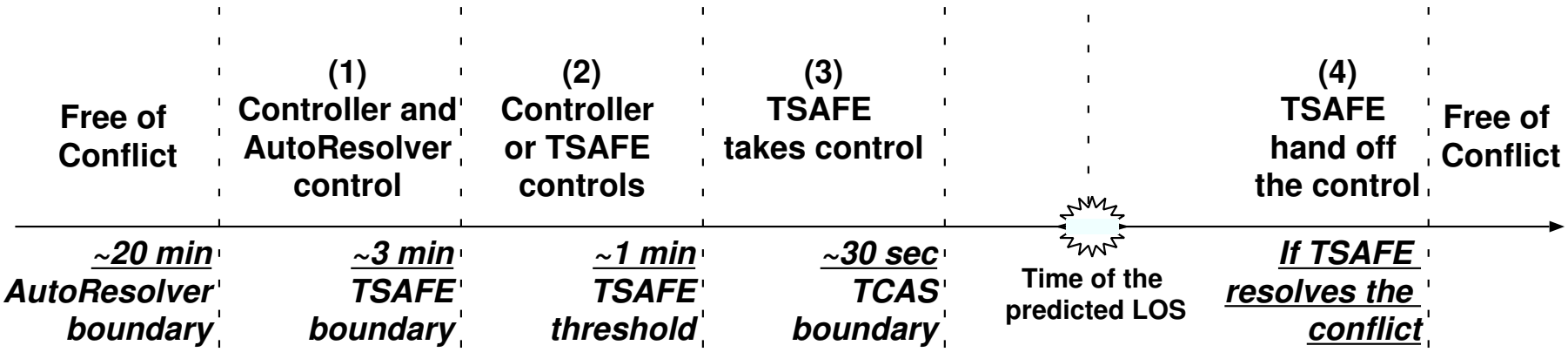
Challenges in Tool Integration: Making Formal Methods Universal

Kristin Yvonne Rozier
Iowa State University

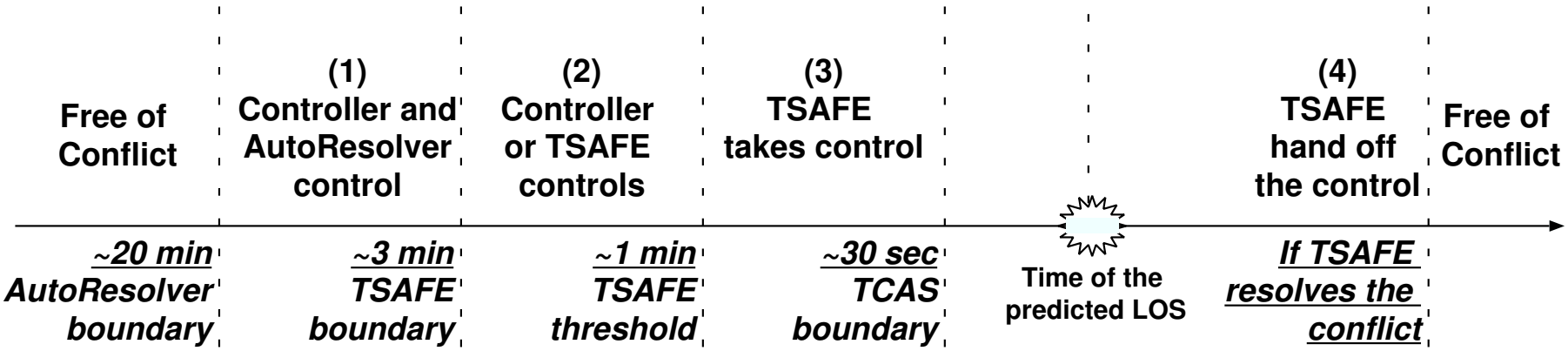
5th Workshop on Cooperative Software Verification (COOP)
April 7, 2024

AAC Operational Concept[1]



[1] H Erzberger, K Heere. "Algorithm and operational concept for resolving short-range conflicts." Proc. IMechE G J. Aerosp. Eng. 224 (2) (2010) 225–243.

AAC Operational Concept[2]



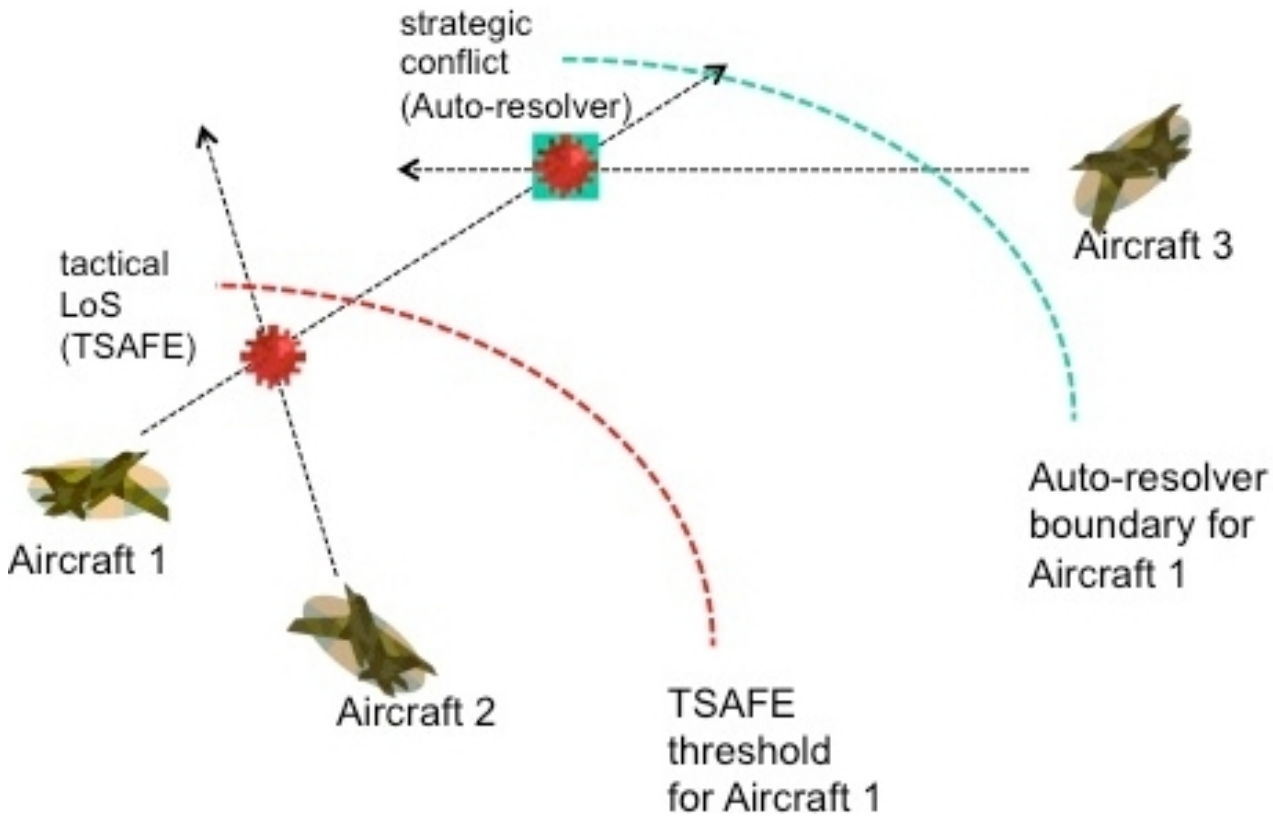
LTL Model Checking triggered system design changes[1]

[1] Y. Zhao and K.Y. Rozier. "Formal Specification and Verification of a Coordination Protocol for an Automated Air Traffic Control System." SCP Journal, vol-96, no-3, pg 337-353, 2014.

[2] H Erzberger, K Heere. "Algorithm and operational concept for resolving short-range conflicts." Proc. IMechE G J. Aerosp. Eng. 224 (2) (2010) 225–243.

Counterexample

Specification: "If the controller hands off the control of an aircraft to TSAFE, this aircraft will not execute commands from the controller or Autoresolver."



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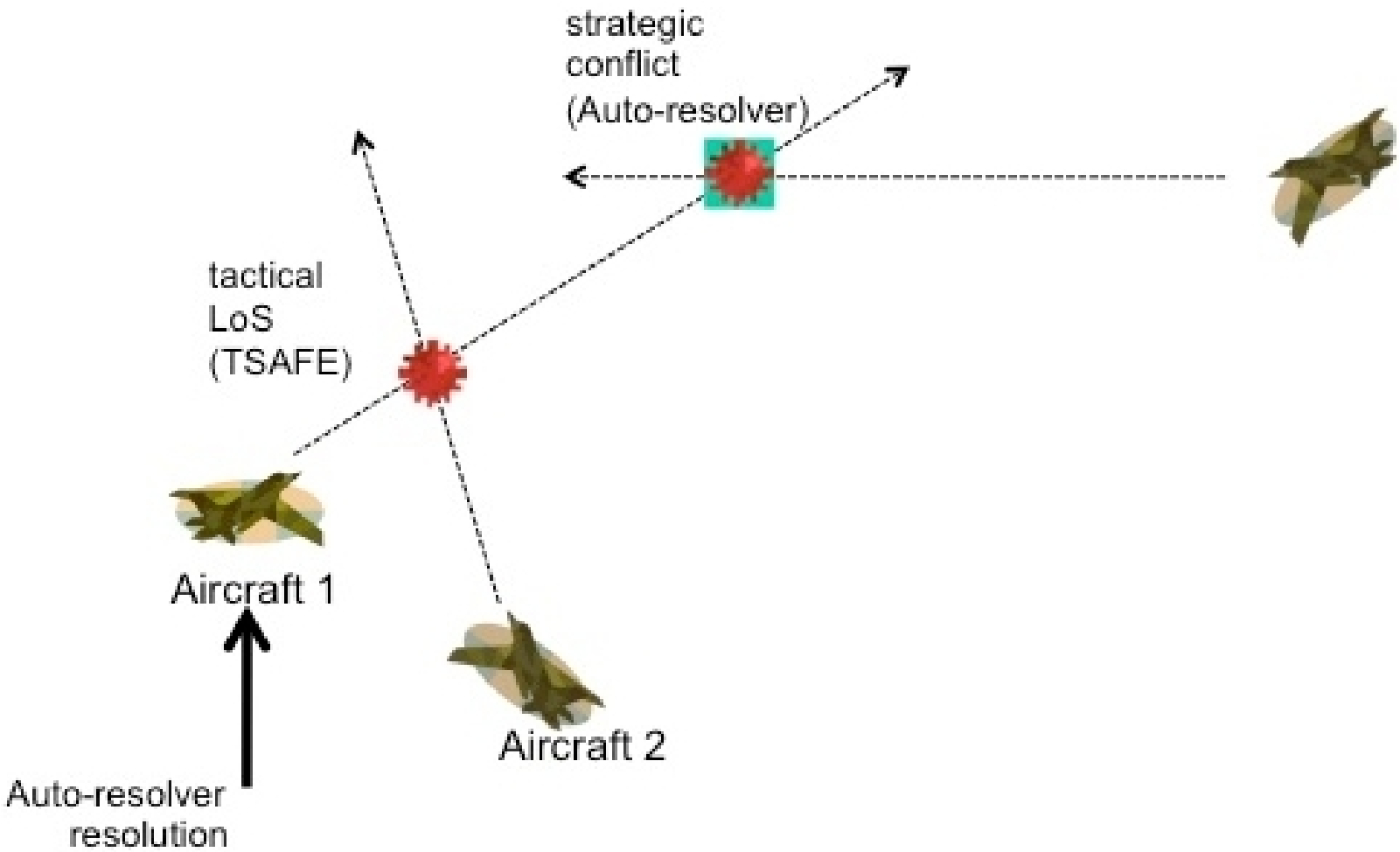

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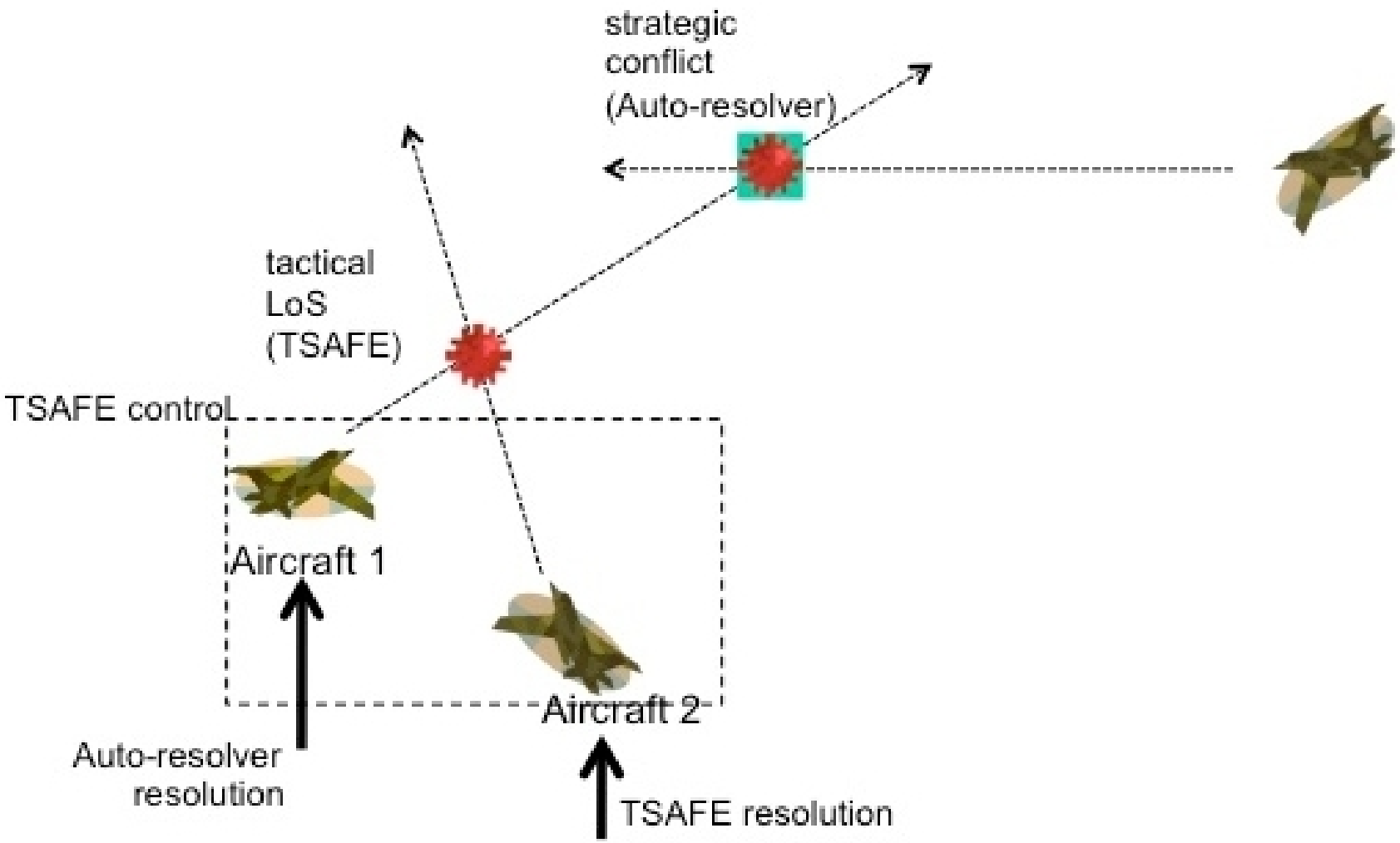
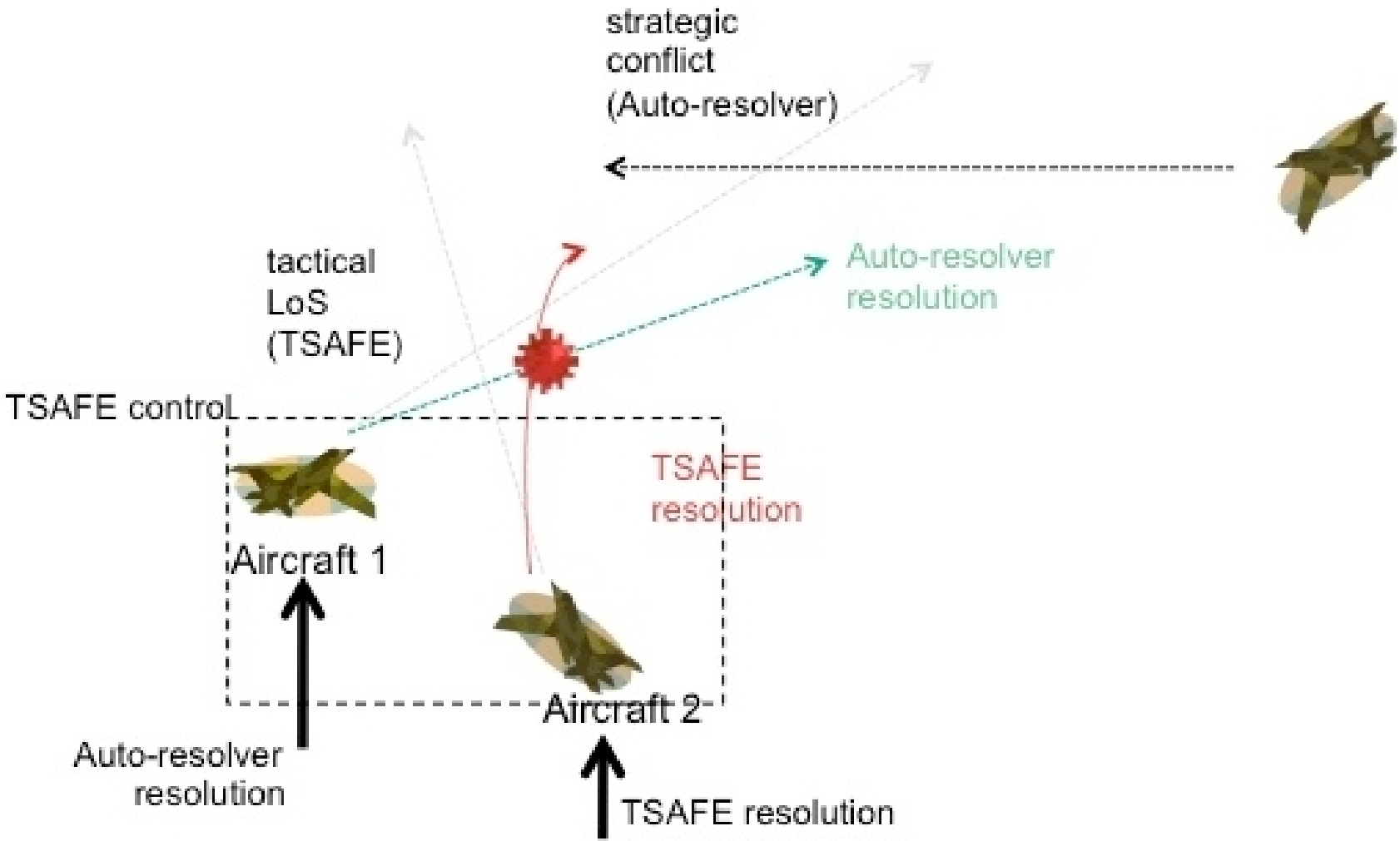


Counterexample



Counterexample: Fixed![3]

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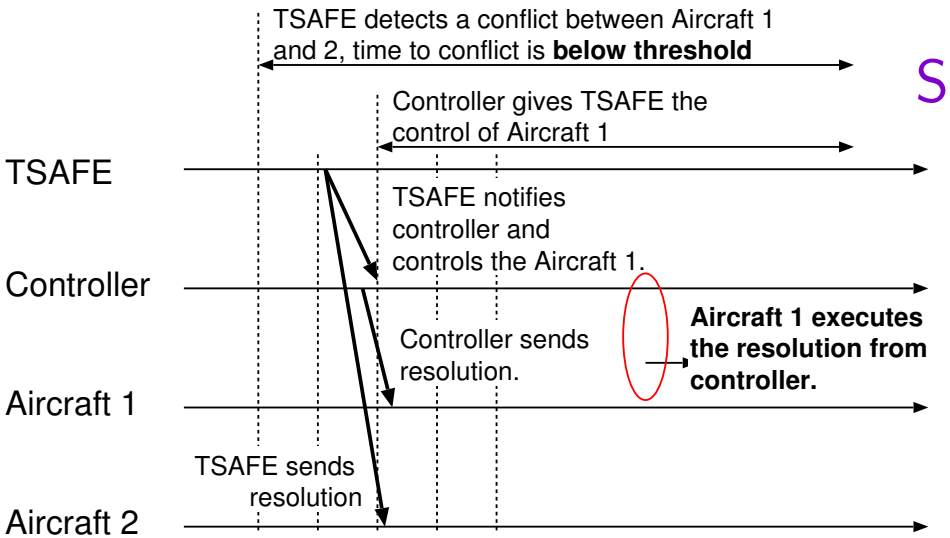
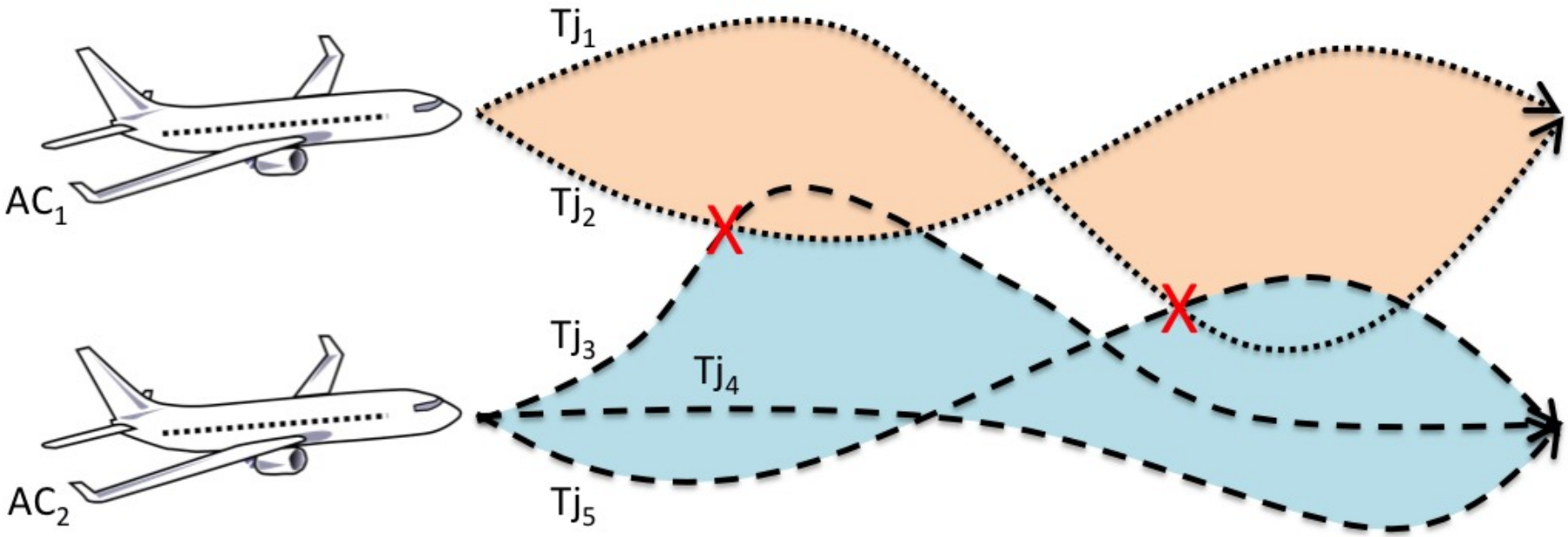


Solution:

- A1 receives notice of control transfer and "hold current route" resolution from TSAFE
- AR/controller's command will be superseded and ignored

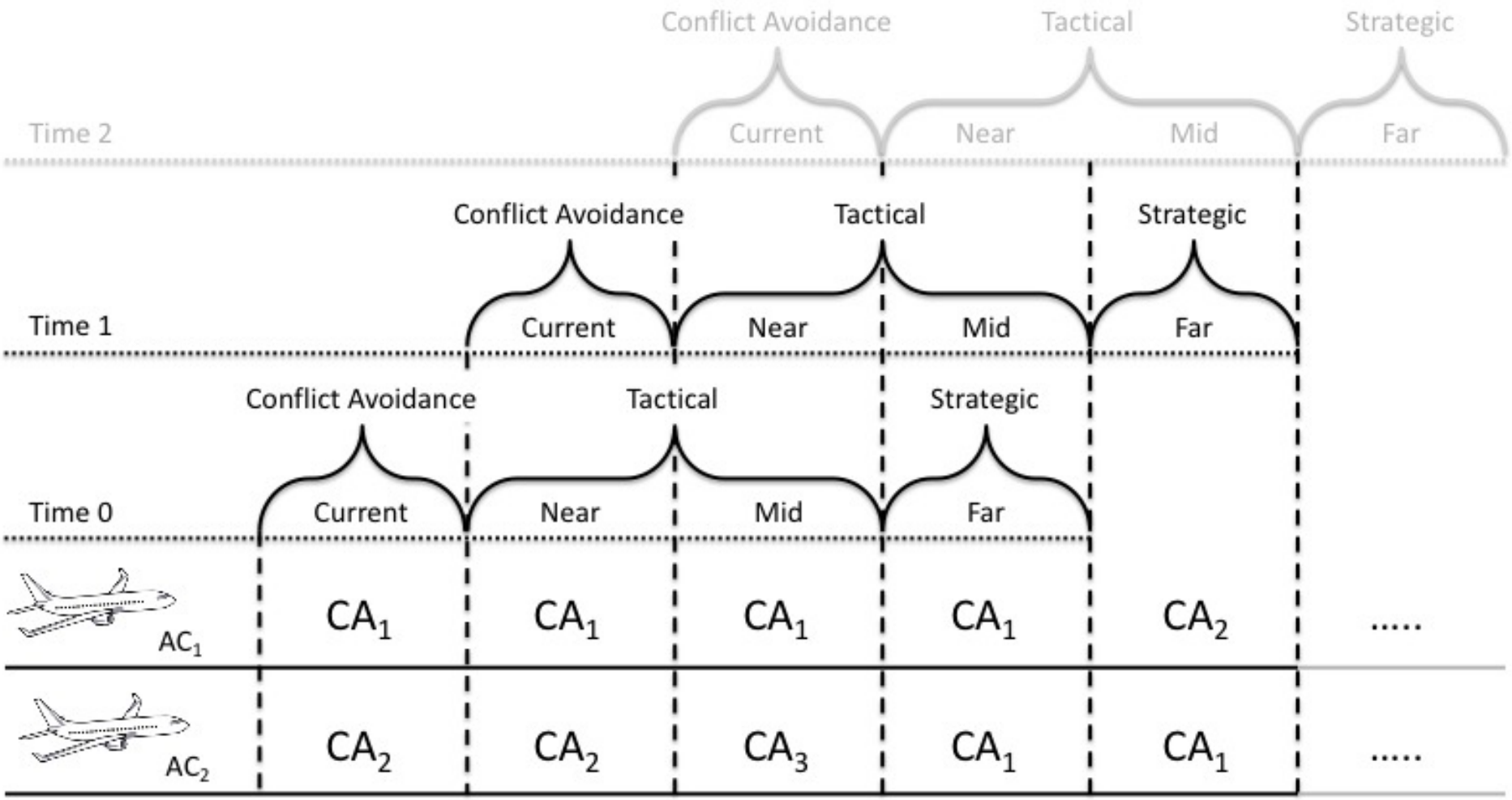
[3] Zhao, Yang, and Rozier, Kristin Yvonne. "Formal Specification and Verification of a Coordination Protocol for an Automated Air Traffic Control System." In AVoCS 2012.

Formal Modeling: Conflict Areas[4]

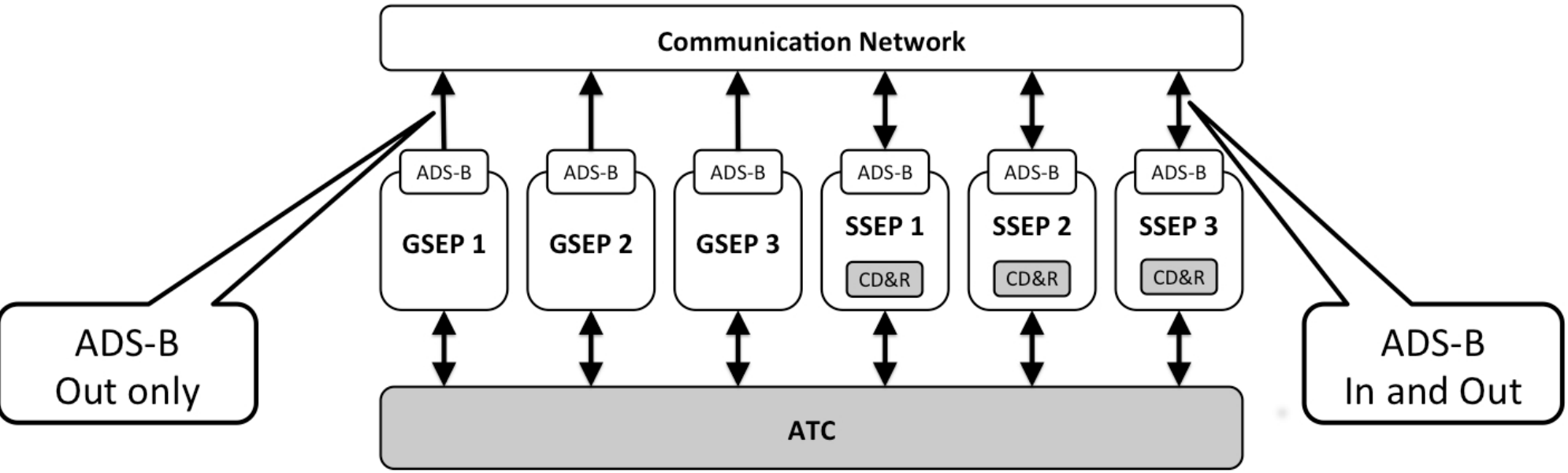


[4] Cristian Mattarei, Alessandro Cimatti, Marco Gario, Stefano Tonetta and Kristin Y. Rozier. "Comparing Different Functional Allocations in Automated Air Traffic Control Design." In Formal Methods in Computer-Aided Design (FMCAD), IEEE/ACM, 2015.

Formal Modeling: Time Windows



Formal Modeling: System Components (via OCRA Contracts)[5]



[5] 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.

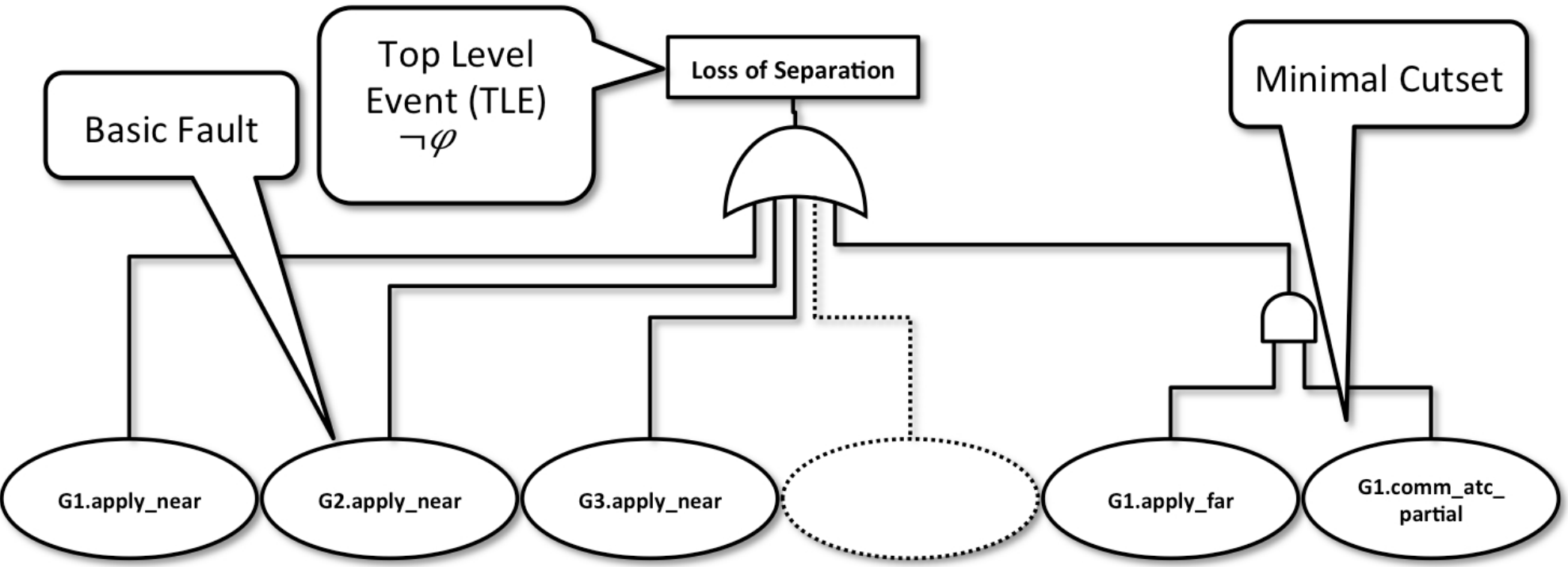
Full-Scale Design Space Verification[6]

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**

[6] 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.

Fault Tree Analysis: xSAP[7]

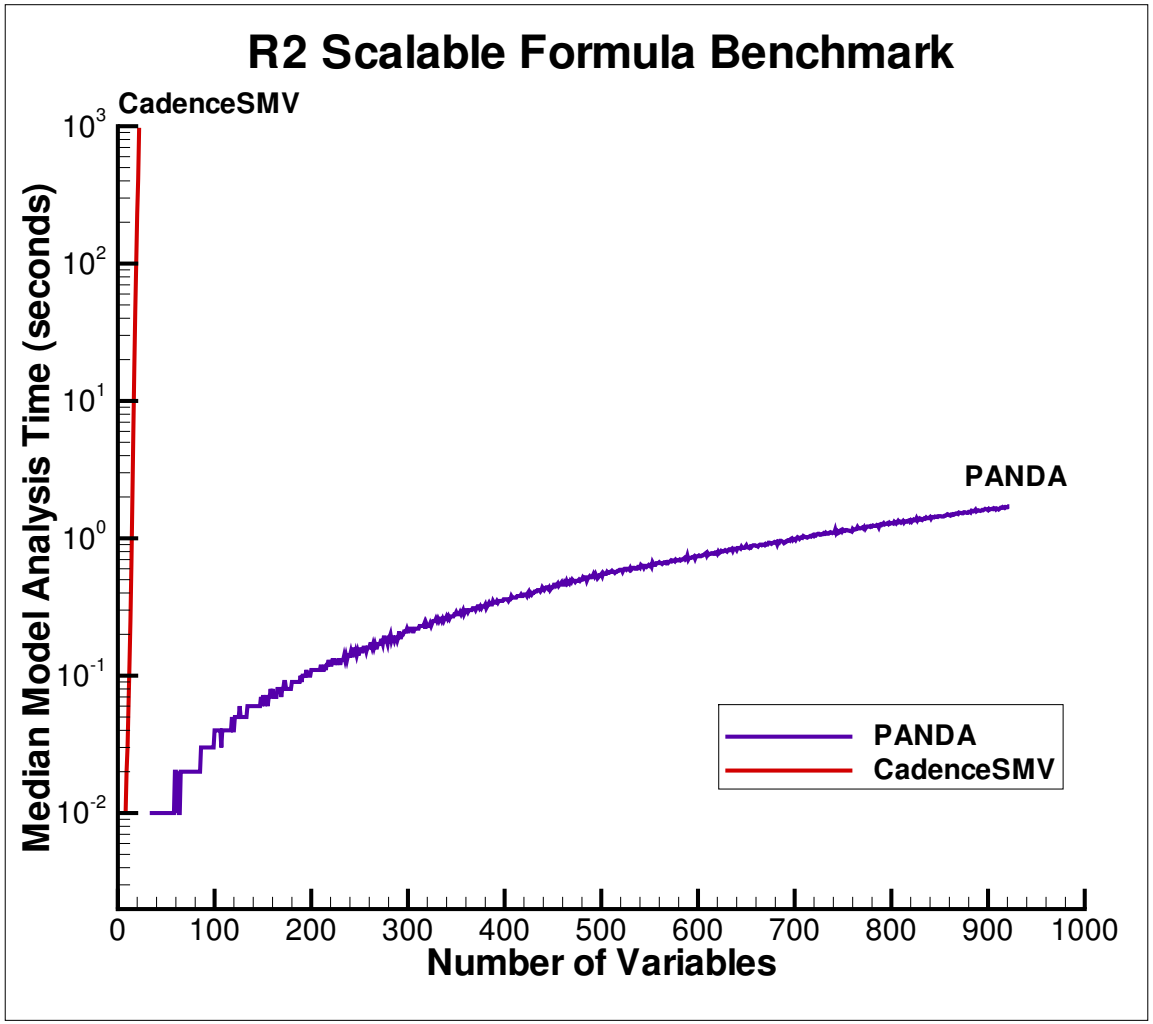


[7] Cristian Mattarei, Alessandro Cimatti, Marco Gario, Stefano Tonetta and Kristin Y. Rozier. "Comparing Different Functional Allocations in Automated Air Traffic Control Design." In Formal Methods in Computer-Aided Design (FMCAD), IEEE/ACM, 2015.

The Next Challenge

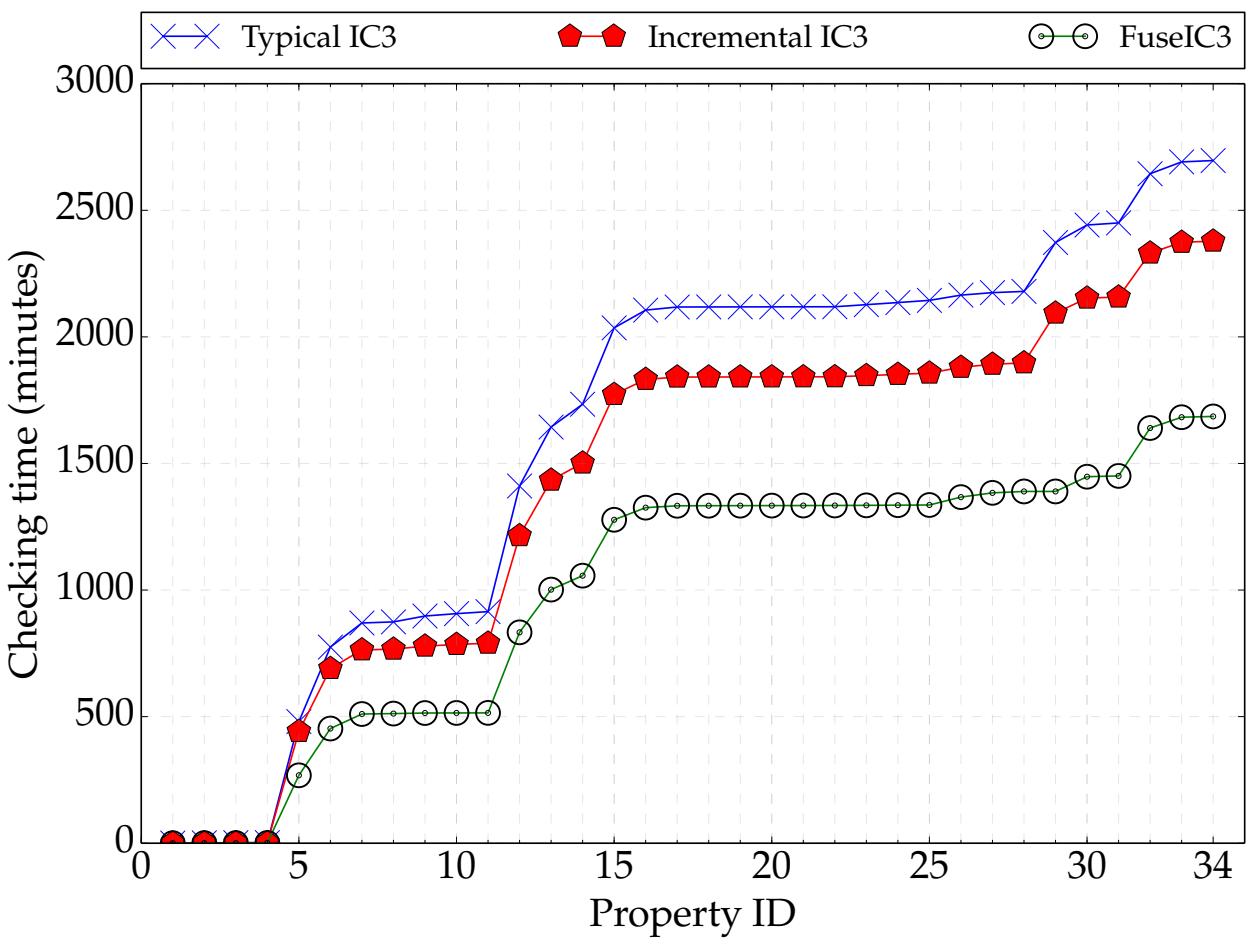
How do we do efficient design-space model checking?

Encoding Matters[8]



[8] 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[9]



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

[9] 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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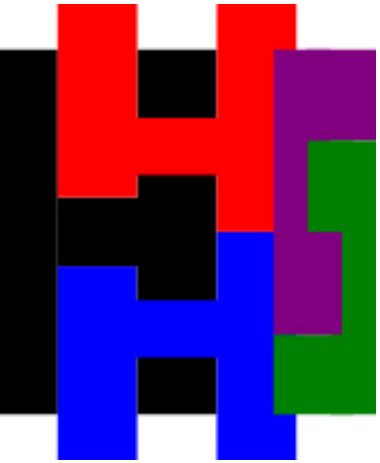
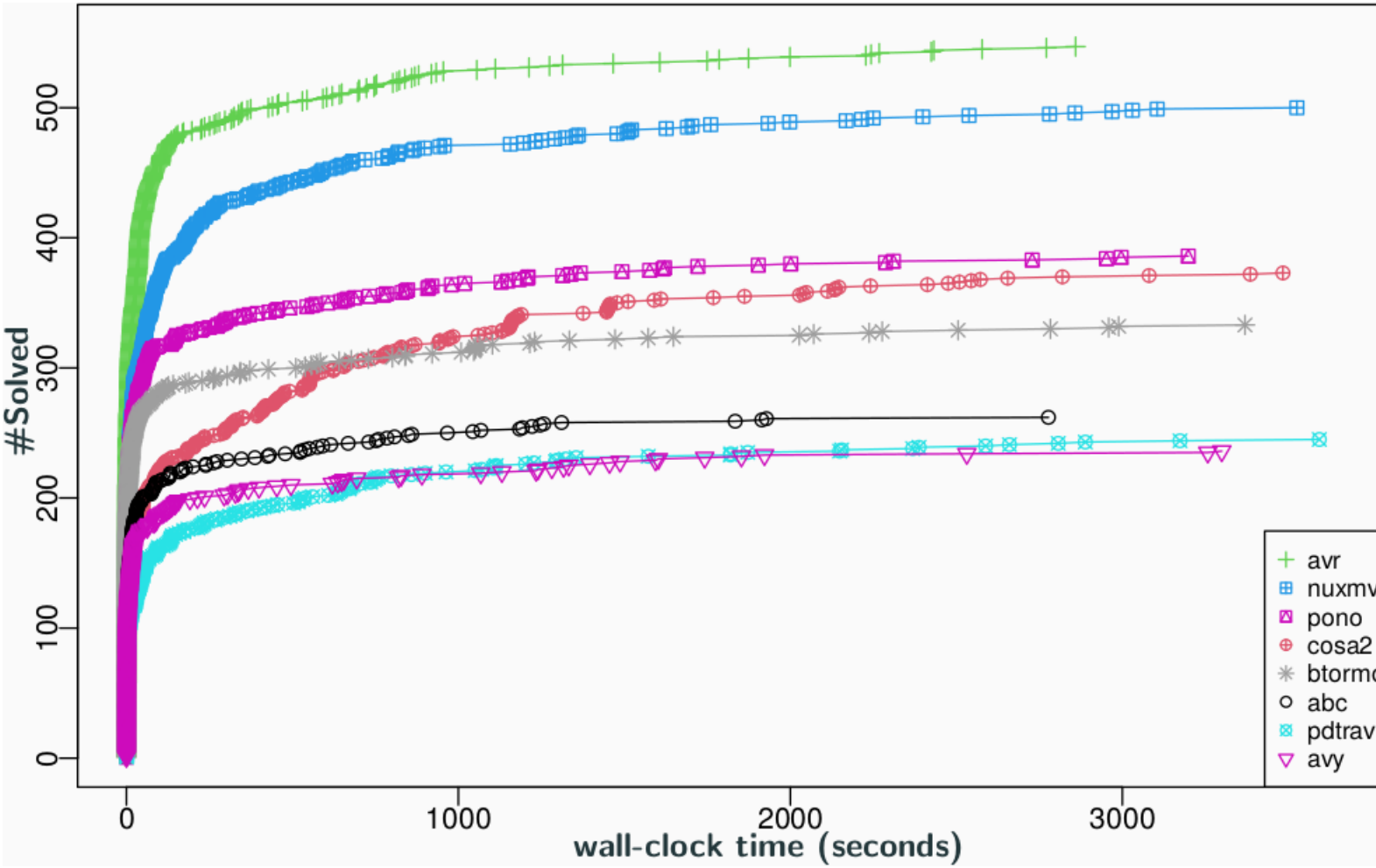
How do we do better?

HWMCC: Hardware Model Checking Competition (2020)



Word-level reasoning

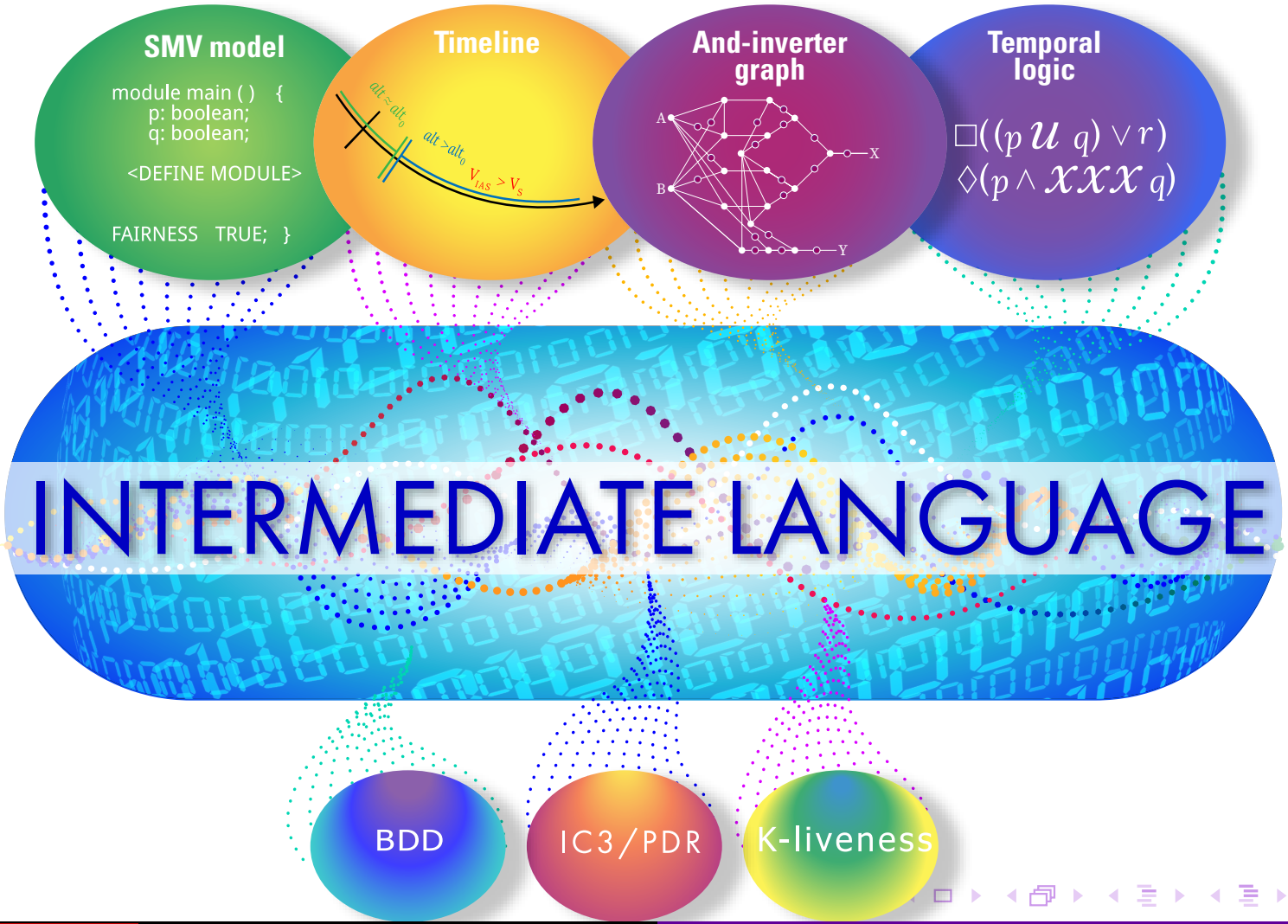
BTOR2



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**

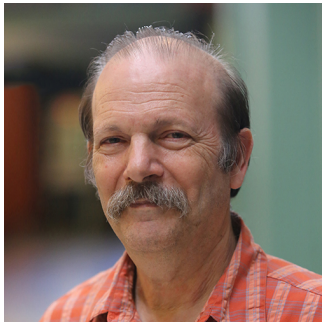
Core Design Team

Investigators:

K.Y. Rozier

Natarajan Shankar

Cesare Tinelli

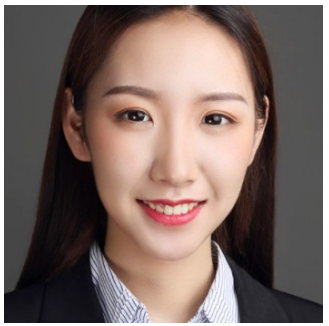


Moshe Vardi

Students:

Laura Gamboa Guzman

Chris Johannsen



Yi Lin

Technical Advisory Board (TAB)

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Armin Biere (Albert-Ludwigs Univ)
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Dimitra Giannakopoulou (Amazon)
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John Matthews (Intel)
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Alan Mishchenko (Berkeley)
Karem Sakallah (Univ of Michigan)
Bernhard Steffen (TU Dortmund)
Aaron Tomb (Amazon)
Stefano Tonetta (FBK)

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

Summary: Model Checking Coordination Effort

The time has come for model-checking community standards

- **Participate: use MoXI**, **SPIN Keynote**, email list, language design feedback, community forums (OSSyM@CAV!)
- Available Now: **SMV** $\leftrightarrow$ **MoXI** $\leftrightarrow$ **BTOR2**
- **Contribute** future translators:
  - Your Modeling Language $\leftrightarrow$ MoXI
  - MoXI $\leftrightarrow$ Your Back-end MC Algorithm
- **Optimize! Expand! Compare! Research!**

modelchecker.temporallogic.org

SBMF Keynote: https://www.youtube.com/watch?v=XjkjVPOKVT8

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

The Next Challenge

What about Runtime Verification?

Shouldn't that be easier?

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Need an RV Benchmark Competition!

What is an RV Benchmark?

A Simple 3-Tuple:

1. Input Stream
2. TL Formula: **MLTL**
3. Output Stream

Quickly gets complicated . . . gold stars for these?

- Sampling? Sensor filters?
- Real-time performance?
- Integrating Hardware/Software?

What are we benchmarking?

- Correctness!
- speed/timing?
- other metrics?

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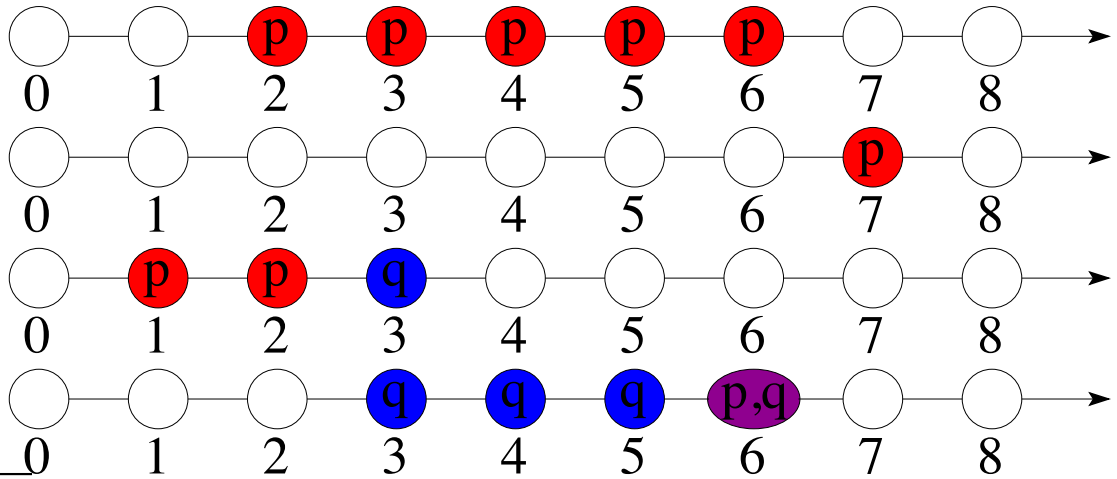
MLTL: A Good Specification Language[10]

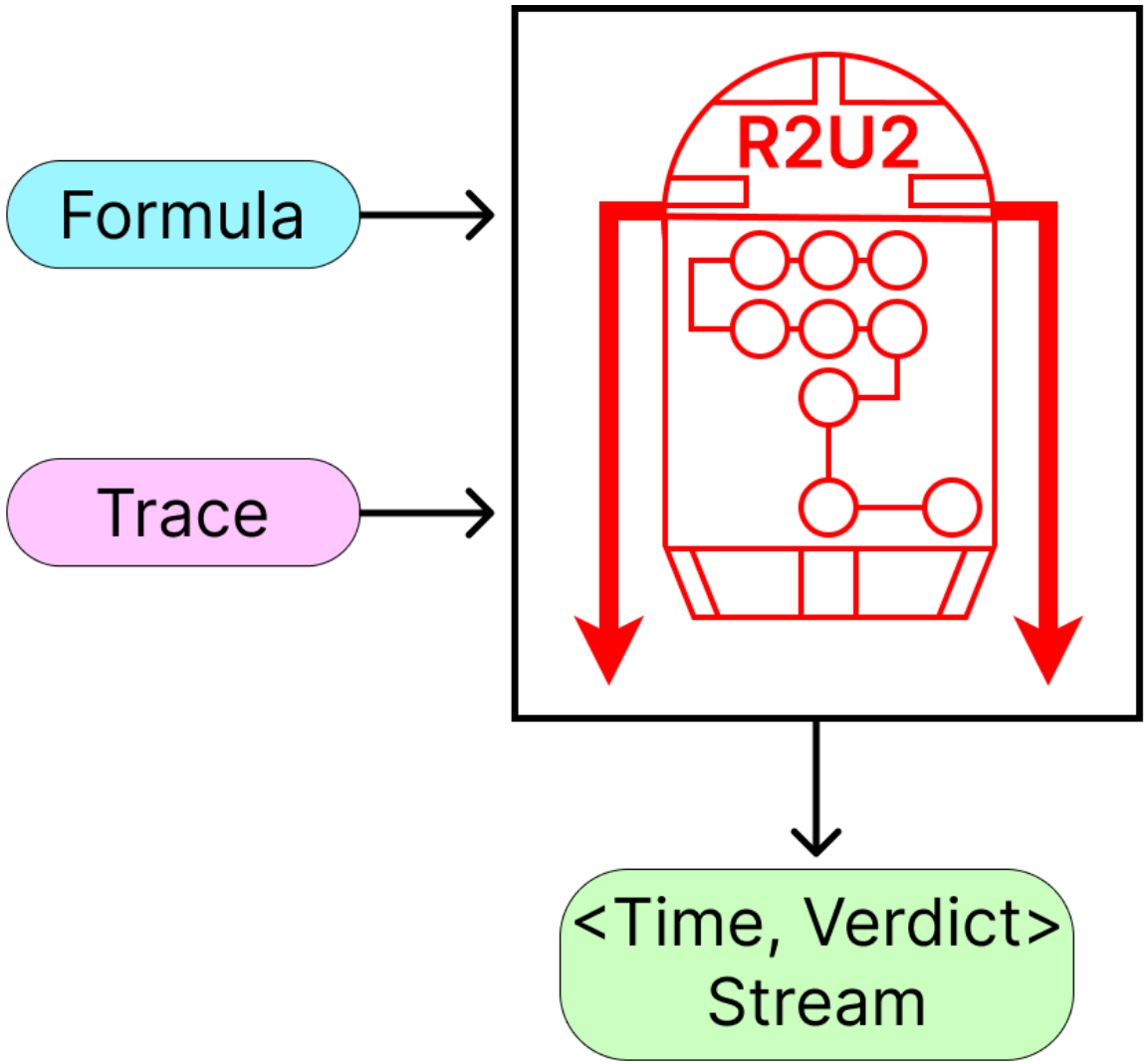
Mission-Time Temporal Logic (MLTL) reasons about *integer-bounded* timelines:

- finite set of atomic propositions {p q}
- Boolean connectives: $\neg$, $\wedge$, $\vee$, and $\rightarrow$
- temporal connectives *with time bounds*:

Symbol	Operator	Timeline
$\Box_{[2,6]} p$	$\text{ALWAYS}_{[2,6]}$	
$\Diamond_{[0,7]} p$	$\text{EVENTUALLY}_{[0,7]}$	
$p \mathcal{U}_{[1,5]} q$	$\text{UNTIL}_{[1,5]}$	
$p \mathcal{R}_{[3,8]} q$	$\text{RELEASE}_{[3,8]}$	



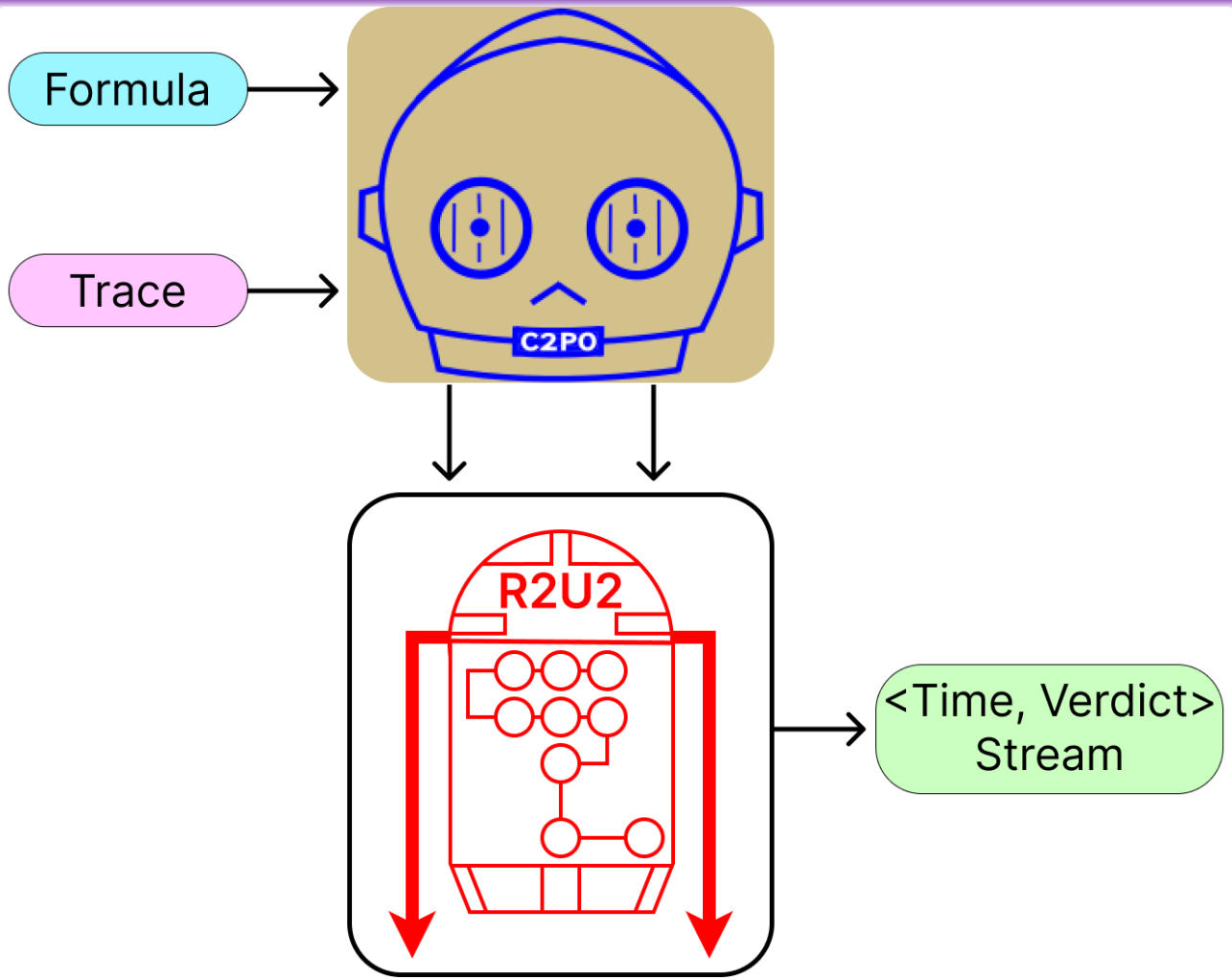
[10] T. Reinbacher, K.Y. Rozier, J. Schumann. "Temporal-Logic Based Runtime Observer Pairs for System Health Management of Real-Time Systems." TACAS 2014.



11 12

[11] K. Y. Rozier, J. Schumann. "R2U2: Tool Overview." RV-CUBES, 2017.

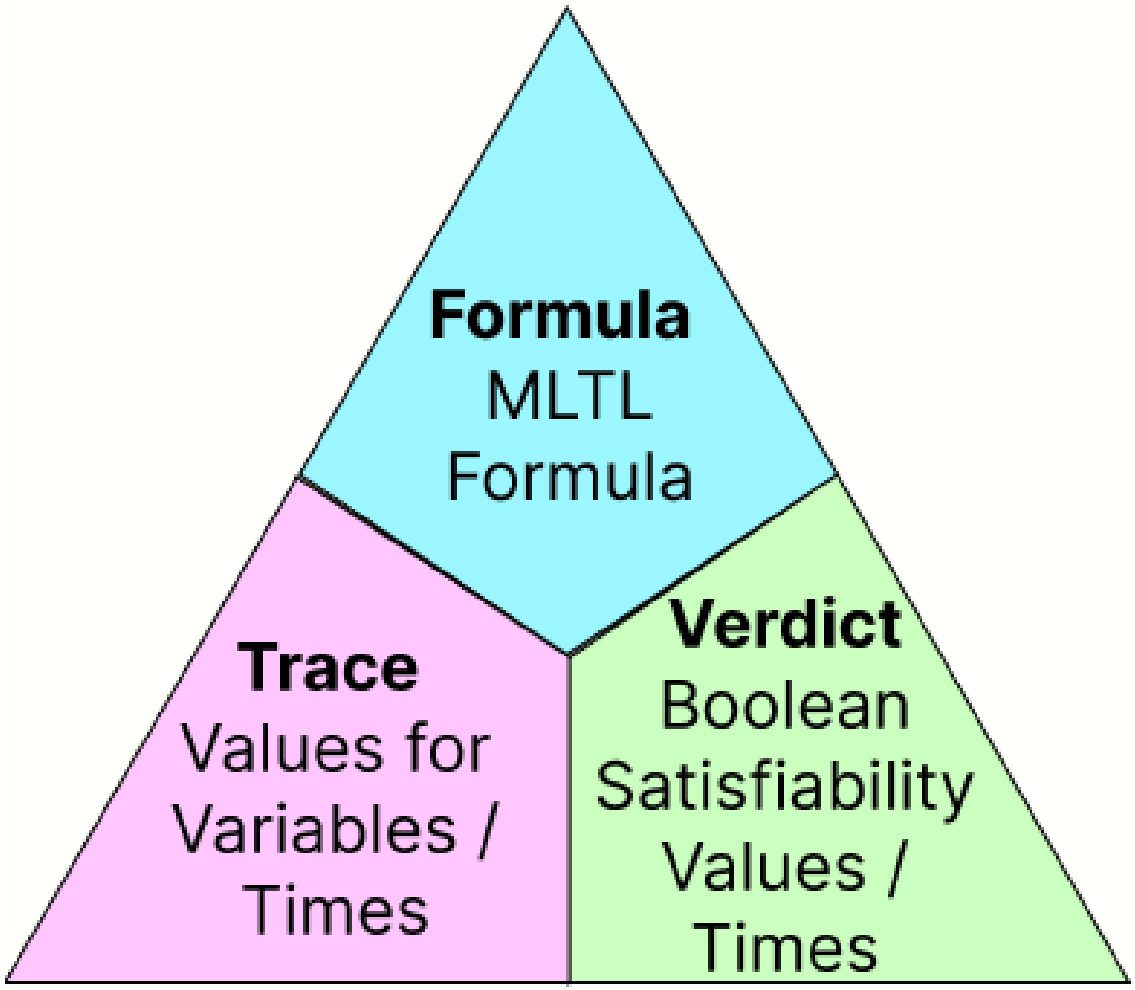
[12] T. Reinbacher, K. Y. Rozier, J. Schumann. "Temporal-Logic Based Runtime Observer Pairs for System Health Management of Real-Time Systems." TACAS, 2014.



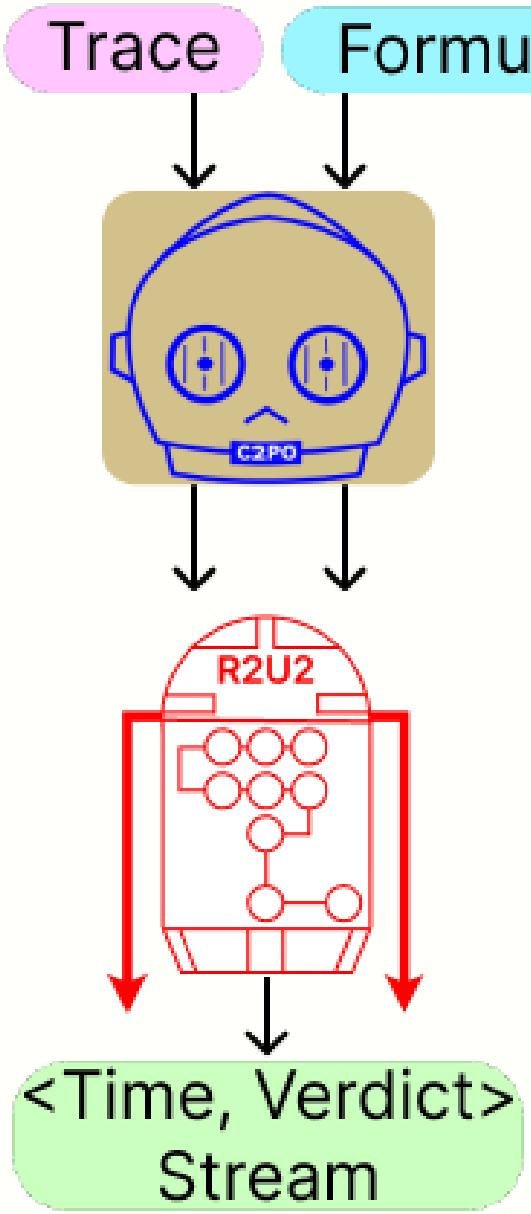
13 14

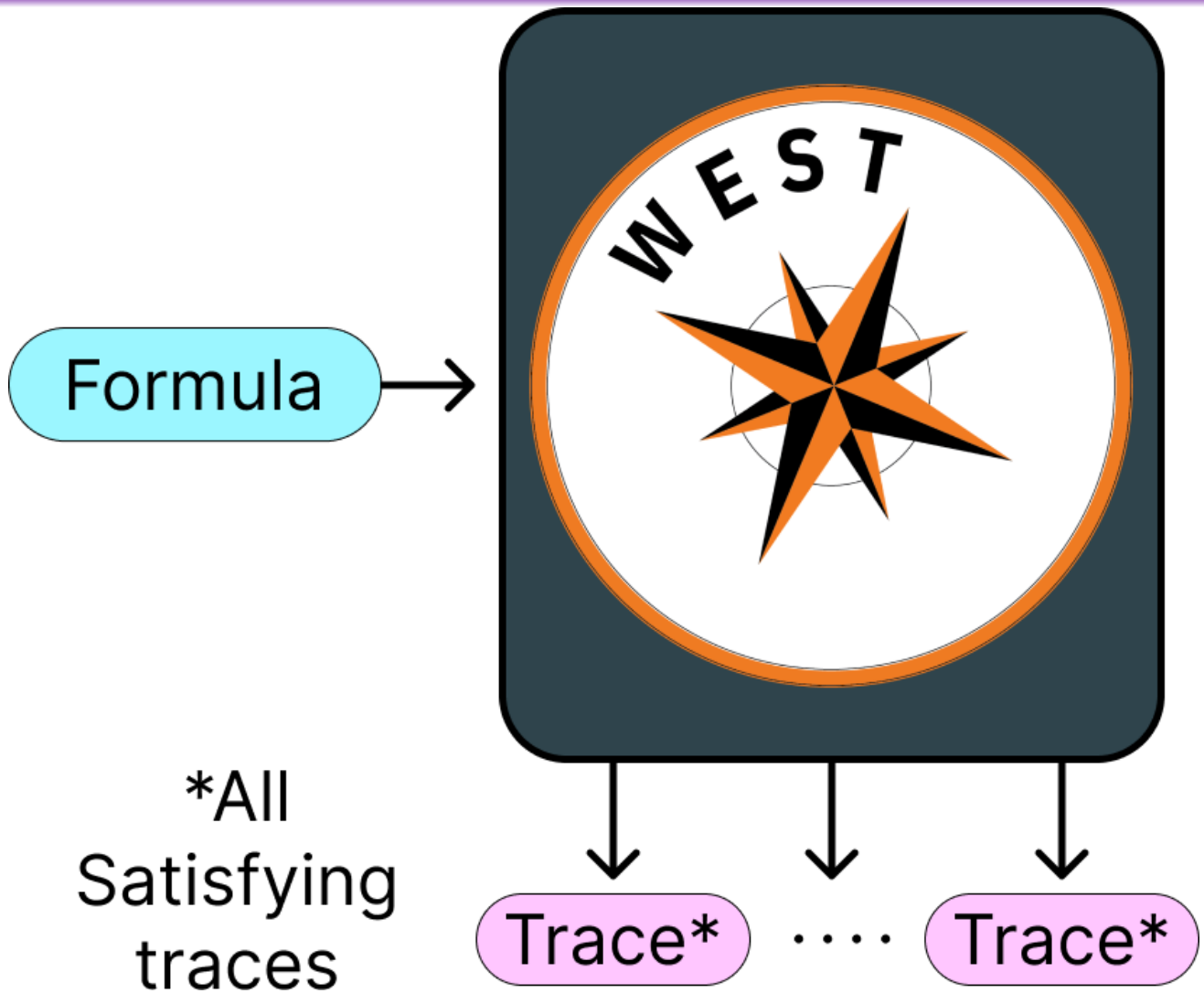
[13] C. Johannsen, P. H.Jones, B. Kempa, K. Y. Rozier, P. Zhang. "R2U2 Version 3.0: Re-imagining a Toolchain for Specification, Resource Estimation, and Optimized Observer Generation for Runtime Verification in Hardware and Software." CAV, 2023.

[14] C. Johannsen, B. Kempa, P. H. Jones, K. Y. Rozier, T. Wongpiromsarn. "Impossible Made Possible: Encoding Intractable Specifications via Implied Domain Constraints." FMICS, 2023.



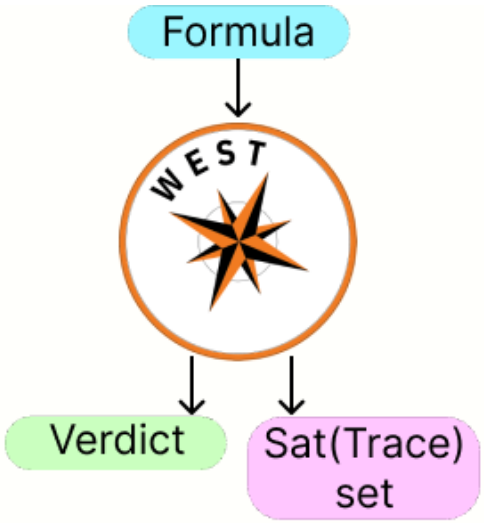
Given any 2 you can find the 3rd

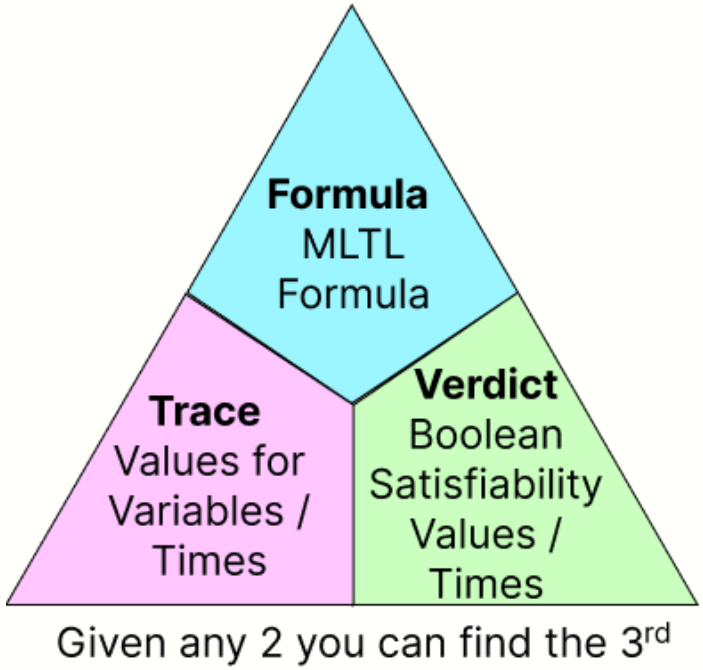


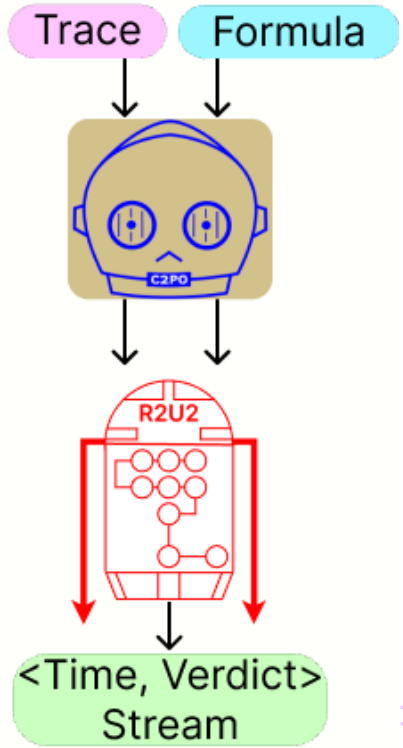


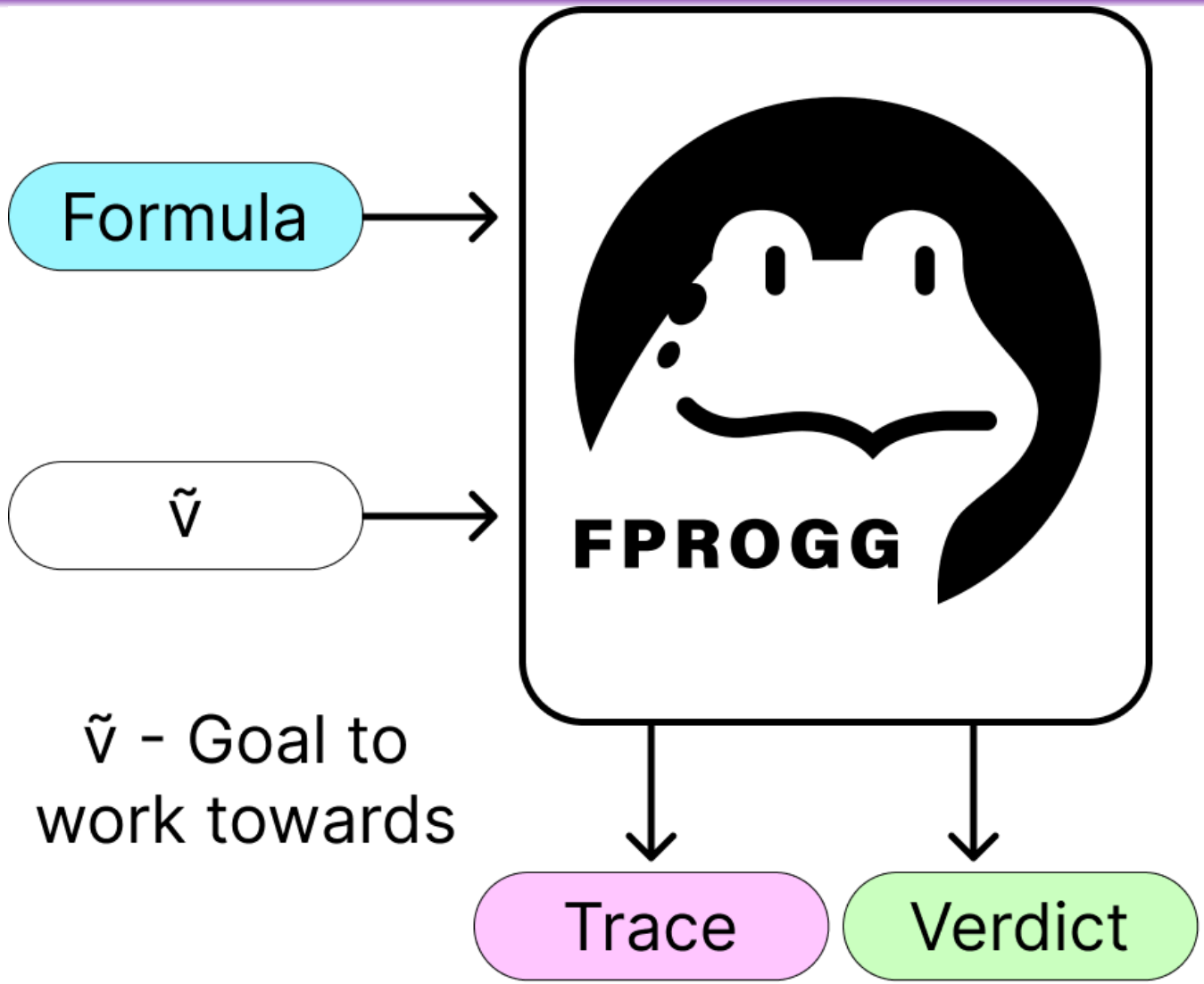
15

[15] J. Elwing, L. Gamboa-Guzman, J. Sorkin, C. Travesset, Z. Wang, K. Y. Rozier. "Mission-Time LTL (MLTL) Formula Validation via Regular Expressions." In *integrated Formal Methods* (iFM), 2023.


Formula
WEST
Verdict
Sat(Trace) set


Formula
MLTL
Formula
Trace
Values for
Variables /
Times
Verdict
Boolean
Satisfiability
Values /
Times
Given any 2 you can find the 3rd


Trace
Formula
C2PO
R2U2
<Time, Verdict>
Stream



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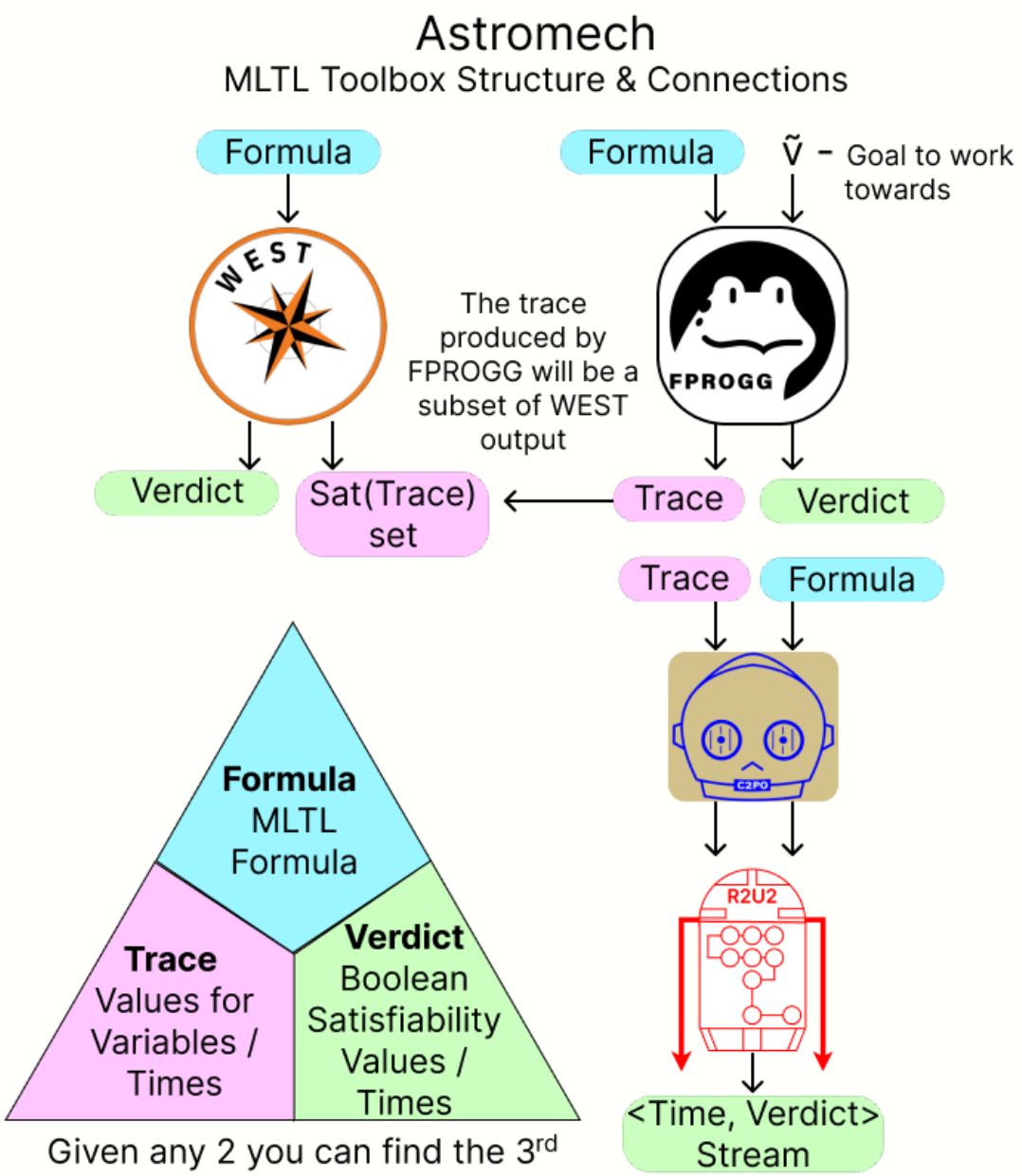
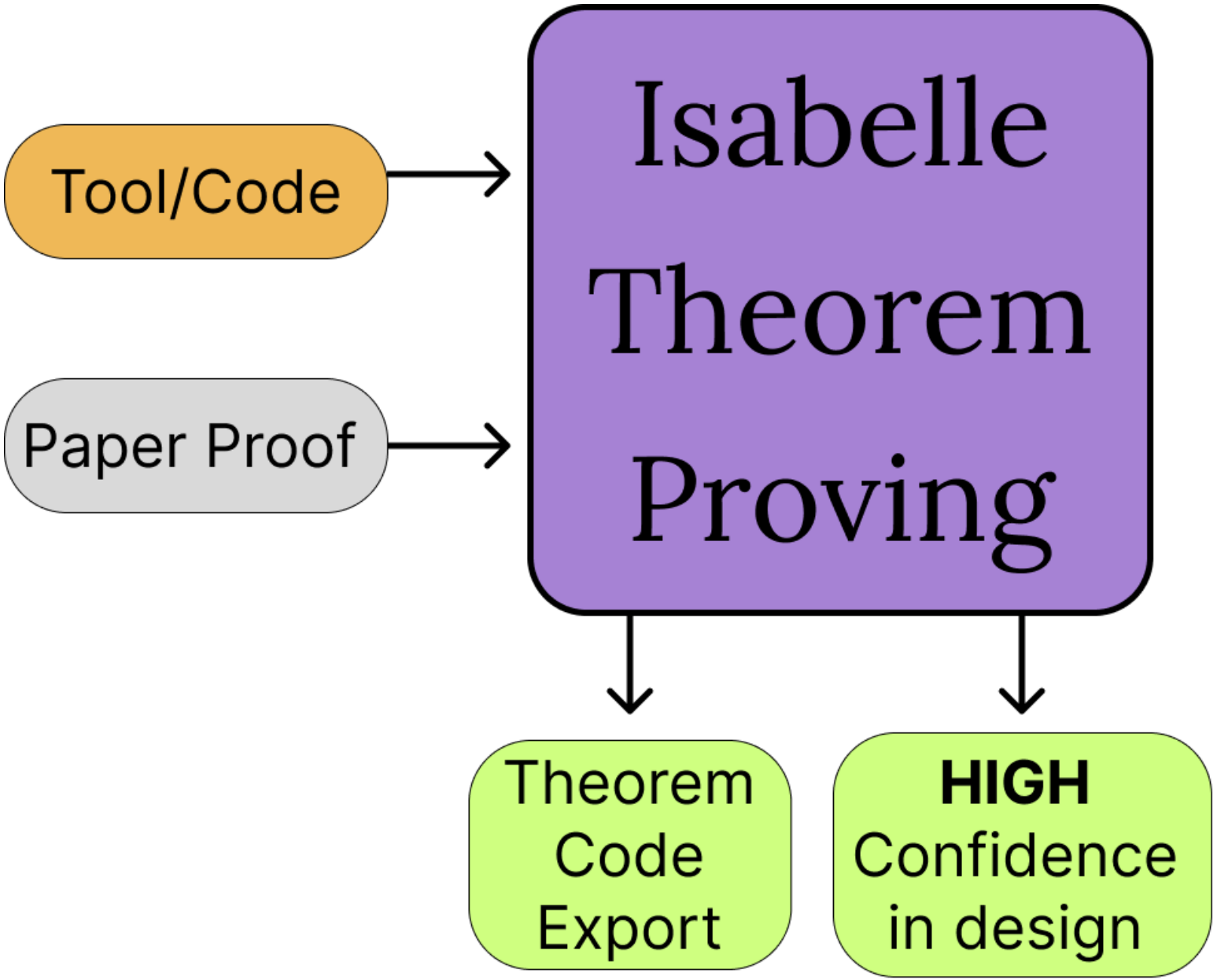
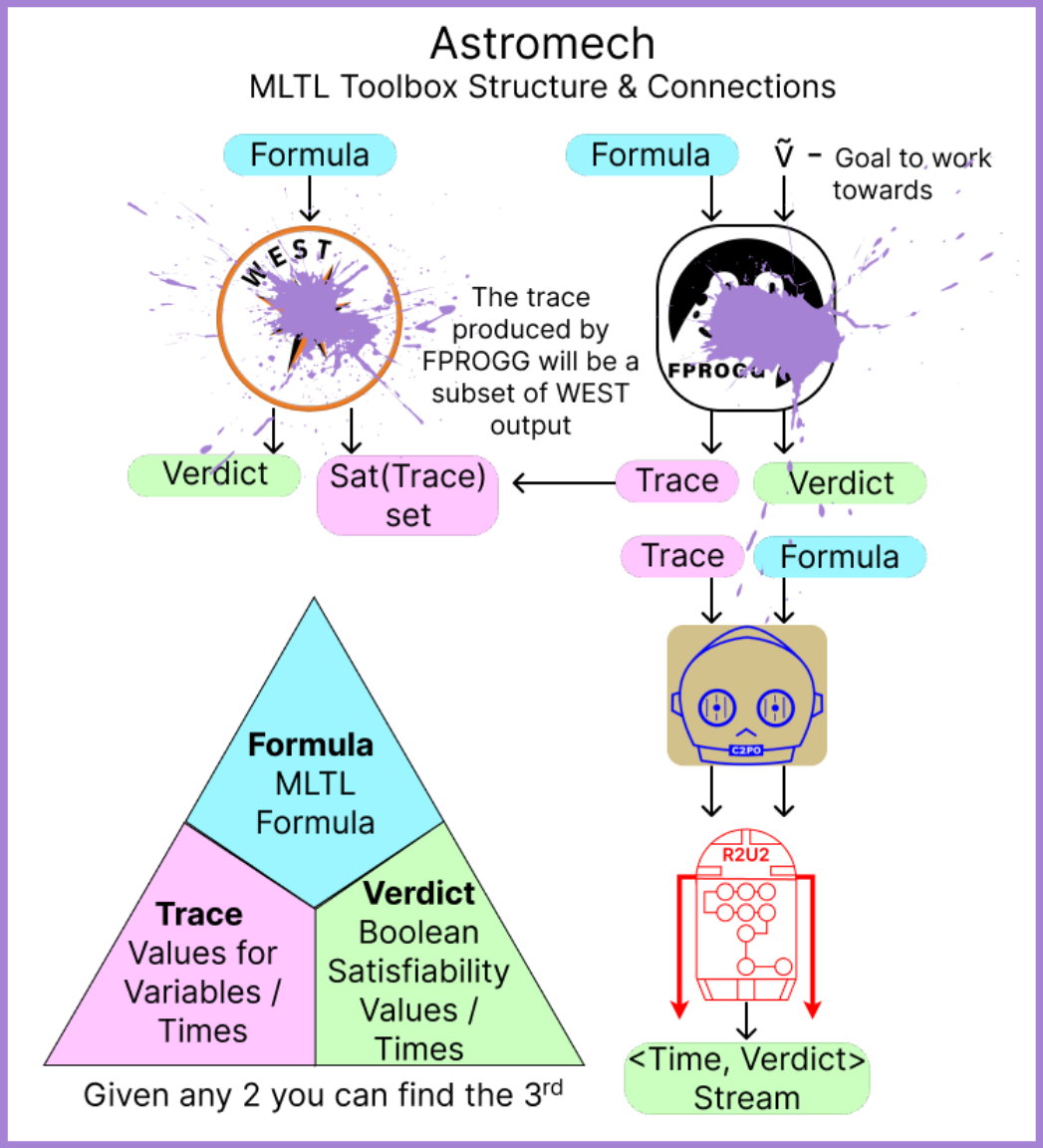
[16] A. Rosentrater, K. Y. Rozier, "FPROGG: A Formula Progression-Based MLTL Benchmark Generator." Under submission, 2024.


Astromech
MLTL Toolbox Structure & Connections
Formula
Formula
$\tilde{V}$ – Goal to work towards
WEST
FPROGG
The trace produced by FPROGG will be a subset of WEST output
Verdict
Sat(Trace) set
Trace
Verdict
Trace
Formula
C2PO
R2U2
<Time, Verdict> Stream
Formula MLTL Formula
Trace Values for Variables / Times
Verdict Boolean Satisfiability Values / Times
Given any 2 you can find the 3rd


Tool/Code
Paper Proof
Isabelle Theorem Proving
Theorem Code Export
HIGH Confidence in design

Isabelle Theorem Proving



Tool Integration Challenges & Opportunities

Center on input logics (e.g., MLTL)

- **FRET** integrates MLTL [17]
- **nuXmv** integrates MLTL[18]
- FRET → **Ogma**[19] → **Copilot**[20]
- **Pacti**[21] ↔ R2U2?

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- How to **catalog tool connections**: when using one tool, **automatically see** what other tools work with it? Giant GitHub page?

Opportunities

- **Specification logic as a common interface**
  - Via specification **validation tools** (e.g., WEST)
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- build model checkers for **MoXI**!

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Tool Integration and Cooperation is Key to Making Formal Methods Universal!

- **International Community Standards:** specification logics, intermediate languages, output formats
- **Documentation & Interfaces**, e.g., for validation
- **Integration Index**: GitHub? How to do this?
- **Open-Source Standards**: methods to build on state of the art without replication

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