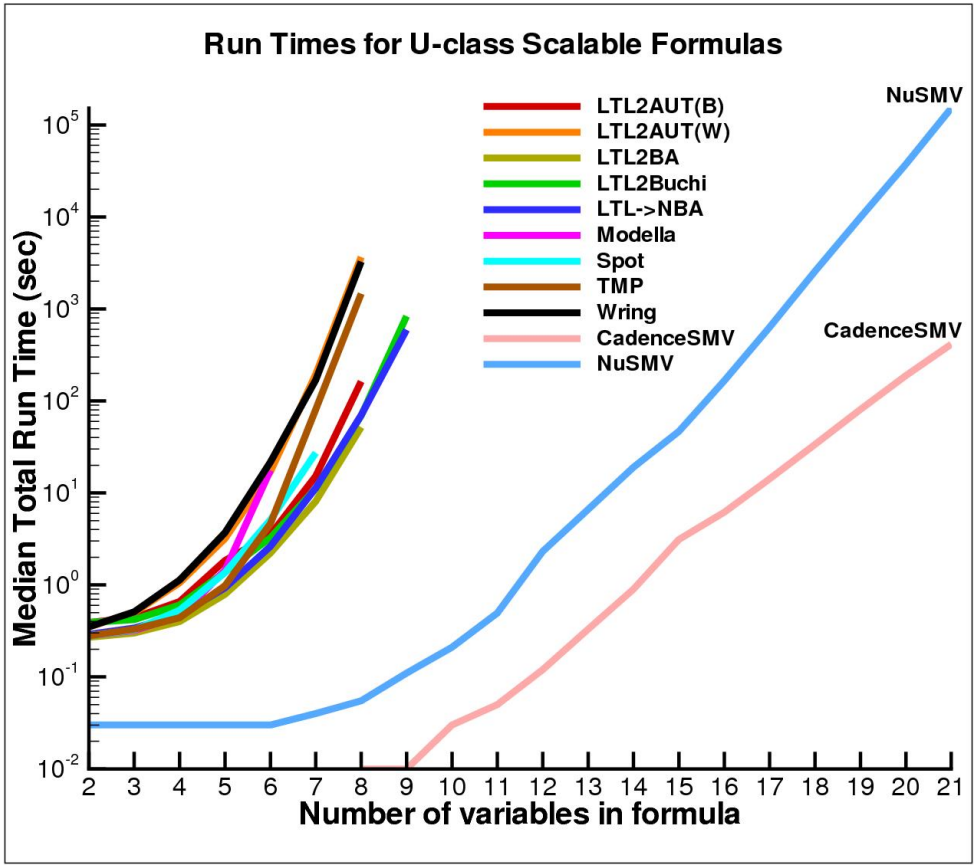
symbolic $A_{\neg\varphi}$ $\otimes$ universal M

$A_{M,\neg\varphi}$  nuXmv:EMPTY?

[3] Clarke, Grumberg, Hamaguchi, "Another look at LTL model checking." FMSD, 1997

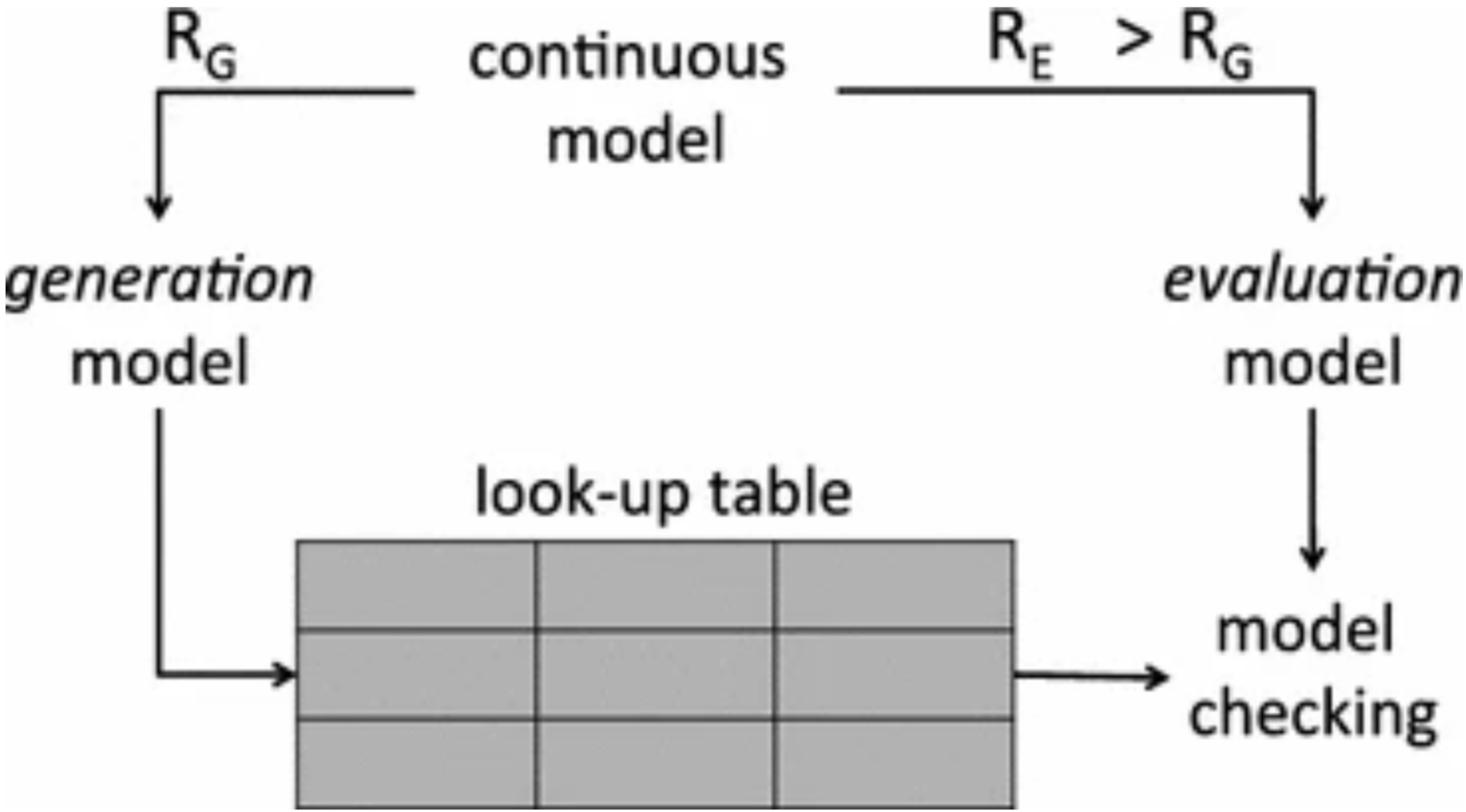
Symbolic Model Checkers in Satisfiability Checking

Symbolic Model Checkers push performance to industrial levels. [4]



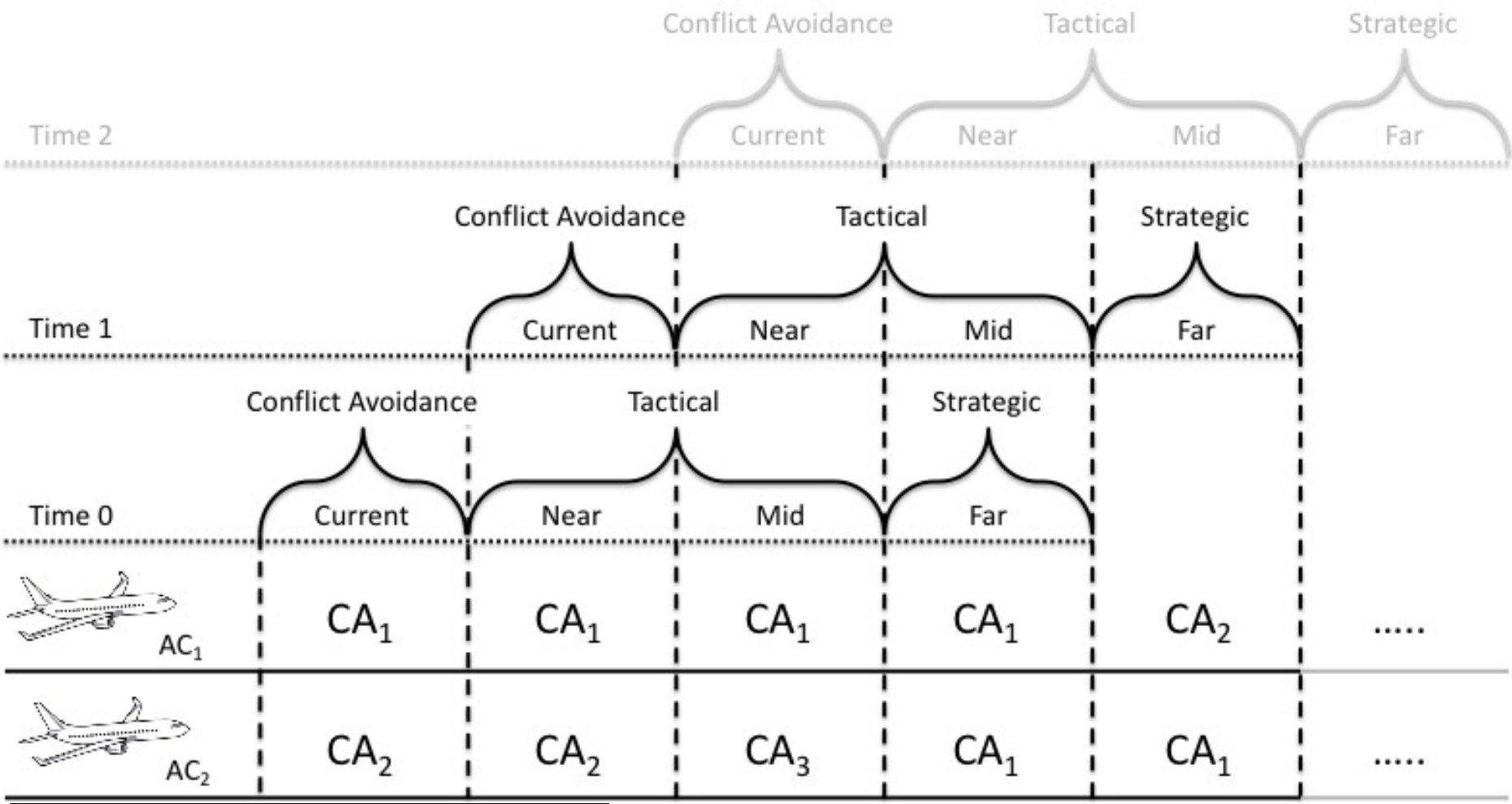
[4] Rozier and Vardi, "LTL Satisfiability Checking." SPIN'07.

Model Checking ACAS-X Controller[5]



[5] C. von Essen, D. Giannakopoulou. "Probabilistic verification and synthesis of the next generation airborne collision avoidance system." TACAS 2014

Formal Modeling: Time Windows[6]



[6] C. Mattarei, A. Cimatti, M. Gario, S. Tonetta, K. Y. Rozier. "Comparing Different Functional Allocations in Automated Air Traffic Control Design." In Formal Methods in Computer-Aided Design (FMCAD), IEEE/ACM, 2015.

Full-Scale Design Space Verification[7]

Summary of modeled dimensions and variants:
NASA Automated Airspace Concept

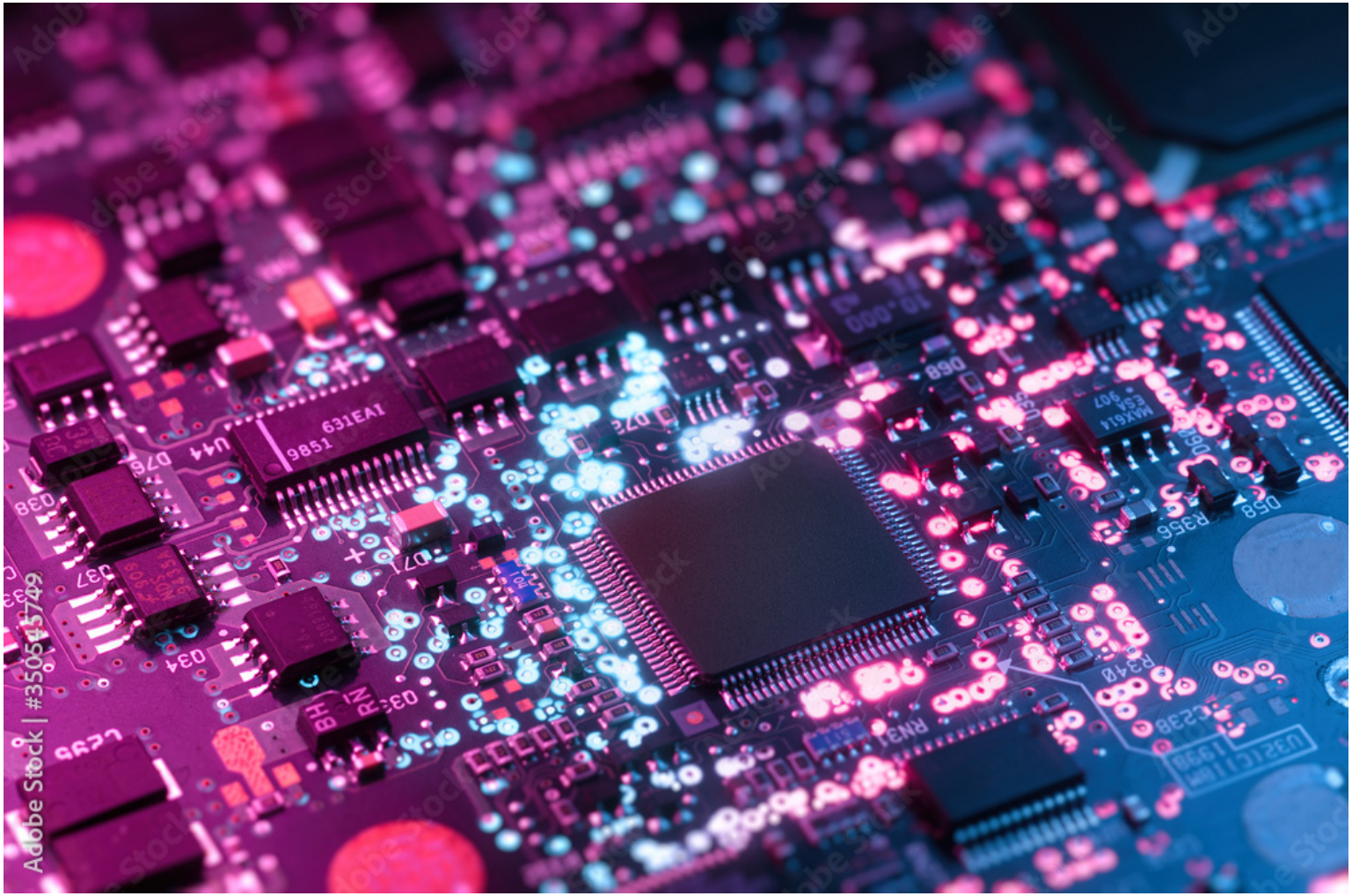
Name	Possible Values	Size
SSEP TS SA	ATC, SELF, SATC	3
SSEP SS SA	ATC, SELF, SATC	3
Instances	4, 3+1, 2+2, 1+3, 4	5
Info Sharing (GSEP-to-SSEP)	None, Current, Near, Mid, Far	5
Info Sharing (SSEP-to-ATC)	None, Current, Near, Mid, Far	5
Burdening Rules	Undef, *GSEP*, *SSEP*	3
ACDR Implementations	Simple, Asymmetric, Non-Receptive	3
Com Steps	1, 2, ...	2
TOTAL	-	**20,250**
Focus group	-	**1,620**

[7] Marco Gario, Alessandro Cimatti, Cristian Mattarei, Stefano Tonetta and Kristin Y. Rozier. "Model Checking at Scale: Automated Air Traffic Control Design Space Exploration." In *Computer Aided Verification (CAV)*, 2016.

Focusing on Linear Models of Time...[8]

[8] Vardi, "Branching vs. Linear Time: Final showdown." TACAS, 2001

Focusing on "Hardware" Model Checking



Evolution of Model-Checking Algorithms

1. BDD-based
2. SAT-based / bounded model checking
3. IC3 / k-liveness

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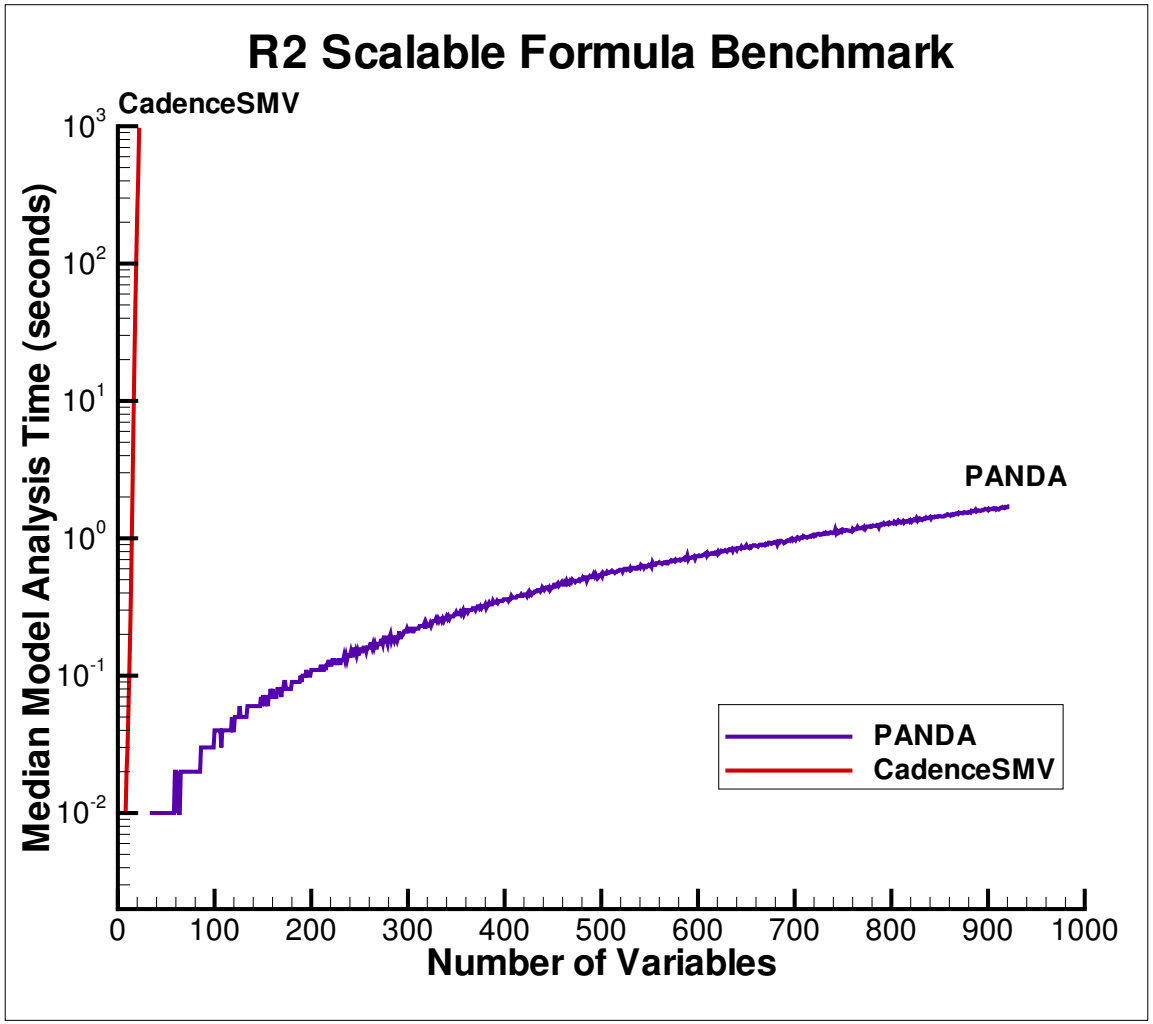
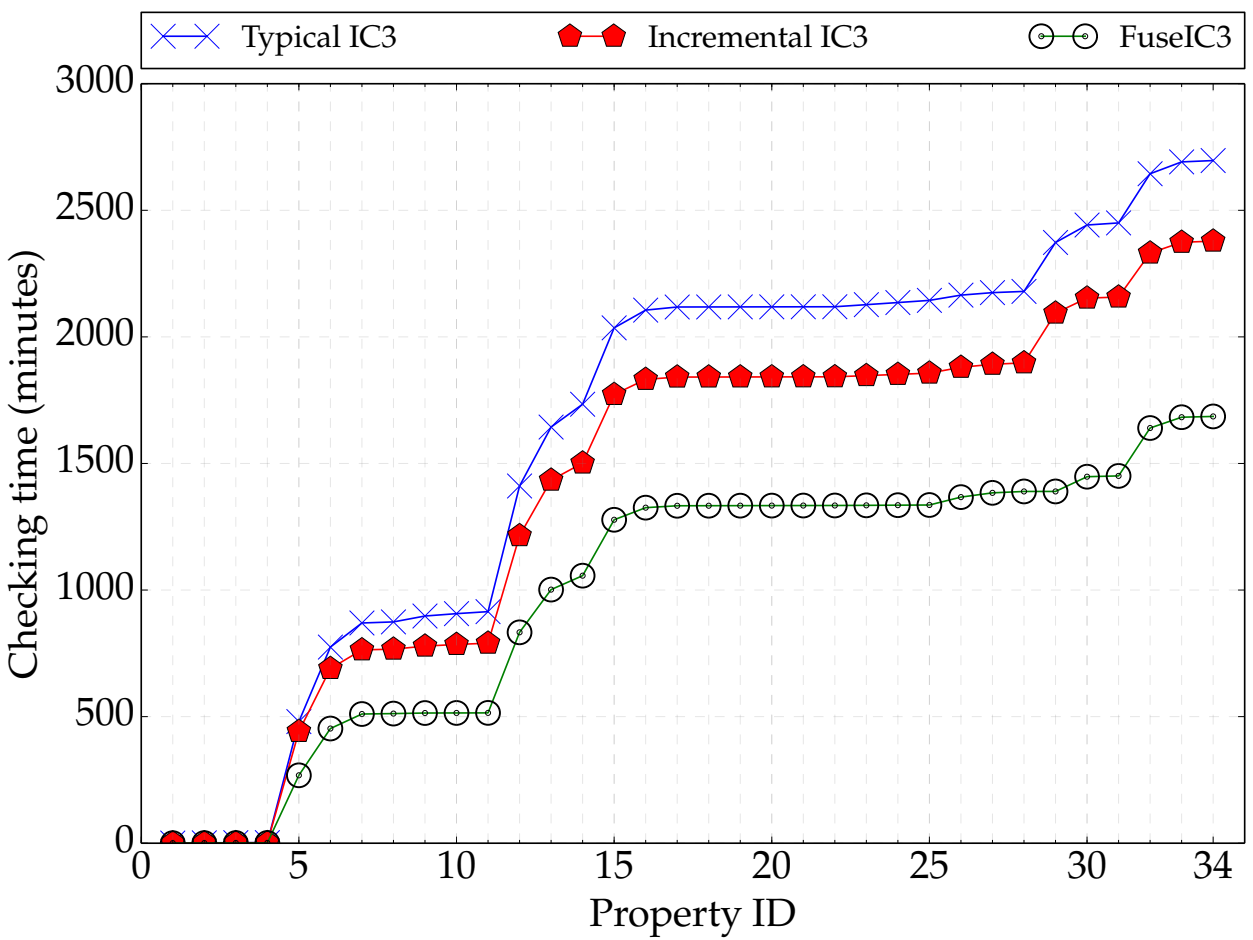
Symbolic model checking progressed from bit-level to word level

The Problem[9]



[9] K.Y.Rozier and M.Y.Vardi, "A Multi-Encoding Approach for LTL Symbolic Satisfiability Checking," FM 2011.

FuseIC3: An Algorithm for Checking Large Design Spaces[10]



Model checking **34 formulas** over **1,620 models** is **5.48x faster**

[10] Rohit Dureja and Kristin Yvonne Rozier. "FuseIC3: An Algorithm for Checking Large Design Spaces." In Formal Methods in Computer-Aided Design (FMCAD), IEEE/ACM, Vienna, Austria, October 2-6, 2017.

The Major Problems

- nuXmv **closed source**: can't check internal algorithm

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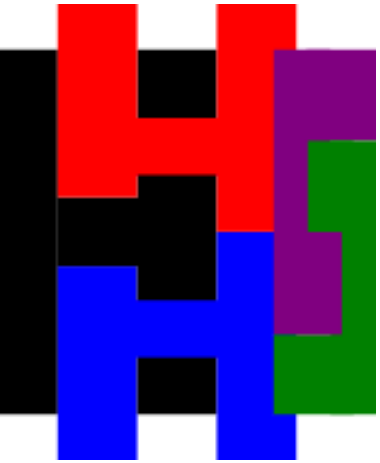
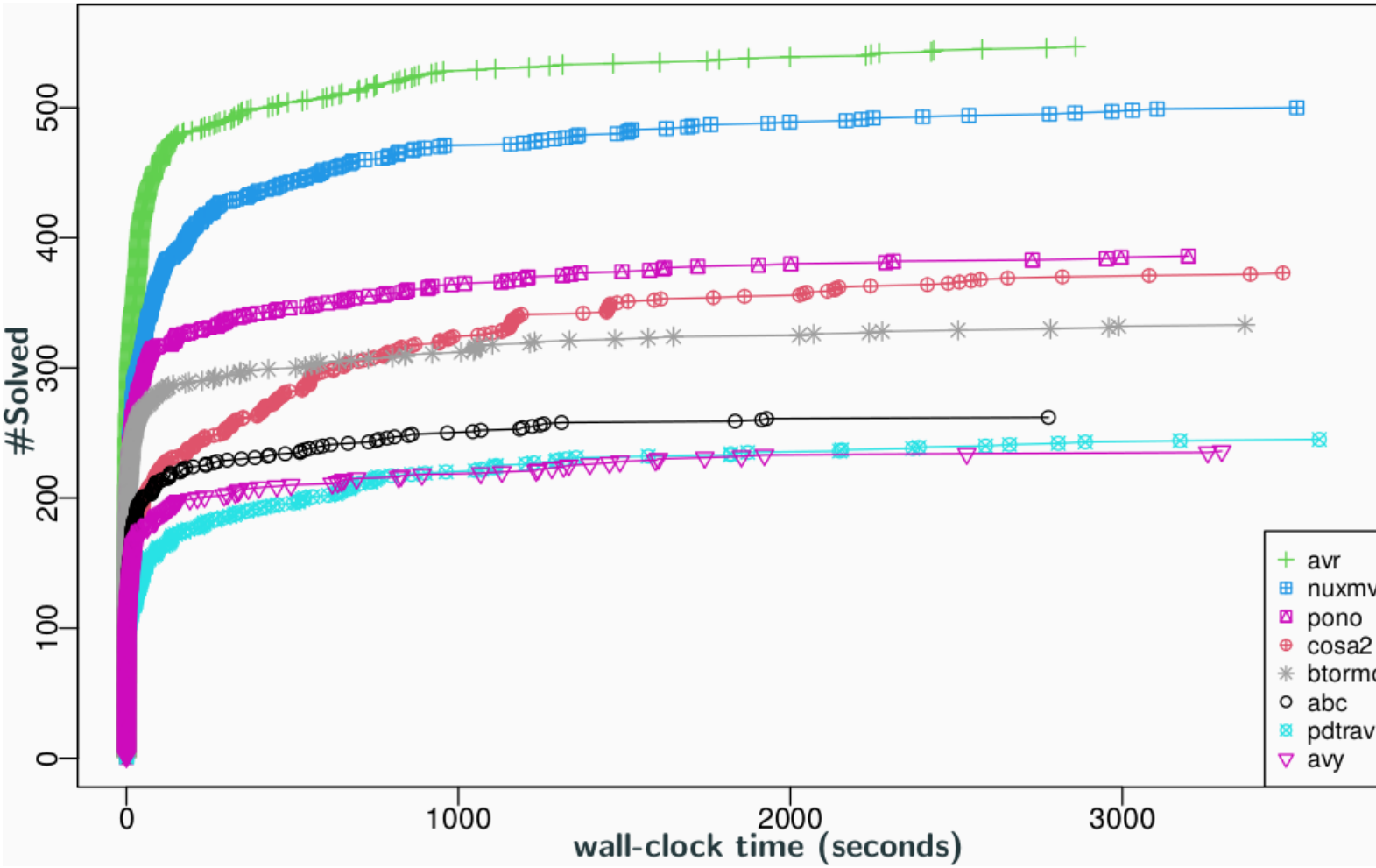
How do we do better?

HWMCC: Hardware Model Checking Competition (2020)



Word-level reasoning

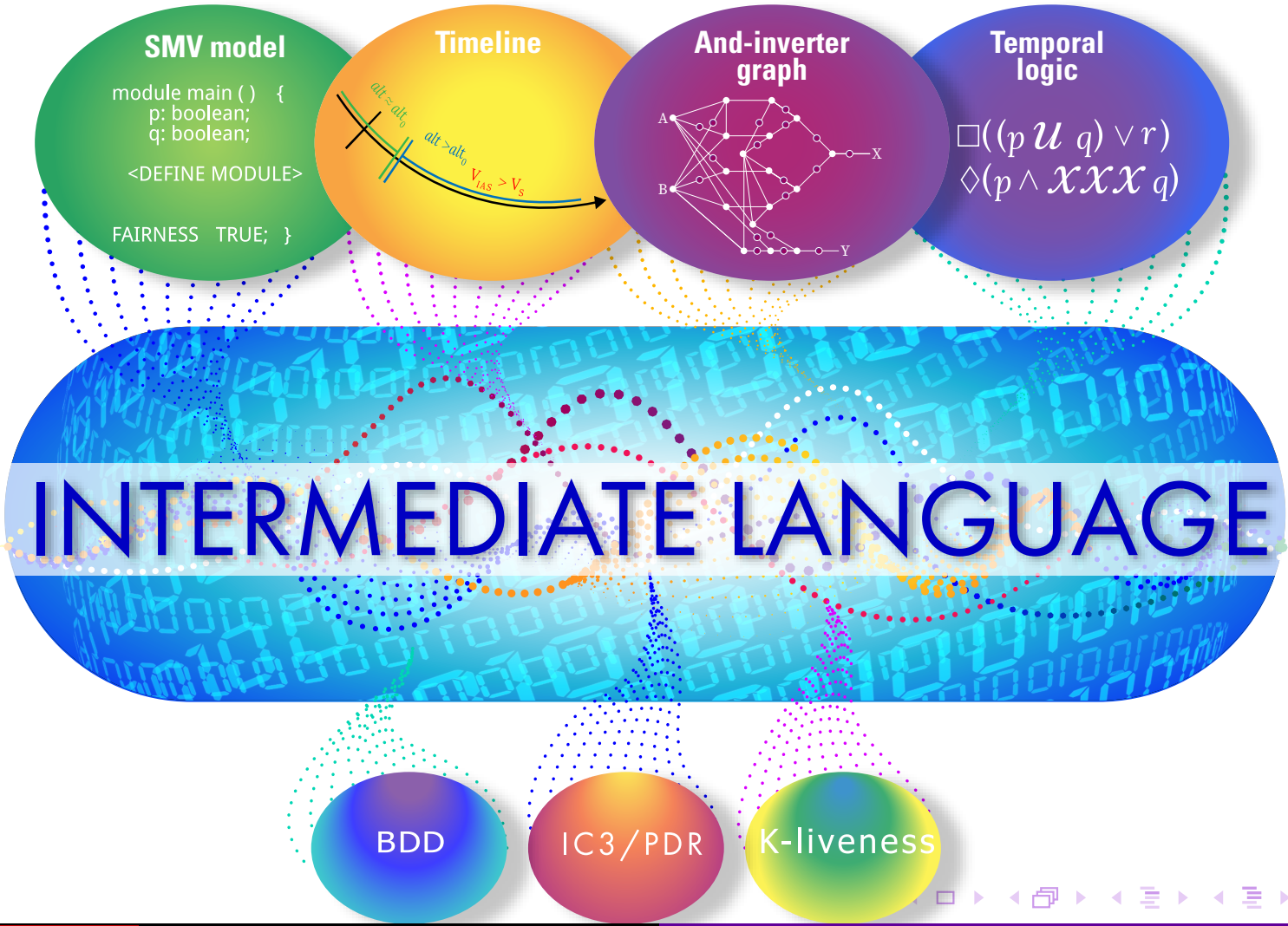
BTOR2



The Problem Continues...

- nuXmv, CadenceSMV, others are **closed source**
- ABC, HWMCC tools are **limited to low-level modeling languages**
- No **open-source, research-enabling connection** between:
  - Rich modeling languages with real-world benchmark models
  - State-of-the-art back-end MC algorithms

MoXI: Model eXchange Interlingua



Goals for Intermediate Language

- Allow adding a **modeling language** via **translation to/from MoXI**
- Allow adding an **MC algorithm** via **translation to/from MoXI**
- MoXI is efficient/accessible so as to **encourage usage in future MCs**
- MoXI: suitable for on-going **community standard**

Basis for MoXI as the Intermediate Language

- **"Best of" previous work**: SMT-LIB, VMT-LIB-Iowa, VMT-LIB-FBK, SAL/Sally, Cryptol, OCRA, synchronous reactive components, ...
- Relatively **simple**, but **complete**
- **Easy to parse**
- Allow **different encodings** (from/to higher/lower levels)

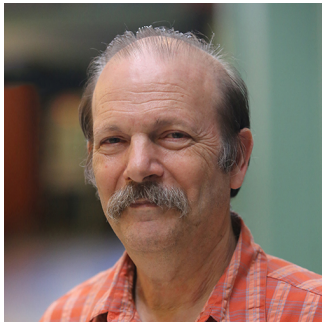
Core Design Team

Investigators:

K.Y. Rozier

Natarajan Shankar

Cesare Tinelli

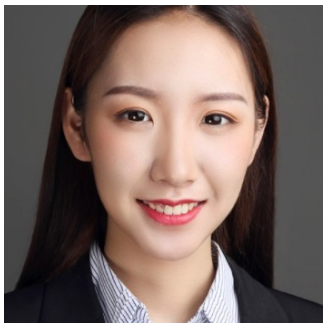


Moshe Vardi

Students:

Laura Gamboa Guzman

Chris Johannsen



Yi Lin

Technical Advisory Board (TAB)

Rajeev Alur (Univ of Pennsylvania)
Clark Barrett (Stanford)
Dirk Beyer (LMU Munich)
Armin Biere (Albert-Ludwigs Univ)
Nikolaj Bjorner (Microsoft Research)
Dimitra Giannakopoulou (Amazon)
Alberto Griggio (FBK)
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Alan Mishchenko (Berkeley)
Karem Sakallah (Univ of Michigan)
Bernhard Steffen (TU Dortmund)
Aaron Tomb (Amazon)
Stefano Tonetta (FBK)

MoXI: Base Logic

- **Many-sorted first-order logic** w/ equality, quantifiers, let binders, algebraic datatypes (like SMT-LIB V2)
- Extention to (first-order) **temporal logic** w/ discrete, linear time, finite & infinite trace-based semantics
- Commands for defining and verifying **multi-component reactive systems**
- Checks for **reachability conditions**, **deadlocks** (indirectly: state & transition invariants)
- Includes **fairness conditions** on system inputs

Language Design Highlights: Transition Systems

Transition system $S = (\ I_S[\boldsymbol{i}, \boldsymbol{o}, \boldsymbol{s}],\quad T_S[\boldsymbol{i}, \boldsymbol{o}, \boldsymbol{s}, \boldsymbol{i'}, \boldsymbol{o'}, \boldsymbol{s'}]\ )$

where

· $\boldsymbol{i}$ and $\boldsymbol{i'}$ are two tuples of *input variables* with the same length and type;
· $\boldsymbol{o}$ and $\boldsymbol{o'}$ are two tuples of *output variables* with the same length and type;
· $\boldsymbol{s}$ and $\boldsymbol{s'}$ are two tuples of *local variables* with the same length and type;
· I_S is the system's *initial state condition*, expressed as a formula with no (free) variables from $\boldsymbol{i'}$, $\boldsymbol{o'}$, and $\boldsymbol{s'}$;
· T_S is the system's *transition condition*, expressed as a formula over the variables $\boldsymbol{i}$, $\boldsymbol{o}$, $\boldsymbol{s}$, $\boldsymbol{i'}$, $\boldsymbol{o'}$, and $\boldsymbol{s'}$.

Language Design Highlights: System Checking Command

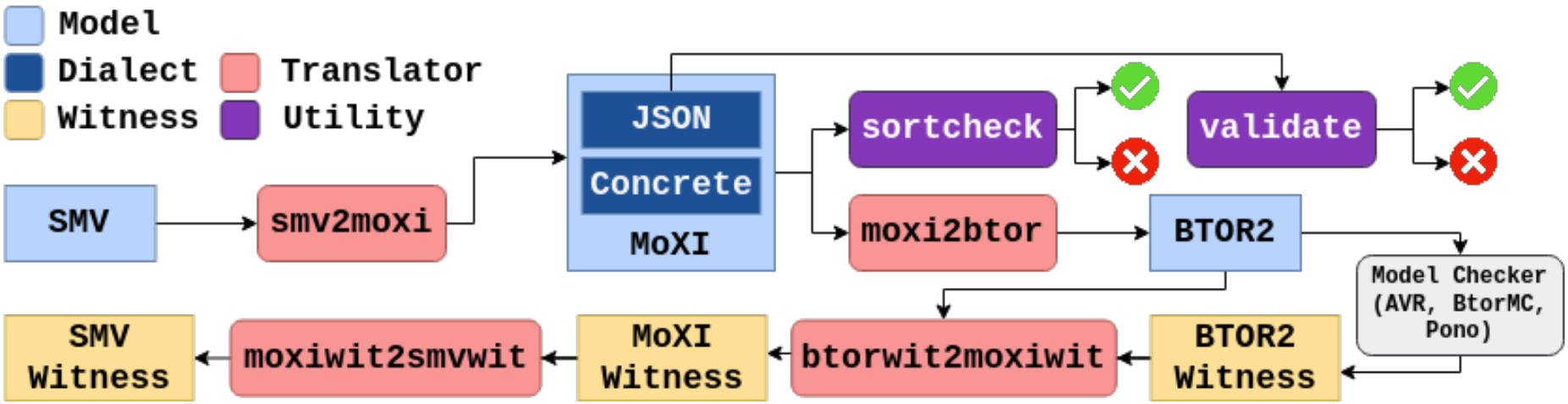
(check-system S
:input ((i_1 δ_1) $\cdots$ (i_m δ_m))
:output ((o_1 τ_1) $\cdots$ (o_n τ_n))
:local ((s_1 σ_1) $\cdots$ (s_p σ_p))
:assumption (a A)
:fairness (f F)
:reachable (r R)
:current (c C)
:query (q (g_1 $\cdots$ g_q))
:queries ((q_1 ($g_{1,1}$ $\cdots$ g_{1,n_1})) $\cdots$ (q_t ($g_{t,1}$ $\cdots$ g_{t,n_t})))
)

Language Design Highlights: Check System Response

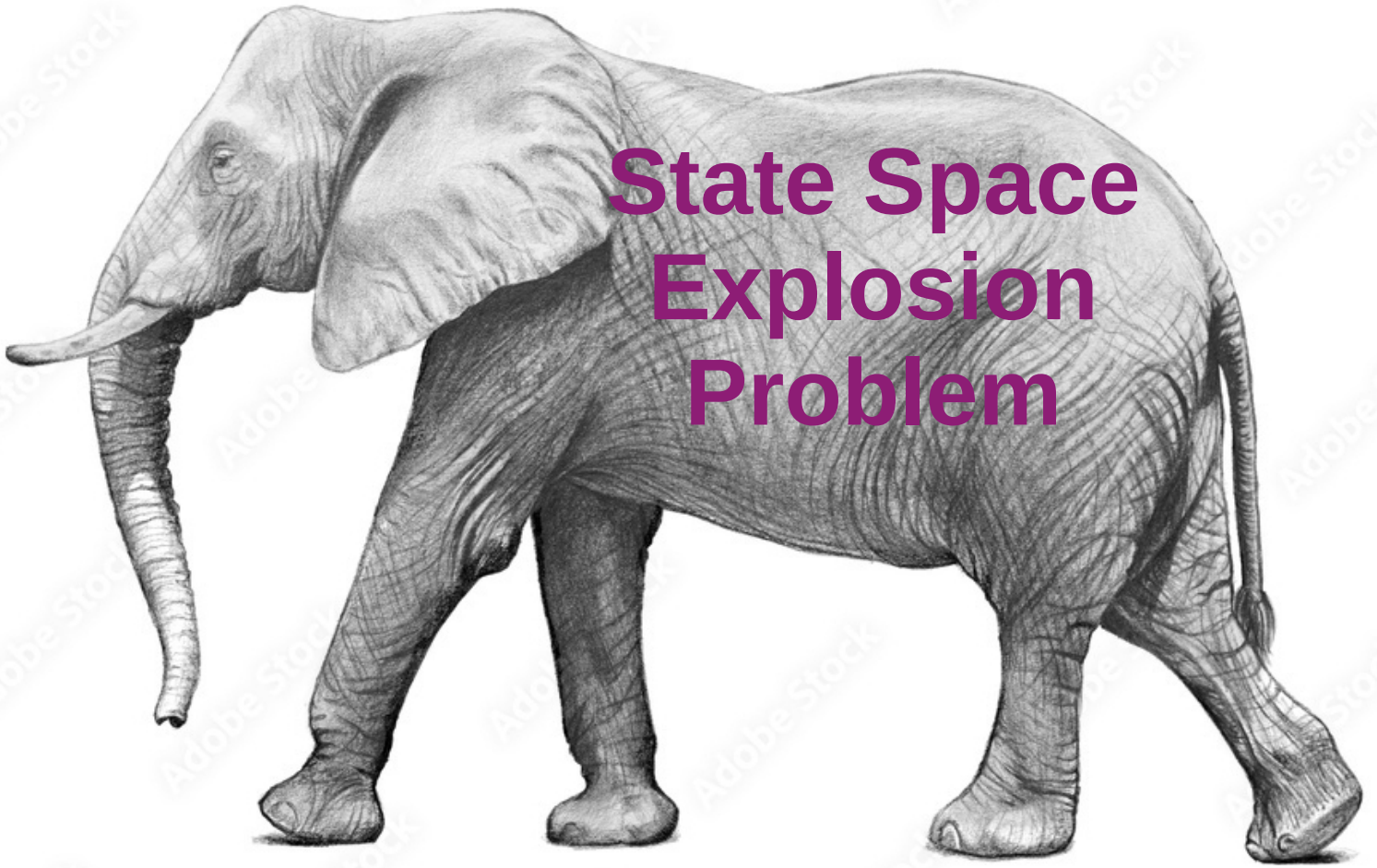
```
(check-system-response
 :query (q1 :result sat :model m :trace t)
 :query (q2 :result unsat :certificate c)
 :query (q3 :result unknown)                    ; for timeouts and other cases
 :trace (t :prefix p :lasso l)                  ; t = pl^omega
 :model (m M)                                   ; M is model in SMT-LIB format

; state/valuation
 :trail (p ( ((i i_0) (o o_0) (s s_0) (r r_0) (f f_0))
               ...
             ((i i_k) (o o_k) (s s_k) (r r_k) (f f_k))
           )
         )
 :trail (l ( ( ... ) ... ( ... ) ))
 :certificate (c :inv F :k n)
)
```

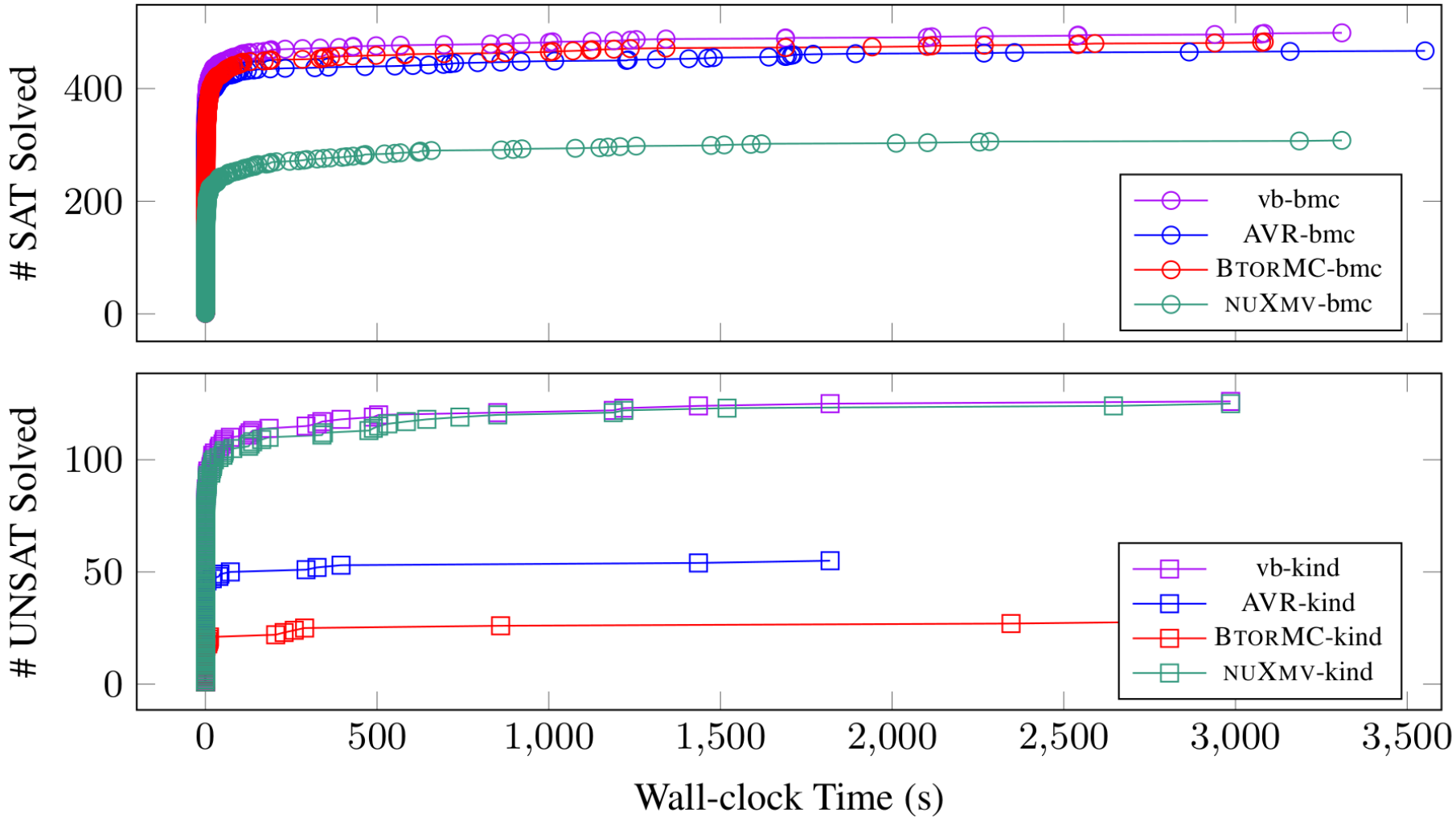
Building the First Translators[11]



[11] C. Johannsen, K. Nukala, R. Dureja, A. Irfan, N. Shankar, C. Tinelli, M. Y. Vardi, K. Y. Rozier. "Symbolic Model-Checking Intermediate-Language Tool Suite." CAV 2024.

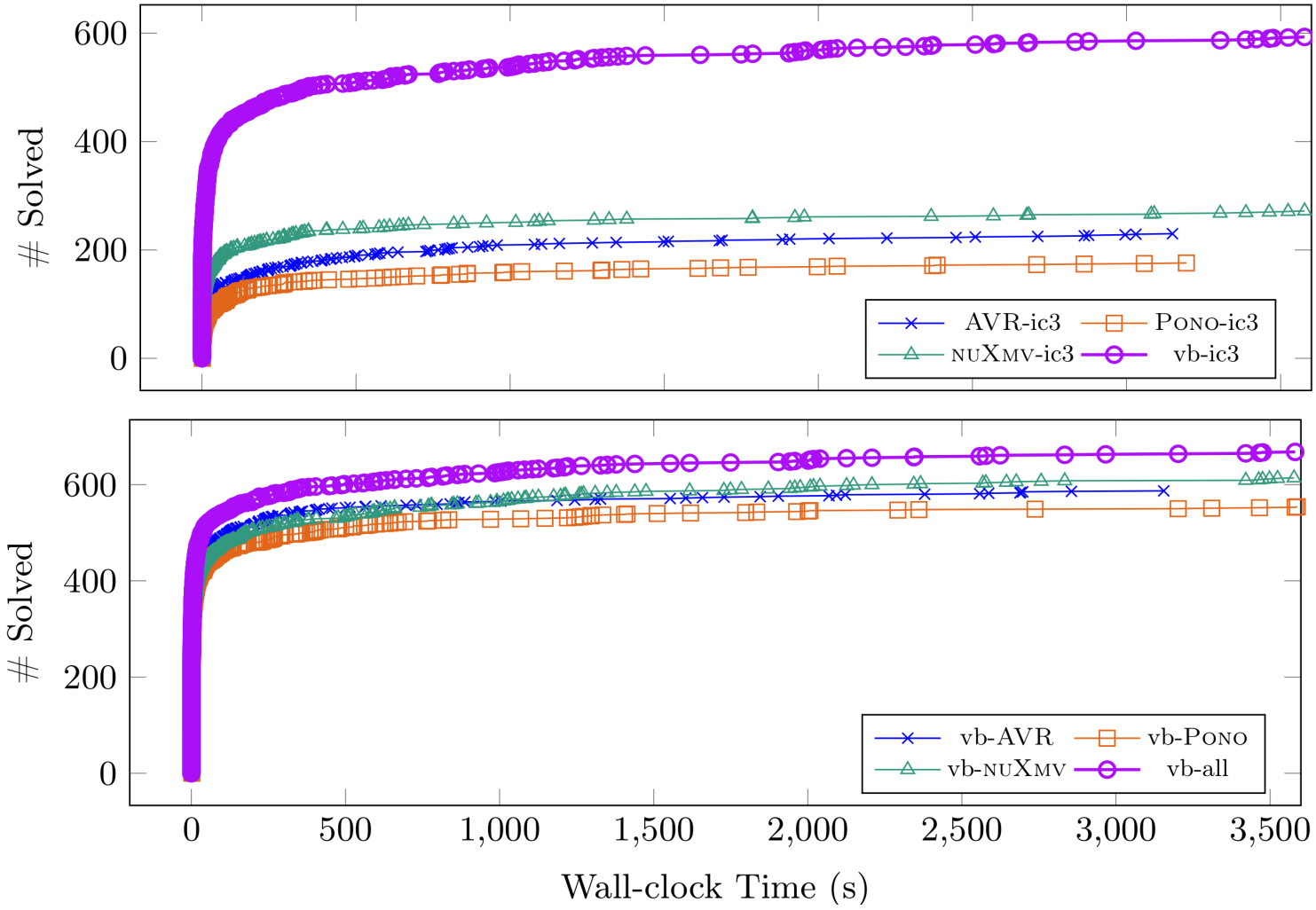

State Space
Explosion
Problem

Experiments: 960 Boolean/word/array SMV Models[12]



[12] C. Johannsen, K. Nukala, R. Dureja, A. Irfan, N. Shankar, C. Tinelli, M. Y. Vardi, K. Y. Rozier. "Symbolic Model-Checking Intermediate-Language Tool Suite." CAV 2024.

960 QF_BV & QF_ABV benchmarks (nuXmv release)[13]



[13] K. Y. Rozier, R. Dureja, A. Irfan, C. Johannsen, K. Nukala, N. Shankar, C. Tinelli, M. Y. Vardi. "MoXI: An Intermediate Language for Symbolic Model Checking." SPIN 2024.

Join the Conversation!

OSSyM

Technical Information | CAV 2024 | Workshop Agenda | Organizational Information

July 23rd 2024

The OSSyM workshop aims to introduce the progress to-date on this collaborative effort and involve the full international research community to reduce barriers to developing new model-checking algorithms and research platforms. The workshop will include tutorials and feedback from the international Model Checking Technical Advisory Board on a design for an extensible framework centering on an intermediate language that will unify popular front-end modeling languages with state-of-the-art back-end model-checking tools.

Open-Source, State-of-the-Art Symbolic Model-Checking Framework for the Model-Checking Research Community

Project Links

Home: https://modelchecker.temporallogic.org

GitHub Organization: https://modelchecker.github.io/

MoXI Language Definition:
https://github.com/ModelChecker/IL/blob/main/description.md

CAV 2024 Workshop: OSSyM:
https://laboratory.temporallogic.org/ossym/

FMCAD 2023 Workshop:
https://github.com/ModelChecker/FMCAD23-Tutorial

SPIN 2024 paper: MoXI semantics:
https://research.temporallogic.org/papers/SPIN2024.pdf

CAV 2024 tool paper: MoXI translators:
https://research.temporallogic.org/papers/CAV2024.pdf
artifact: https://zenodo.org/records/10946779

Summary

The time has come for model-checking community standards

- **Participate:** email list, language design feedback, community forum: **OSSyM@CAV 2024**
- Available Now: **SMV** $\leftrightarrow$ **MoXI** $\leftrightarrow$ **BTOR2**
- **Contribute** future translators:
  - Your Modeling Language $\leftrightarrow$ **MoXI**
  - **MoXI** $\leftrightarrow$ Your Back-end MC Algorithm
  - **MoXI** $\leftrightarrow$ Your Proof Assistant
- **Optimize! Extend! Benchmark! Compare! Research!**

modelchecker.temporallogic.org