

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

Kristin Yvonne Rozier

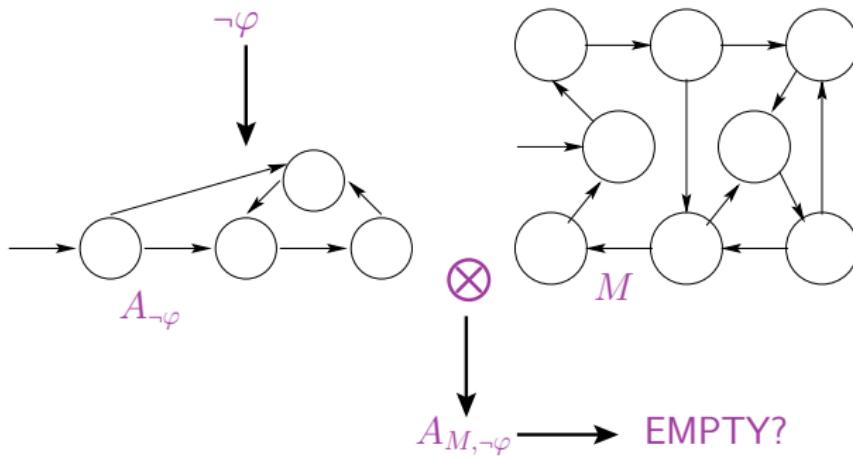
Iowa State University



OSSyM @ CAV

June 23, 2024

Automata-Theoretic Approach to Model Checking¹



¹Vardi, Wolper, LICS, 1986

Small Aircraft Transportation System (SAT)²

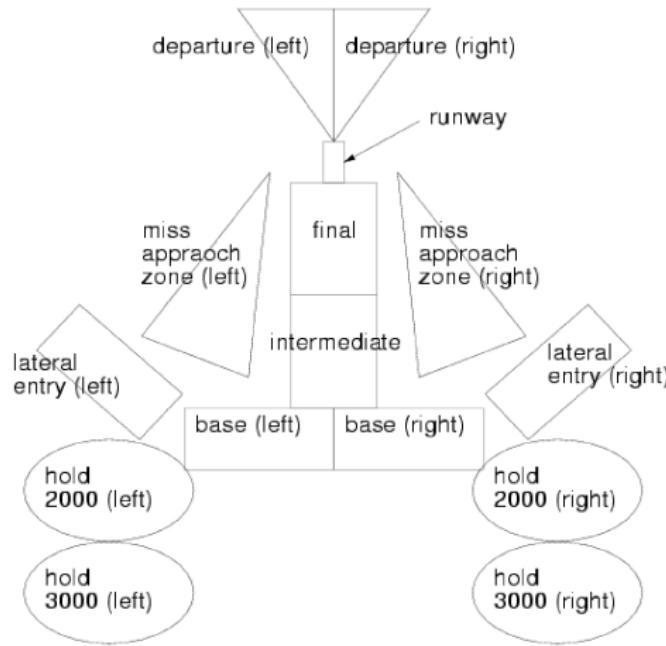


Figure 2. Operational Zones of the SCA.

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

Symbolic Model Checking³

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

1

```
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);  
    module main() {  
        TRANS (EL_X_p_U_q = (next(S_p_U_q) ))  
        p: boolean;  
        FAIRNESS (!S_p_U_q | q)  
        q: boolean;  
        SPEC !(S_p_U_q & EG TRUE) }  
        FAIRNESS TRUE; }
```

symbolic $A_{\neg\psi}$

⊗

universal *M*

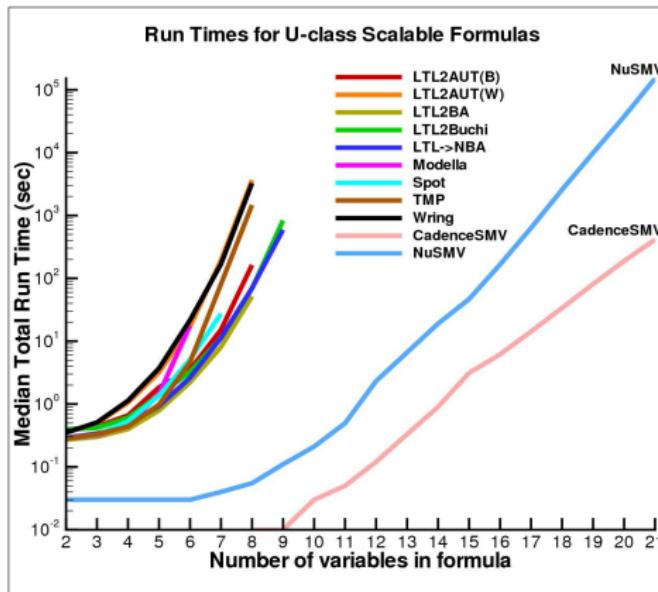
$$A_{M, \neg\varphi}$$

nuXmv:EMPTY?

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

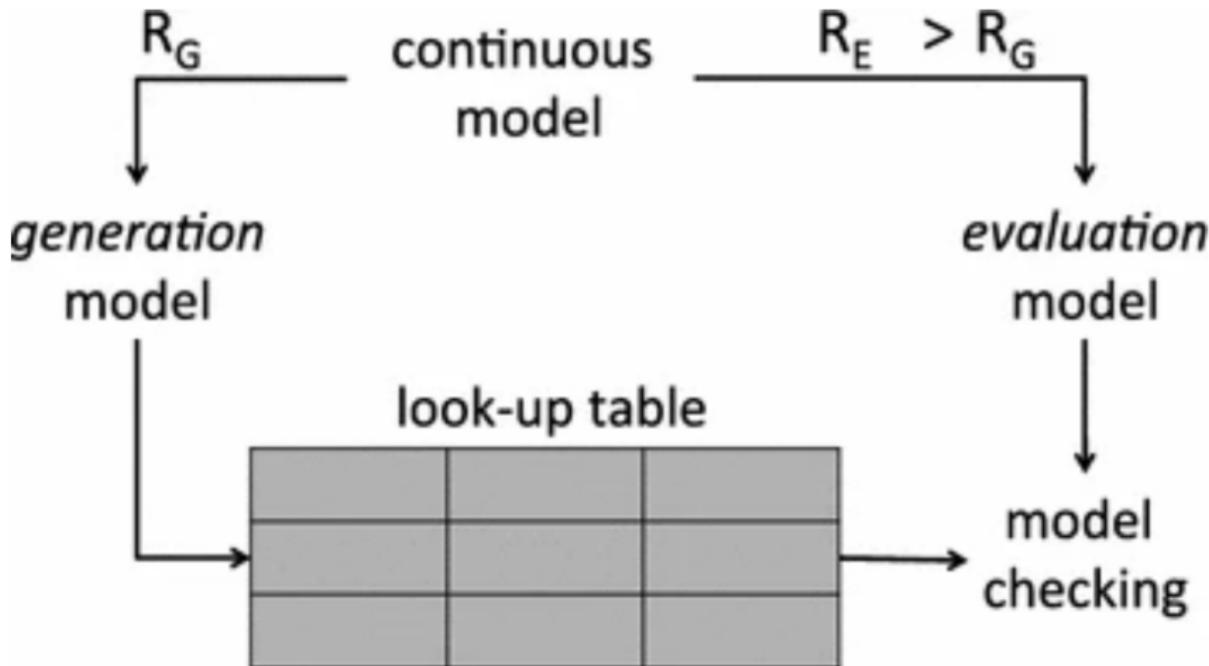
Symbolic Model Checkers in Satisfiability Checking

Symbolic Model Checkers push performance to industrial levels. 4



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

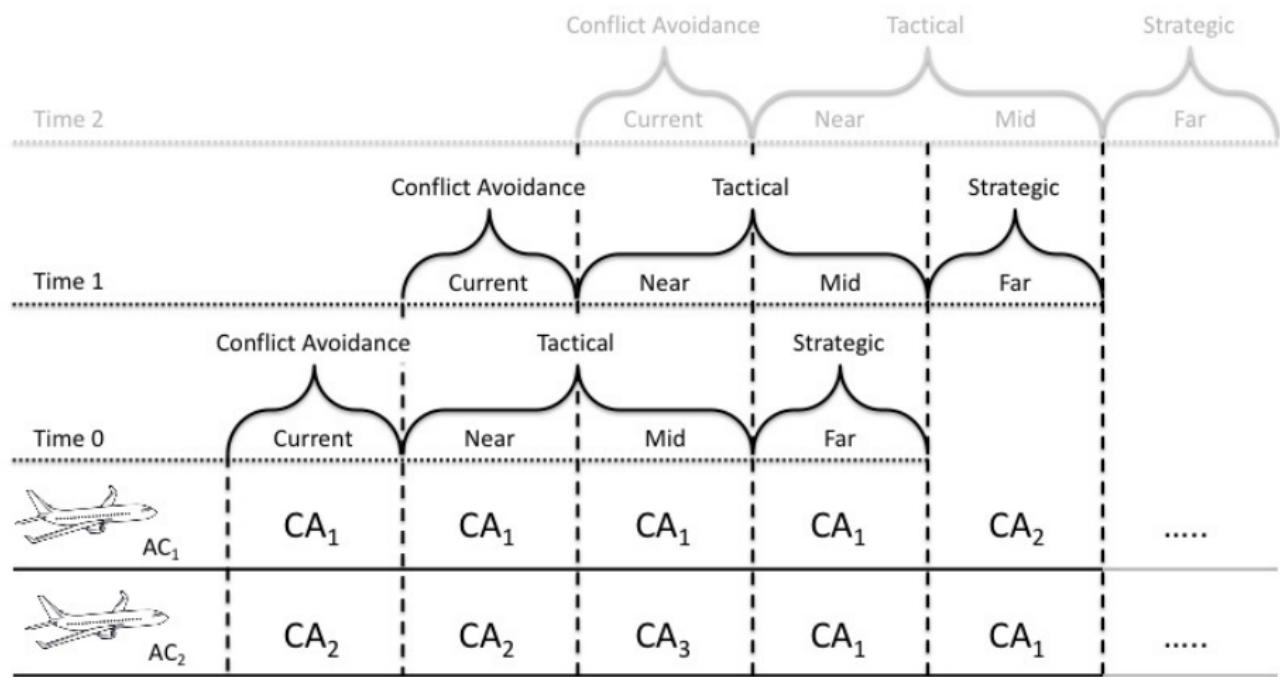
Model Checking ACAS-X Controller⁵



5

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

Formal Modeling: Time Windows⁶



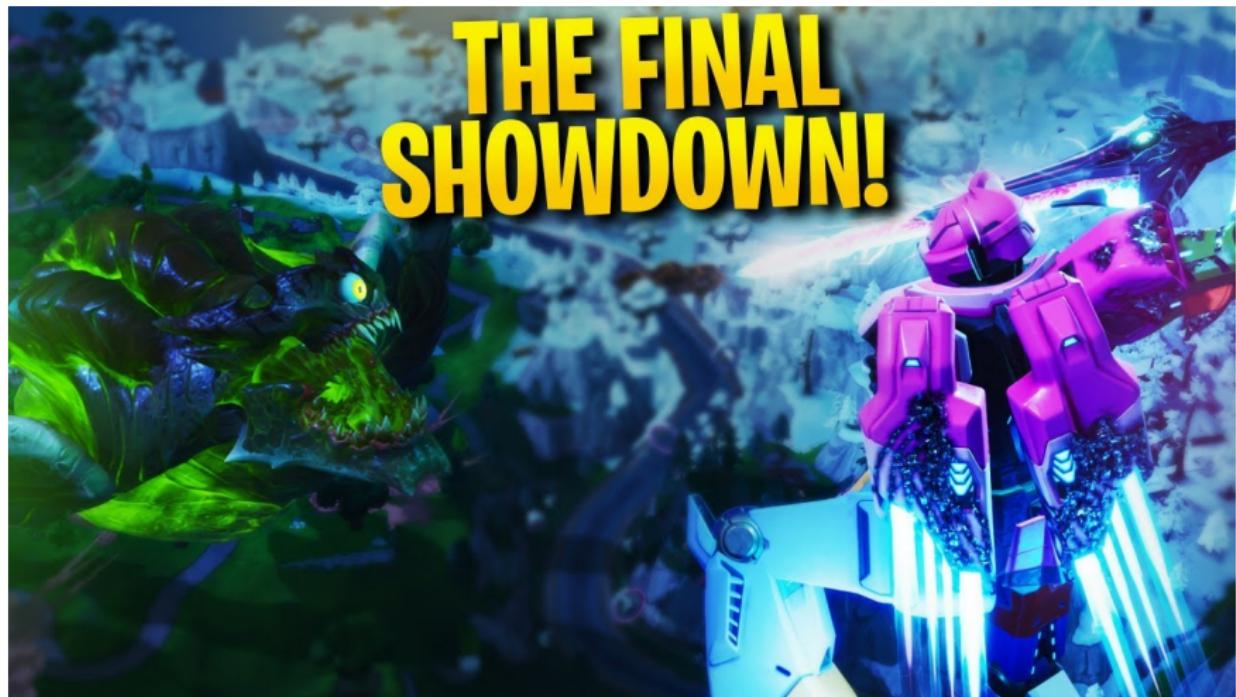
Full-Scale Design Space Verification⁷

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, <i>GSEP, SSEP</i>	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. ▶ ▷ 🔍

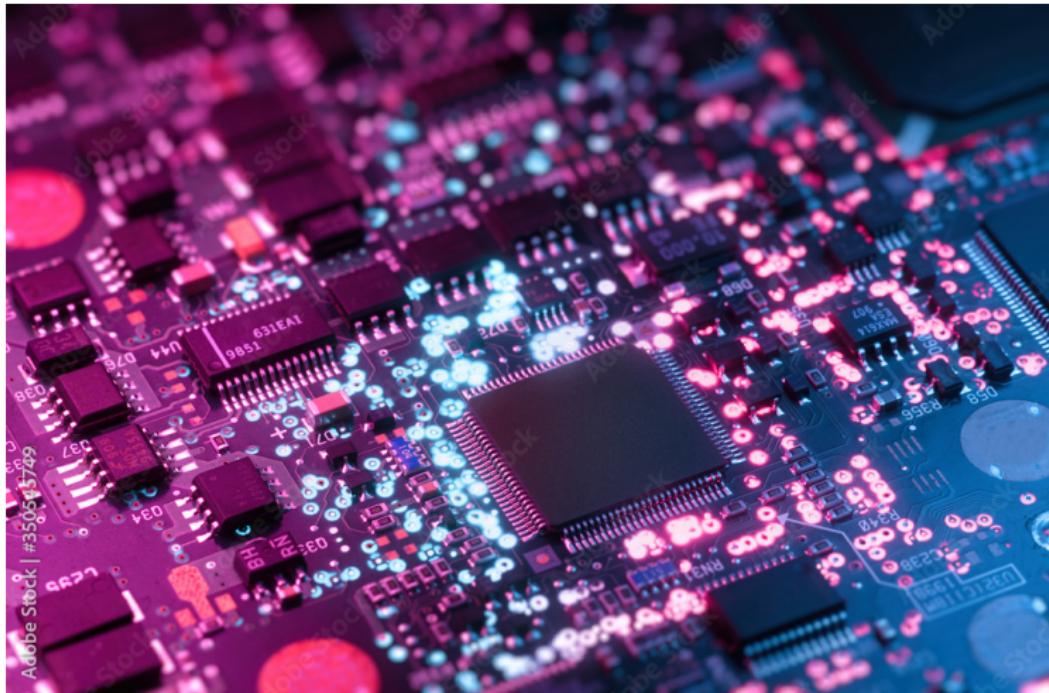
Focusing on Linear Models of Time...⁸



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



Focusing on “Hardware” Model Checking



Evolution of Model-Checking Algorithms

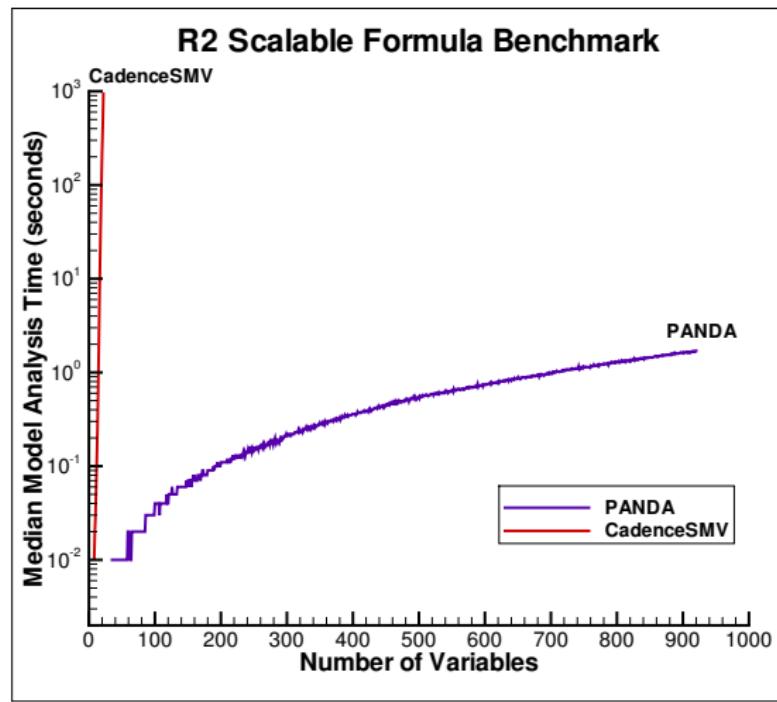
- ➊ BDD-based
- ➋ SAT-based / bounded model checking
- ➌ IC3 / k-liveness

Evolution of Model-Checking Algorithms

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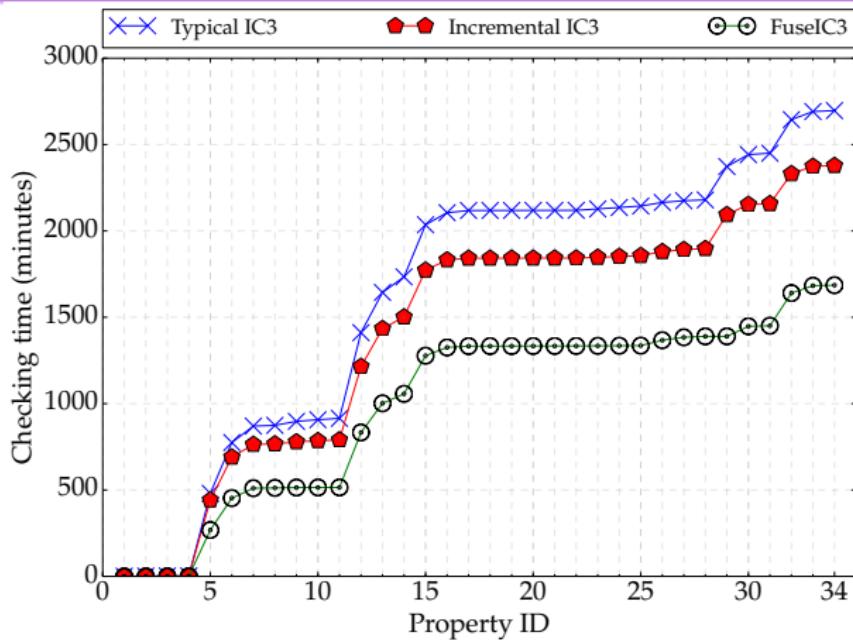
Symbolic model checking progressed from bit-level to word level

The Problem⁹



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 Spaces¹⁰



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

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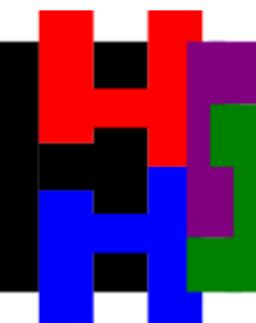
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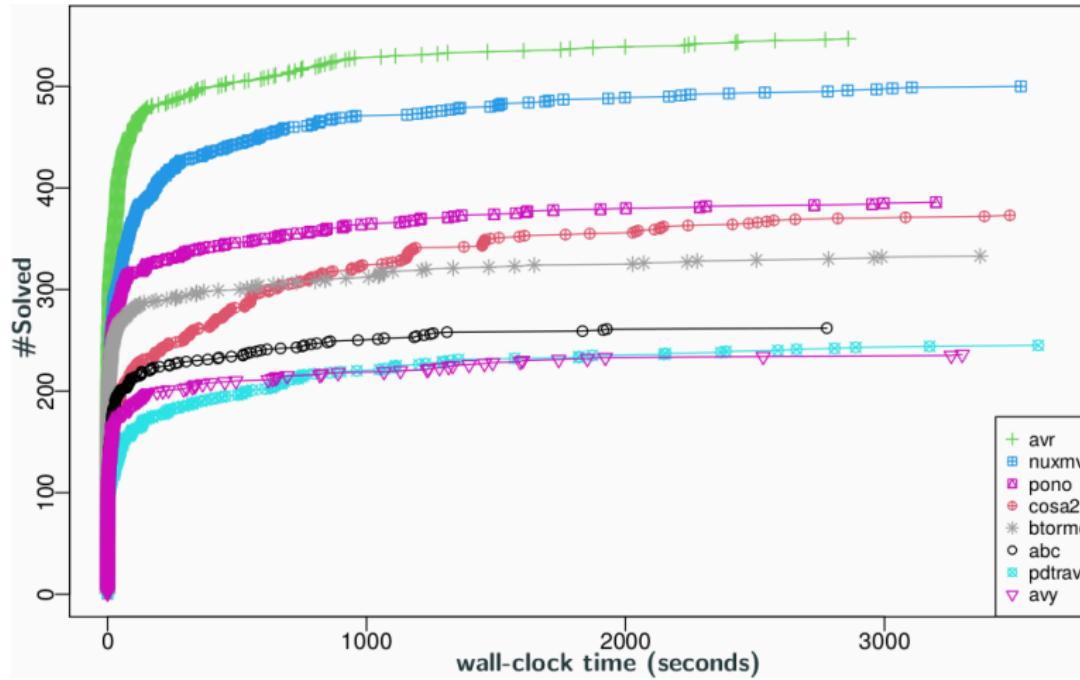
How do we do better?

HWMCC: Hardware Model Checking Competition (2020)



Word-level reasoning

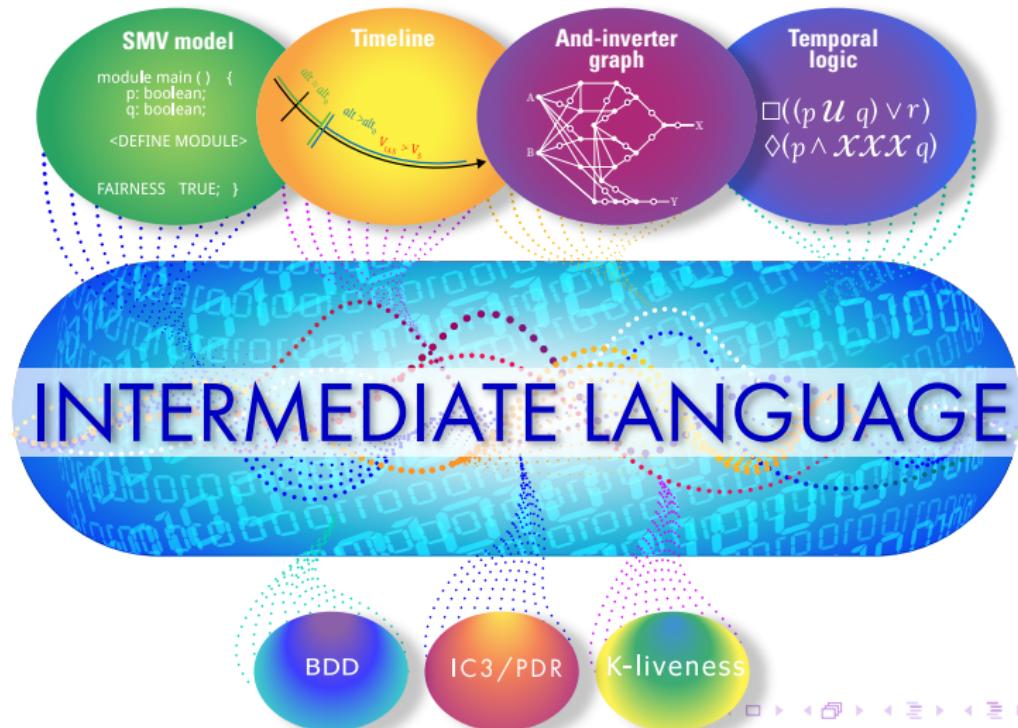
BTOR2



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

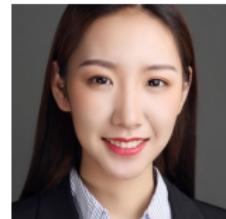
Students:



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Chris Johannsen



Yi Lin

Technical Advisory Board (TAB)

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Armin Biere (Albert-Ludwigs Univ)

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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)
- Extension 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 $S = (I_S[i, o, s], \quad T_S[i, o, s, i', o', s'])$

where

- i and i' are two tuples of *input variables* with the same length and type;
- o and o' are two tuples of *output variables* with the same length and type;
- s and 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 i' , o' , and s' ;
- T_S is the system's *transition condition*, expressed as a formula over the variables i , o , s , i' , o' , and s' .

Language Design Highlights: System Checking Command

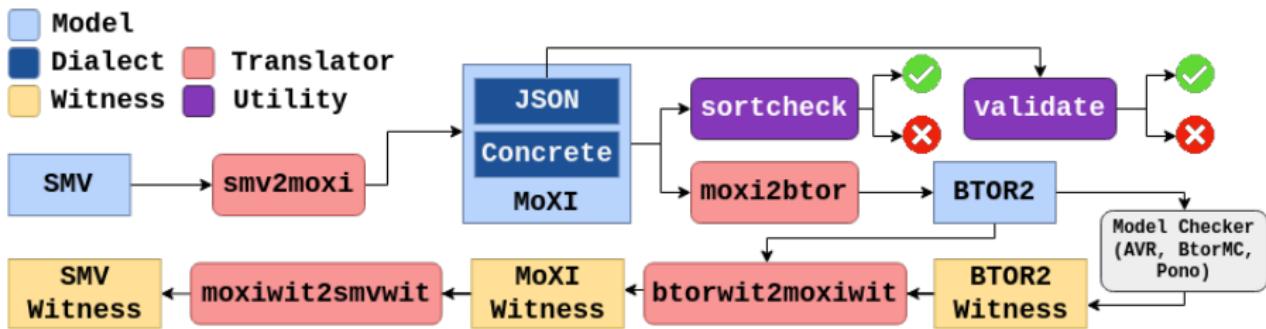
```
(check-system  $S$ 
  :input ( (  $i_1 \delta_1$  )  $\cdots$  (  $i_m \delta_m$  ) )
  :output ( (  $o_1 \tau_1$  )  $\cdots$  (  $o_n \tau_n$  ) )
  :local ( (  $s_1 \sigma_1$  )  $\cdots$  (  $s_p \sigma_p$  ) )
  :assumption (  $a A$  )
  :fairness (  $f F$  )
  :reachable (  $r R$  )
  :current (  $c C$  )
  :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

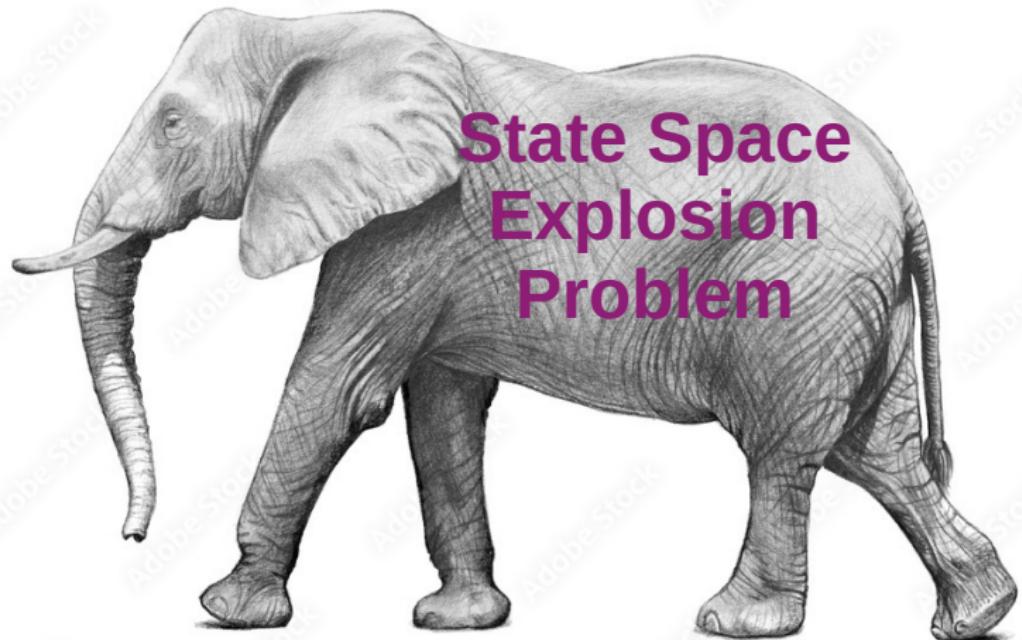
```
(check-system-response
:query (q1 :result sat :model m :trace t)
:query (q2 :result unsat :certificate c)
:query (q3 :result unknown) ; for timeouts and other cases
:trace (t :prefix p :lasso l) ; t = pl^omega
:model (m M) ; M is model in SMT-LIB format

; 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)
)
```

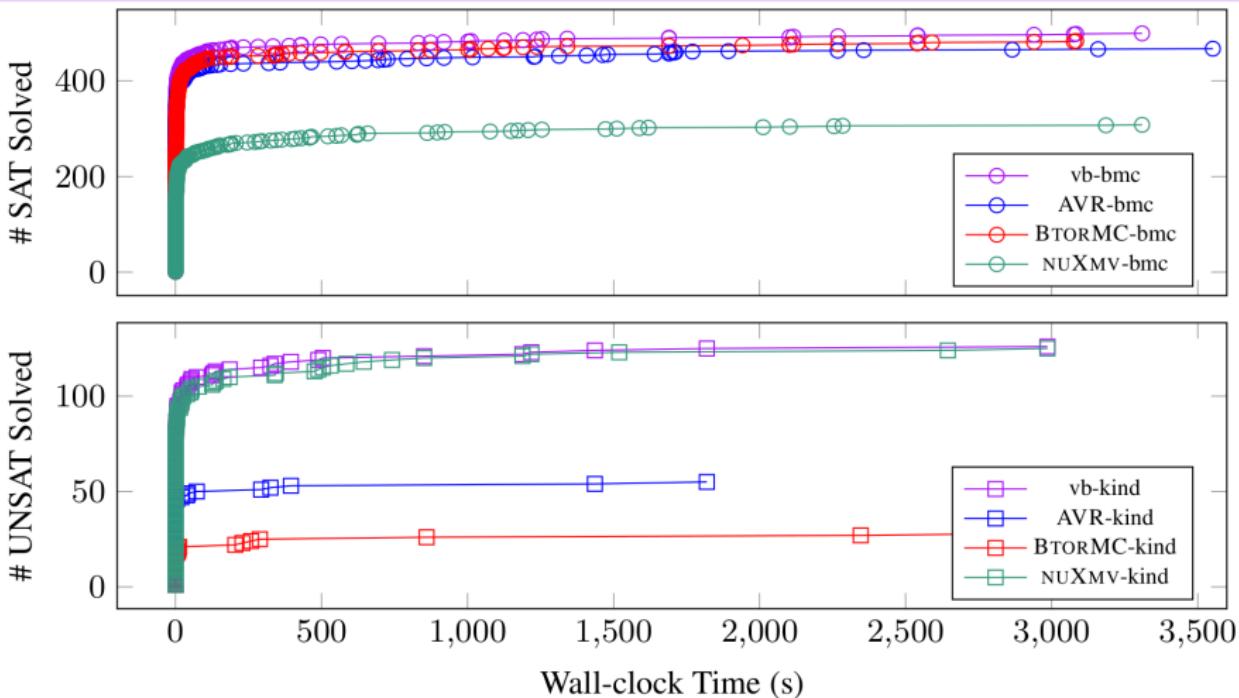
Building the First Translators¹¹



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.

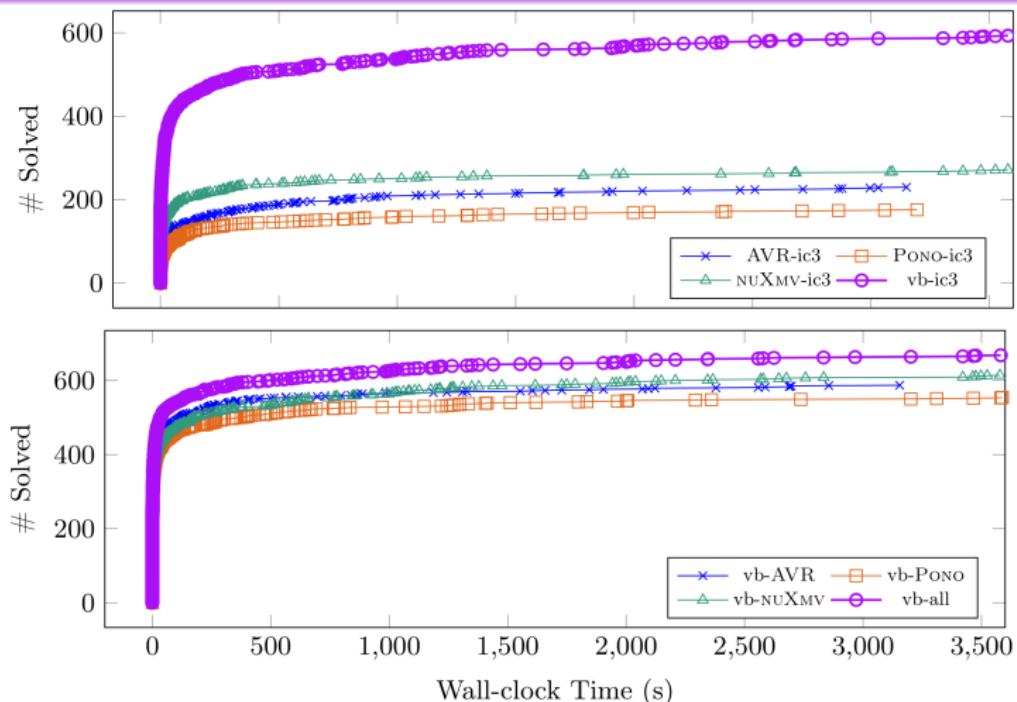


Experiments: 960 Boolean/word/array SMV Models¹²



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

