

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

Kristin Yvonne Rozier

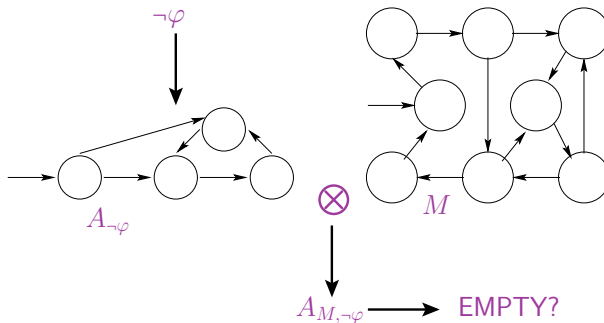
Iowa State University



OSSyM @ CAV

June 23, 2024

Automata-Theoretic Approach to Model Checking¹



¹Vardi, Wolper, LICS, 1986

Small Aircraft Transportation System (SAT)²

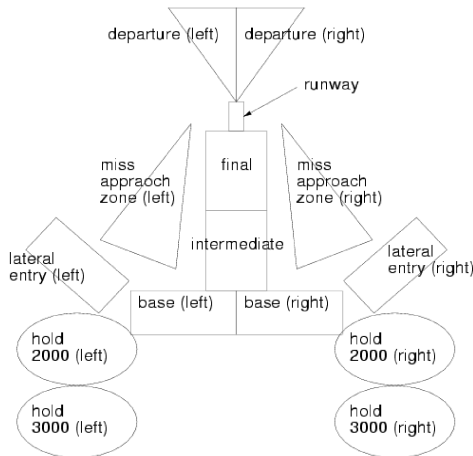


Figure 2. Operational Zones of the SCA.

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

Symbolic Model Checking³

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



```

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) }

```

symbolic $A_{\neg\varphi}$



universal M

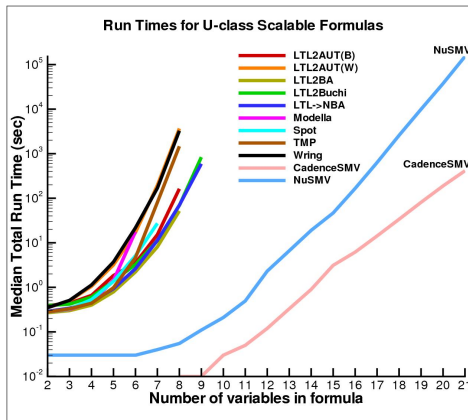


$A_{M, \neg\varphi} \longrightarrow \text{nuXmv:EMPTY?}$

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

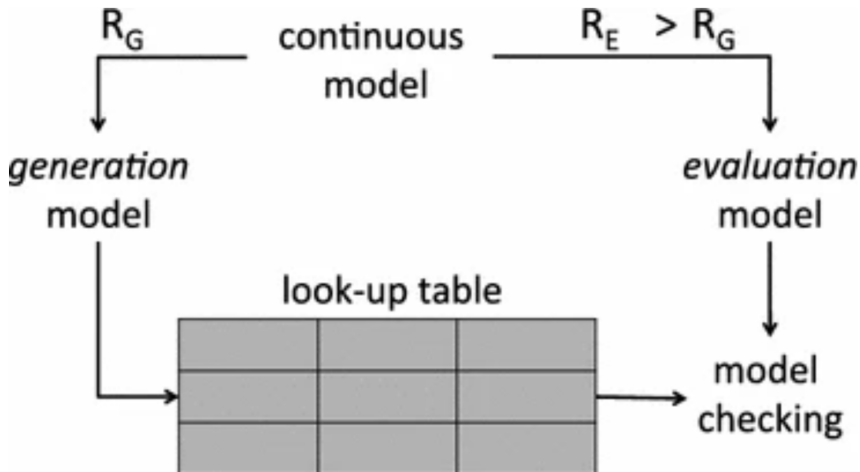
Symbolic Model Checkers in Satisfiability Checking

Symbolic Model Checkers push performance to industrial levels. ⁴



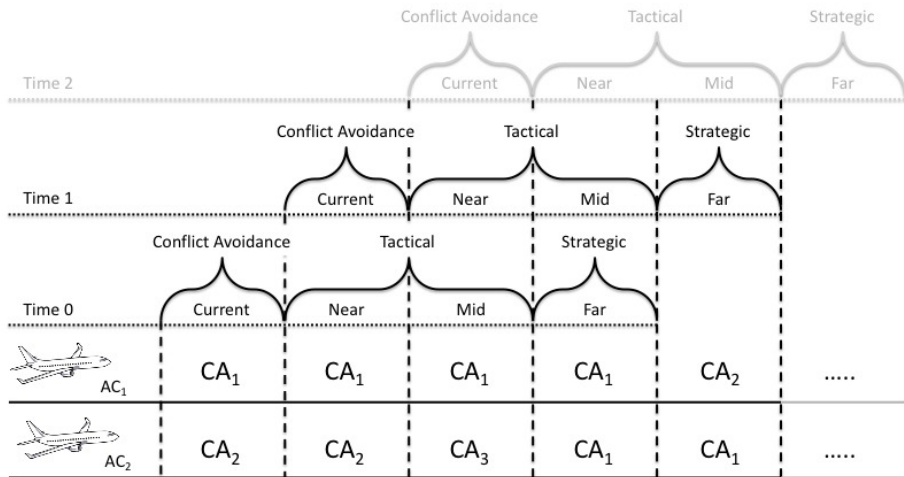
⁴Rozier and Vardi, “LTL Satisfiability Checking.” SPIN’07.

Model Checking ACAS-X Controller⁵



⁵ 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</i> , <i>SSEP</i>	3
ACDR Implementations	Simple, Asymmetric, Non-Receptive	3
Com Steps	1, 2, ...	2
TOTAL	-	20,250
Focus group	-	1,620

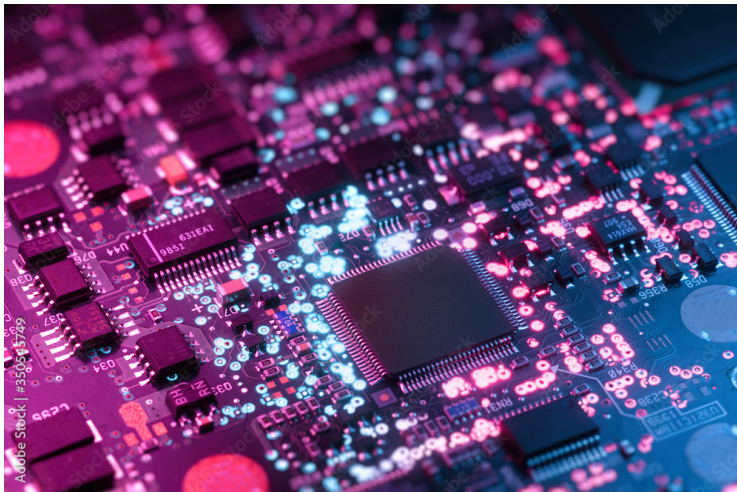
⁷ Marco Gario, Alessandro Cimatti, Cristian Mattarei, Stefano Tonetta and Kristin Y. Rozier. "Model Checking at Scale: Automated Air Traffic Control Design Space Exploration." In *Computer Aided Verification (CAV)*, 2016. ▶ ◀ ≡ ≡ ≡ 🔍 ↺

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

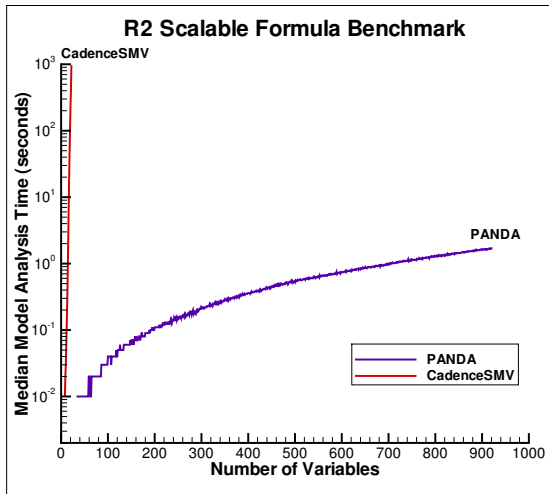
- 1 BDD-based
- 2 SAT-based / bounded model checking
- 3 IC3 / k-liveness

Evolution of Model-Checking Algorithms

- ① BDD-based
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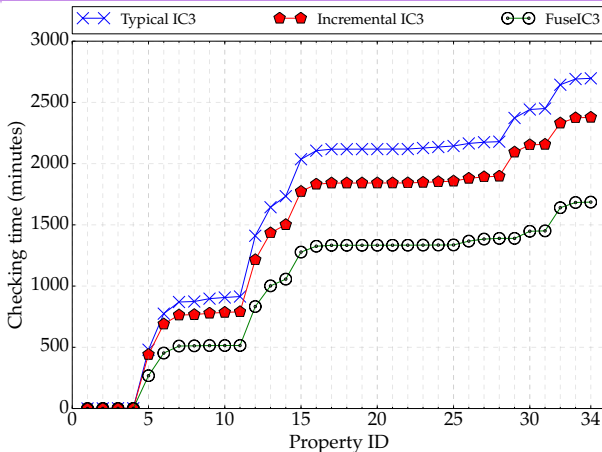
Symbolic model checking progressed from bit-level to word level

The Problem⁹



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

FuselC3: 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. "FuselC3: 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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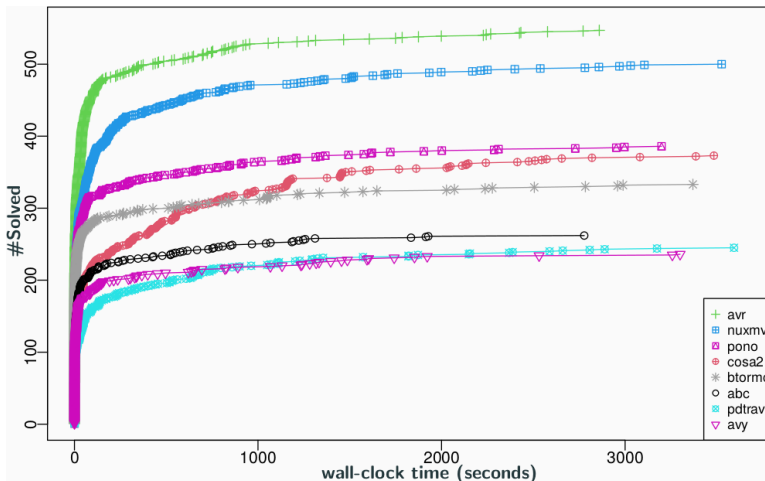
How do we do better?

HWMCC: Hardware Model Checking Competition (2020)



Word-level
reasoning

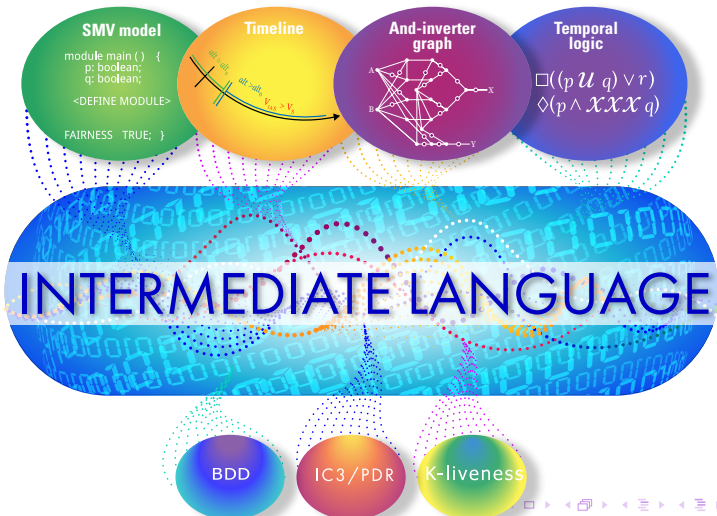
BTOR2



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

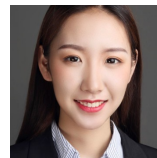
Students:



Laura Gamboa Guzman



Chris Johannsen



Yi Lin

Technical Advisory Board (TAB)

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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 $S = (I_S[i, o, s], T_S[i, o, s, i', o', s'])$

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

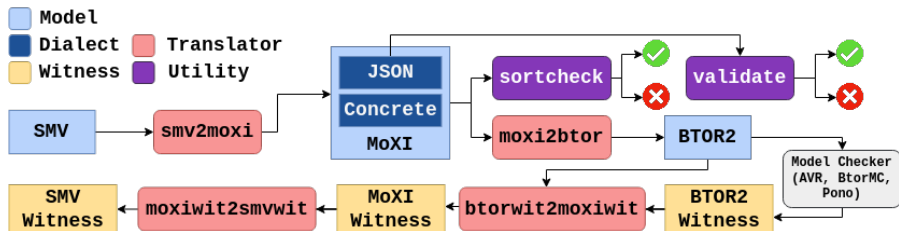
```
(check-system S
  :input ( (  $i_1$   $\delta_1$  )  $\cdots$  (  $i_m$   $\delta_m$  ) )
  :output ( (  $o_1$   $\tau_1$  )  $\cdots$  (  $o_n$   $\tau_n$  ) )
  :local ( (  $s_1$   $\sigma_1$  )  $\cdots$  (  $s_p$   $\sigma_p$  ) )
  :assumption (  $a$   $A$  )
  :fairness (  $f$   $F$  )
  :reachable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

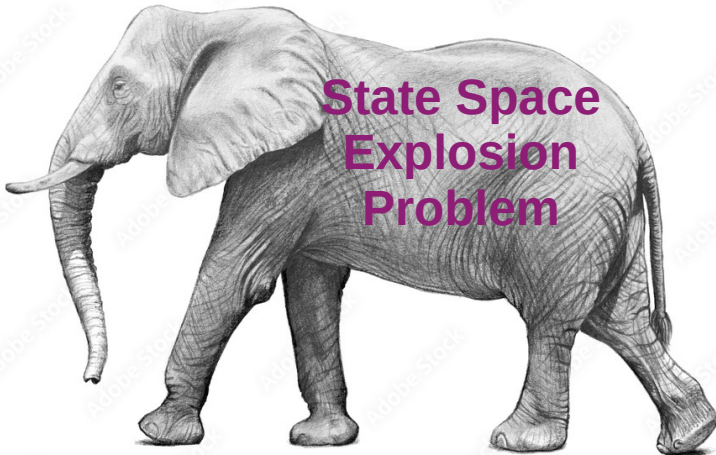
```
(check-system-response
 :query (q1 :result sat :model m :trace t)
 :query (q2 :result unsat :certificate c)
 :query (q3 :result unknown)           ; for timeouts and other cases
 :trace (t :prefix p :lasso l)         ; t = plomega
 :model (m M)                          ; M is model in SMT-LIB format

; 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)
)
```

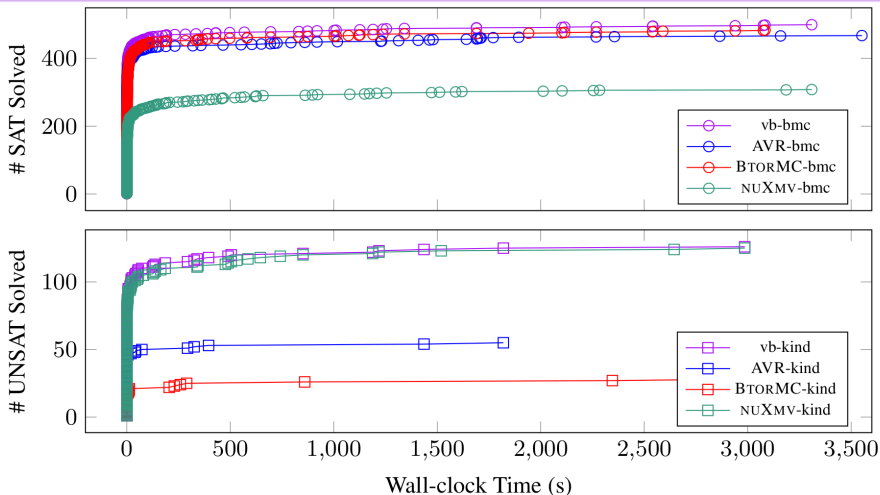
Building the First Translators¹¹



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.

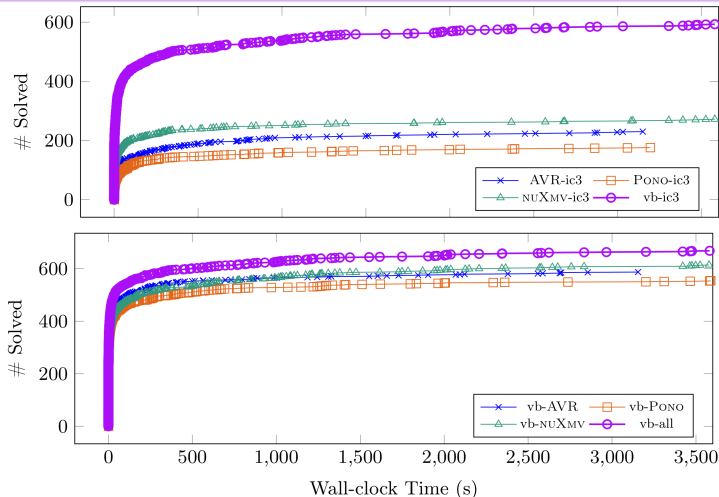


Experiments: 960 Boolean/word/array SMV Models¹²



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



¹³K. 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** ↔ **MoXI** ↔ **BTOR2**
- **Contribute** future translators:
 - Your Modeling Language ↔ **MoXI**
 - **MoXI** ↔ Your Back-end MC Algorithm
 - **MoXI** ↔ Your Proof Assistant
- **Optimize! Extend! Benchmark! Compare! Research!**

modelchecker.temporallogic.org