FuseIC3

An Algorithm for Checking Large Design Spaces

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fmcad.17

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What is a Design Space?

Airspace Allocation

Design of allocation policies to ensure all airborne agents are safely separated.

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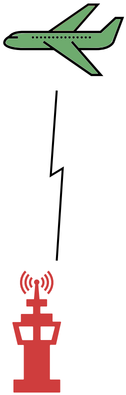

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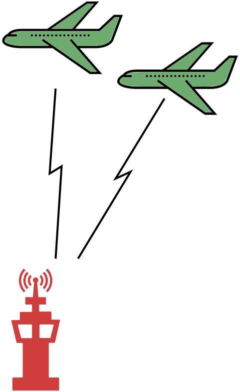

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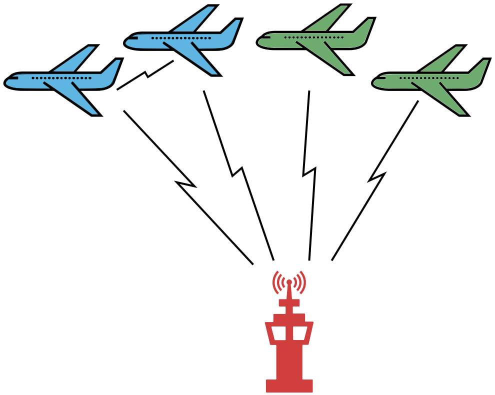

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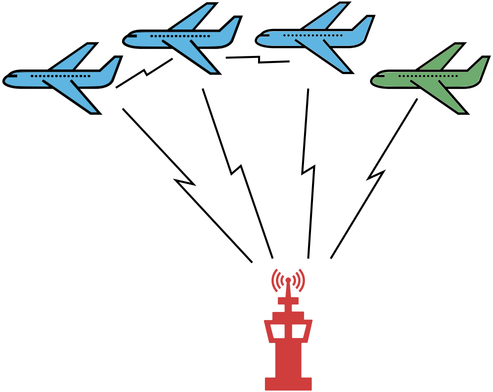

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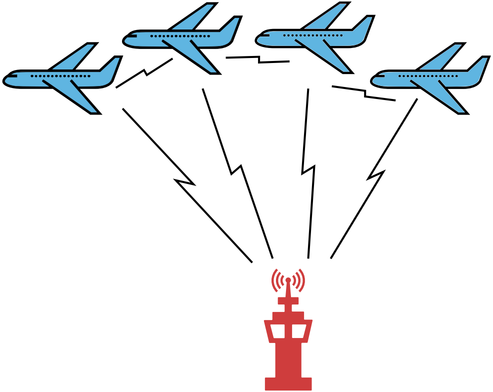

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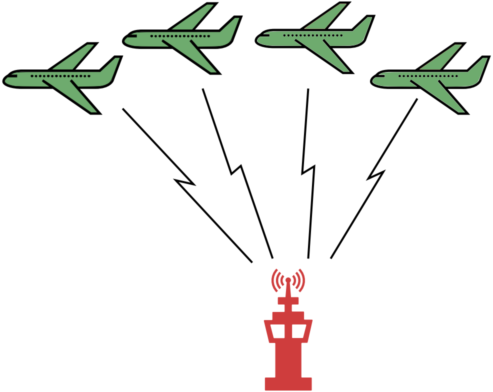

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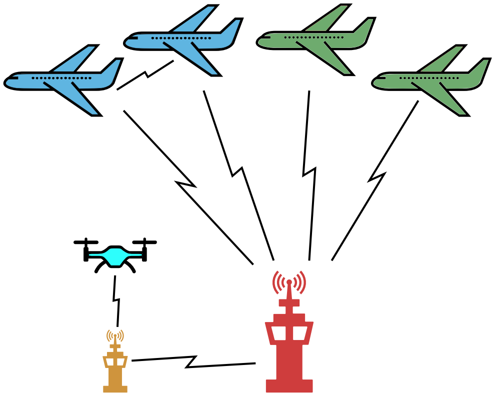

Airspace Allocation

Design of allocation policies to ensure all airborne agents are safely separated.

Lots of design choices!

What is a Design Space?

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Set of Design Choices for a System.

Design Problem

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Complex systems are often modeled as **design spaces**.

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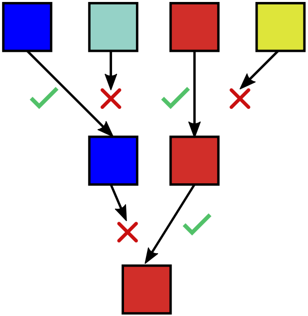

Alternative Comparison

Design Problem

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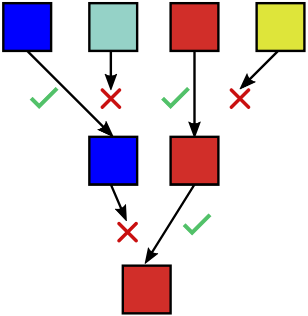

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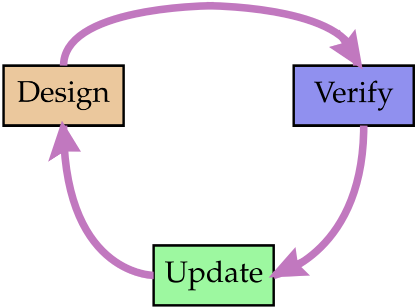
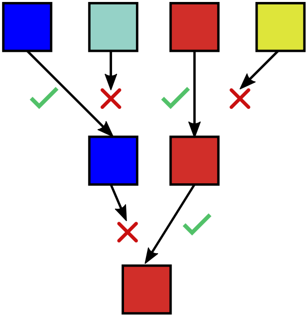


Incremental Development

Design Problem

Complex systems are often modeled as **design spaces**.



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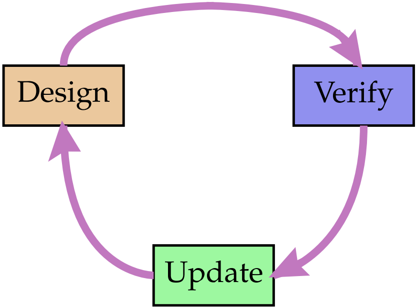
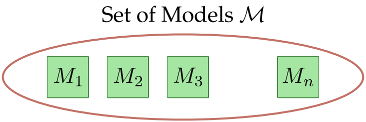


Incremental Development

Model checking!

Classical Model Checking of a Design Space



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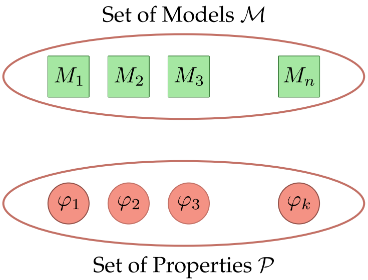

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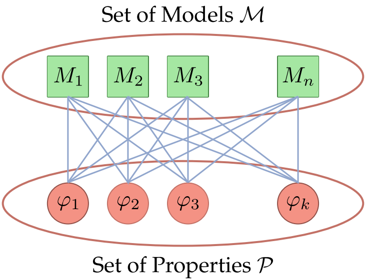

For every $M \in \mathcal{M}$ and $\varphi \in \mathcal{P}$
check if $M \models \varphi$?

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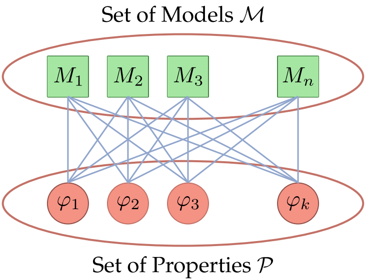

For every $M \in \mathcal{M}$ and $\varphi \in \mathcal{P}$ check if $M \models \varphi$?

- Inefficient for large design spaces
  - may not scale to handle combinatorial size of the design space.

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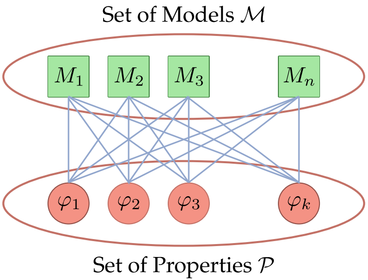

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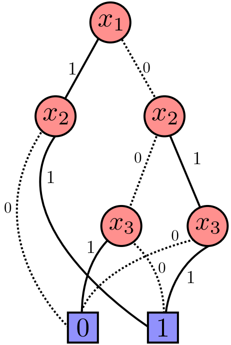
Can we do better?

Related Work

1. Reusing BDD variable orderings

$$x_1 < x_2 < x_3$$



(Beer et al., 1996; Yang et al., 1998)

Related Work

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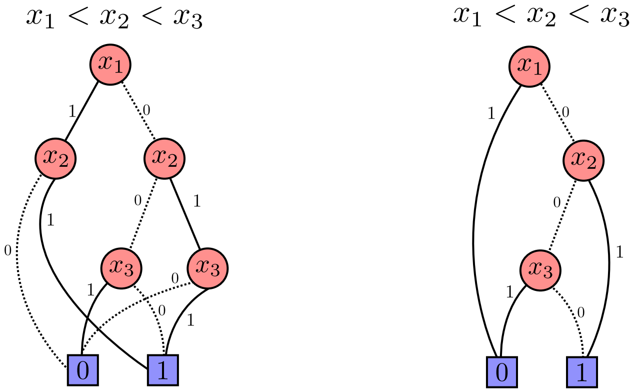
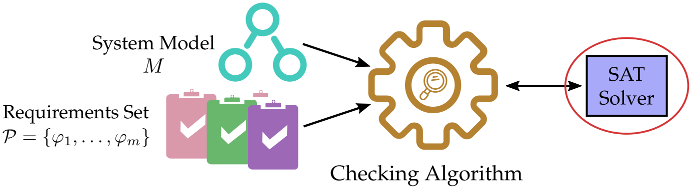


FuseIC3 is SAT-based

(Beer et al., 1996; Yang et al., 1998)

Related Work

2. SAT solver optimizations and clause reuse



(Marques-Silva, 2007; Schrammel et al., 2016; Chockler et al., 2011; Khasidashvili et al., 2006; Khasidashvili & Nadel, 2012)

Related Work

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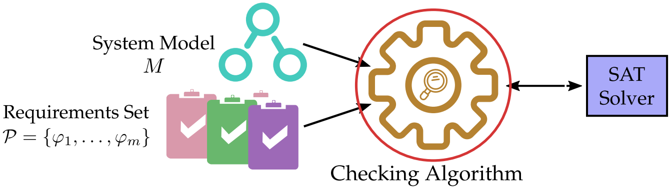
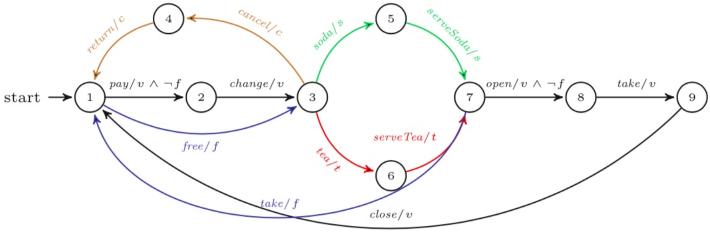


FuseIC3 reuses model checking artifacts

(Marques-Silva, 2007; Schrammel et al., 2016; Chockler et al., 2011; Khasidashvili et al., 2006; Khasidashvili & Nadel, 2012)

Related Work

3. Software product line verification



(Ben-David et al., 2015; Classen et al., 2012, 2011, 2010; Dimovski et al., 2015)

Related Work

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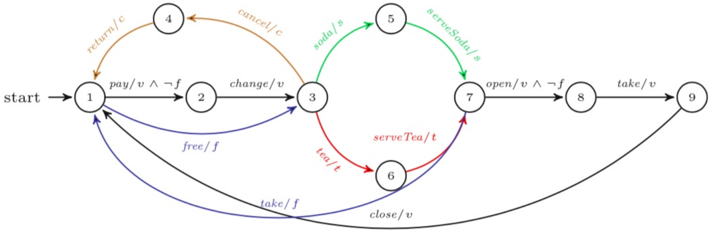

FuseIC3 does not require custom modeling

(Ben-David et al., 2015; Classen et al., 2012, 2011, 2010; Dimovski et al., 2015)

High-level View of IC3/PDR

Model $M = (\Sigma, Q_M, Q_{0_M}, \delta_M)$ and Safety property φ

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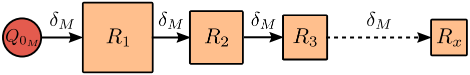

Frame Sequence R

Frame Invariants

1. for $i > 0$, R_i is CNF, over-approximated states reachable in up to i steps
2. $R_{i+1} \subseteq R_i$ (monotonic)
3. $R_i \wedge \delta_M \models R'_{i+1}$
4. for $i < x$, $R_i \models \varphi$

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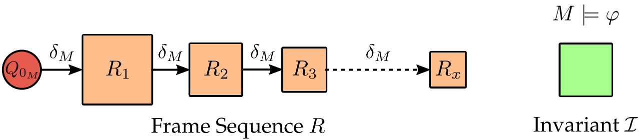

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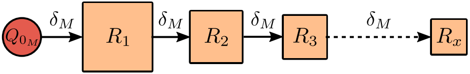
$M \not\models \varphi$



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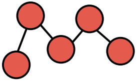

Error Trace $\mathcal{E}$

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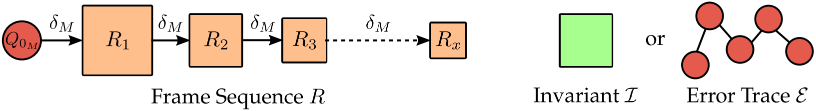

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Overview of FuseIC3

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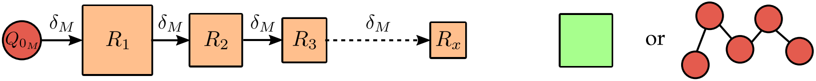

Frame Sequence R

Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

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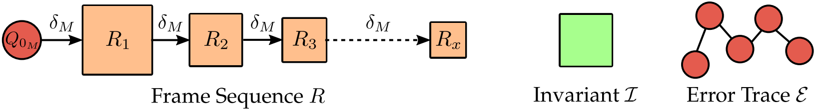

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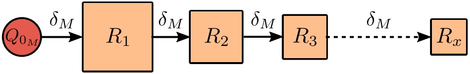

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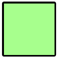
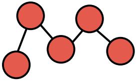


Invariant $\mathcal{I}$



Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

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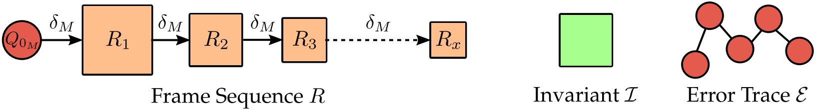

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for model N

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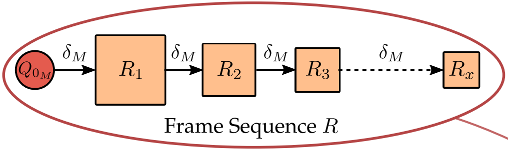

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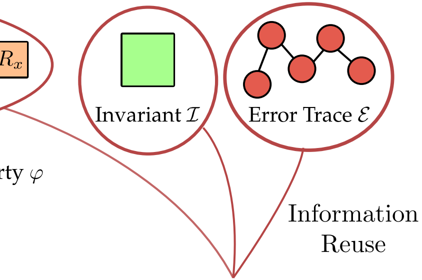

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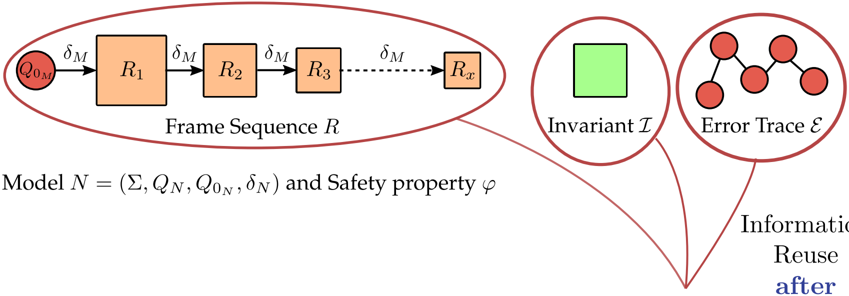

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Information Reuse **after Repair**

Goal: Compute frame sequence S for model N

Assumptions and Intuition

Assumption 1

The different models in the design space are related, i.e., have overlapping reachable states.

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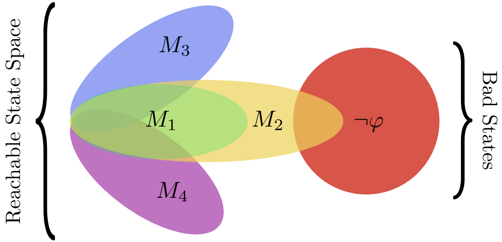
Intuition

Set of related models $\{M_1, M_2, M_3, M_4\}$

Safety property φ



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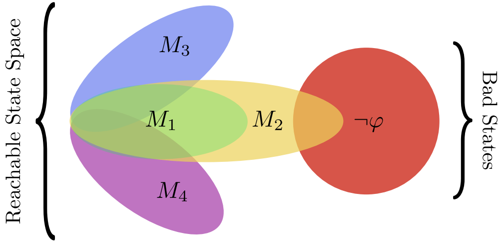

1. Check M_1 with φ

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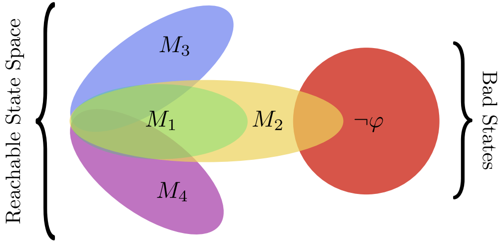

1. Check M_1 with $\varphi \longrightarrow M_1 \models \varphi$

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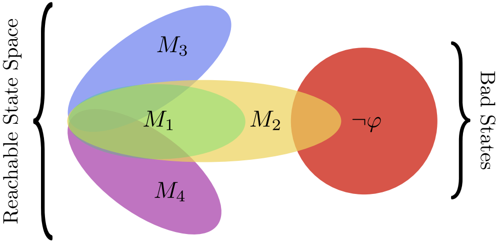
Safety property φ



1. Check M_1 with $\varphi \longrightarrow$ $M_1 \models \varphi$
2. Check M_2 with $\varphi \longrightarrow$

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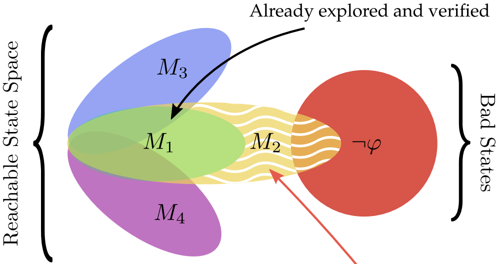

1. Check M_1 with $\varphi \longrightarrow$ $M_1 \models \varphi$
2. Check M_2 with $\varphi \longrightarrow$

When checking M_2, FuseIC3 reuses the already explored and verified state space of M_1 and only checks

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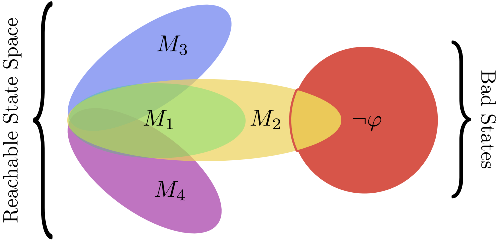
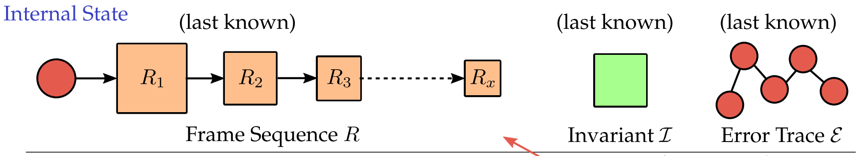


1. Check M_1 with $\varphi \longrightarrow$ $M_1 \models \varphi$
2. Check M_2 with $\varphi \longrightarrow$ $M_2 \not\models \varphi$

Internal State

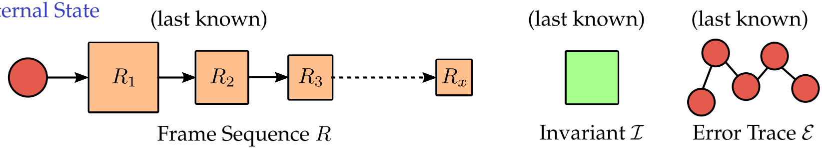


Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Internal state maintained by FuseIC3

Basic Checks

Internal State



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Goal: Compute frame sequence S for mode N

Basic Checks

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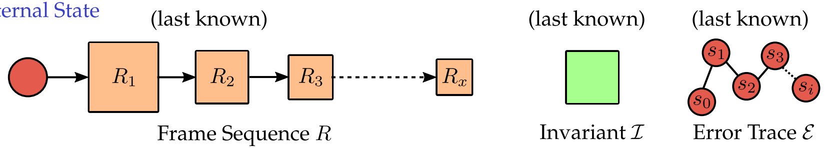

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CHECKINVARIANT

$\mathcal{I}$ is inductive invariant w.r.t model N

Basic Checks

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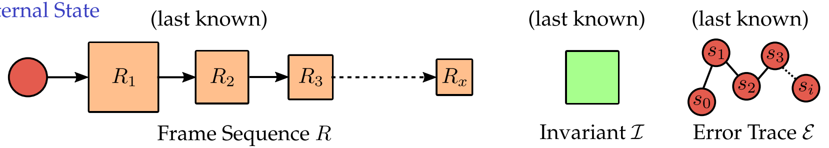

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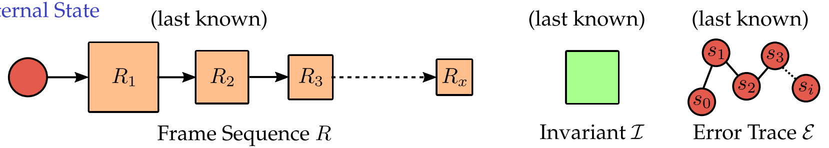

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CheckInvariant

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✓ $N \models \varphi$

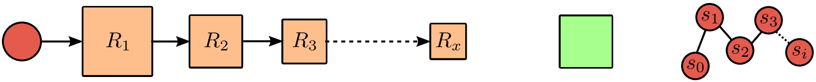
SimulateCex

$\mathcal{E}$ is valid trace w.r.t to model N

Basic Checks

Internal State

(last known) (last known) (last known)



Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

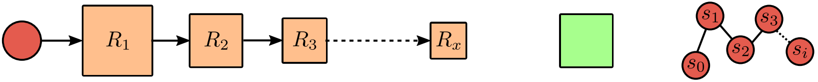
Goal: Compute frame sequence S for mode N

CheckInvariant	SimulateCex
$\mathcal{I}$ is inductive invariant w.r.t model N	$\mathcal{E}$ is valid trace w.r.t to model N
✓ $N \models \varphi$	✓ $N \not\models \varphi$

Basic Checks

Internal State

(last known) (last known) (last known)



Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

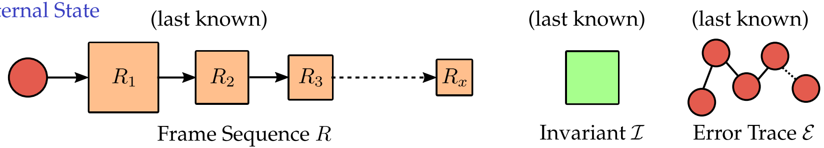
Goal: Compute frame sequence S for mode N

CheckInvariant	SimulateCex
$\mathcal{I}$ is inductive invariant w.r.t model N	$\mathcal{E}$ is valid trace w.r.t to model N
✓ $N \models \varphi$	✓ $N \not\models \varphi$

Instant Verification

Frame Reuse

Internal State

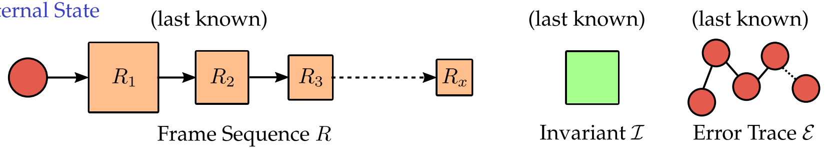


Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N

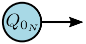
Frame Reuse

Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

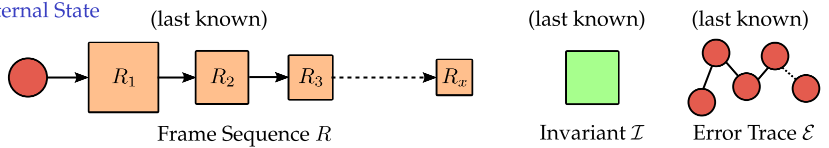
Goal: Compute frame sequence S for mode N



Frame Sequence S

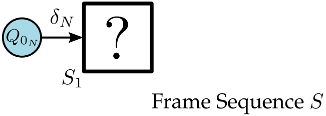
Frame Reuse

Internal State



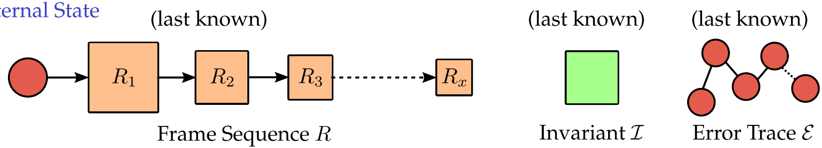
Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



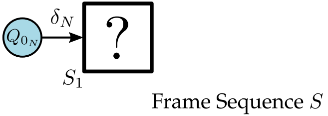
Frame Reuse

Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

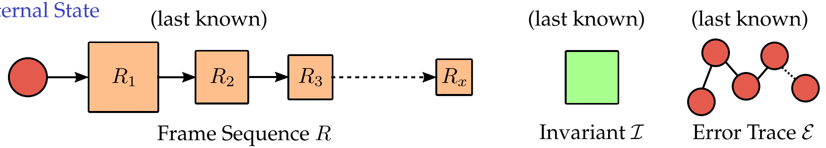
Goal: Compute frame sequence S for mode N



We want to compute S_1 using known information

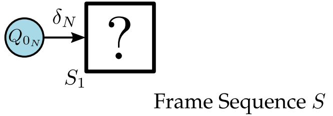
Frame Reuse

Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N

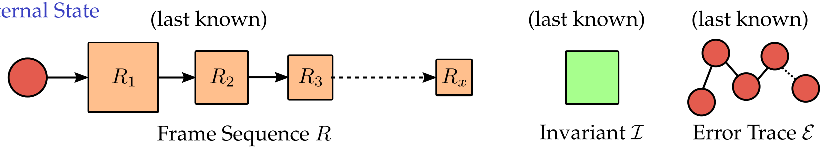


We want to compute S_1 using known information

$$S_0 \wedge \delta_N \rightarrow R_1'?$$

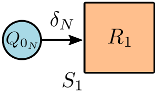
Frame Reuse

Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S

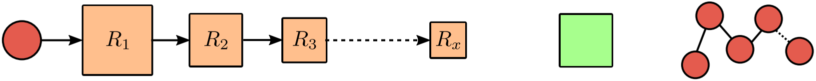
We want to compute S_1 using known information

$$S_0 \wedge \delta_N \rightarrow R_1'?$$ ✓

Frame Reuse

Internal State

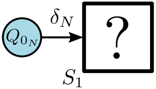
(last known) (last known) (last known)



Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S

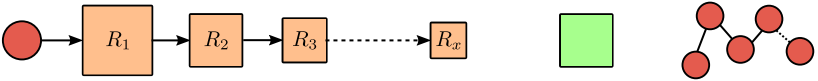
We want to compute S_1 using known information

$$S_0 \wedge \delta_N \rightarrow R_1'?$$

Frame Reuse

Internal State

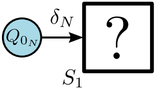
(last known) (last known) (last known)



Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S

We want to compute S_1 using known information

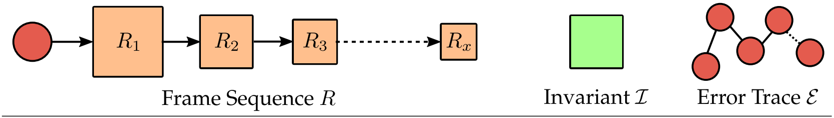
$$S_0 \wedge \delta_N \rightarrow R_1'?$$

Repair R_1

Frame Repair

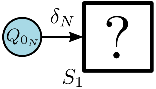
Internal State

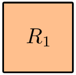
(last known) (last known) (last known)



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



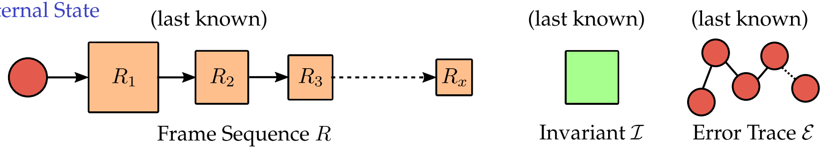


Frame Sequence S

Repair R_1 to $\hat{R}_1$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R}_1{}'$ is valid

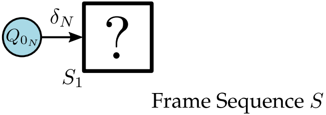
Frame Repair

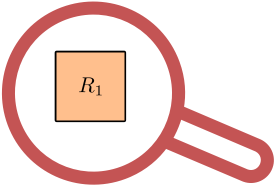
Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N

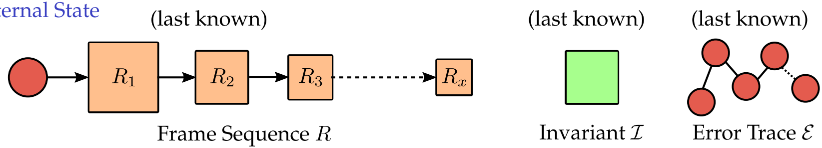




Repair R_1 to $\hat{R}_1$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R}_1{}'$ is valid

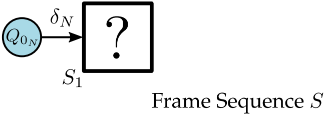
Frame Repair

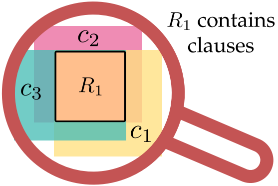
Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



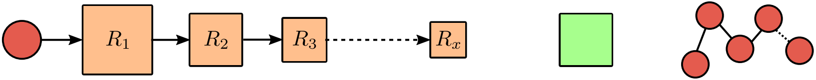


Repair R_1 to $\hat{R}_1$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R}_1{}'$ is valid

Frame Repair

Internal State

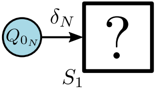
(last known) (last known) (last known)



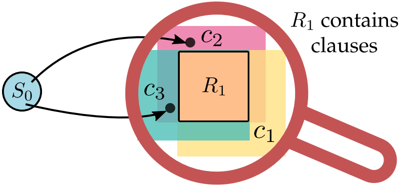
Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S



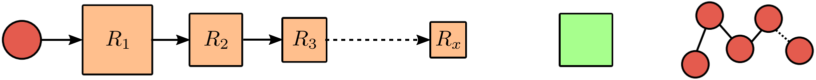
Reason for $S_0 \wedge \delta_N \not\to R_1$

Repair R_1 to $\hat{R}_1$ s.t. $S_0 \wedge \delta_N \to \hat{R}_1{}'$ is valid

Frame Repair

Internal State

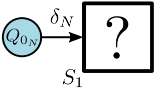
(last known) (last known) (last known)



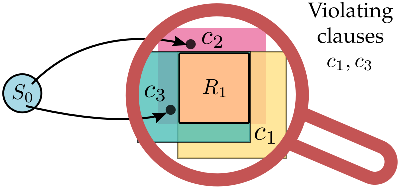
Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S



Violating clauses c_1, c_3

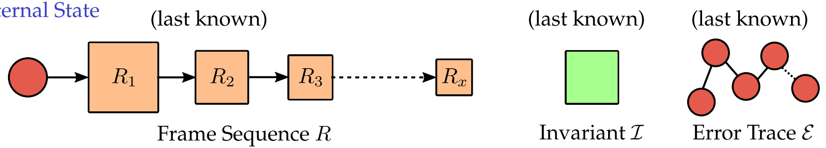
Reason for $S_0 \wedge \delta_N \not\to R_1$

Repair R_1 to $\hat{R}_1$ s.t. $S_0 \wedge \delta_N \to \hat{R}_1{}'$ is valid

FINDCLAUSES

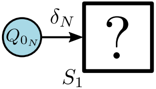
Frame Repair

Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

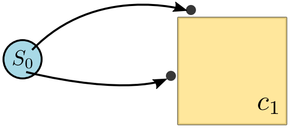
Goal: Compute frame sequence S for mode N



Frame Sequence S

Violating clauses

c_1, c_3

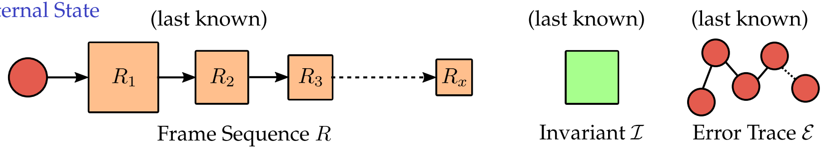


$S_0 \wedge \delta_N \not\rightarrow c_1'$

Repair R_1 to $\hat{R_1}$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R_1}'$ is valid

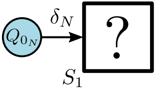
Frame Repair

Internal State

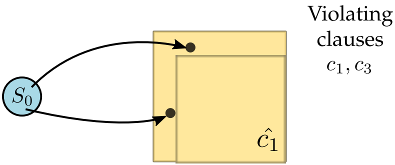


Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S



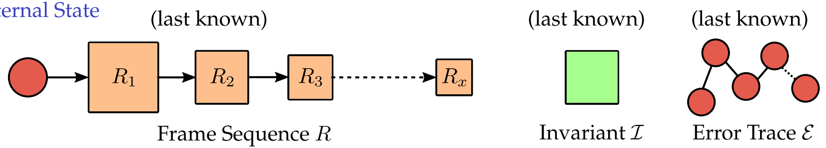
$S_0 \wedge \delta_N \rightarrow \hat{c_1}'$

Repair R_1 to $\hat{R_1}$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R_1}'$ is valid

EXPANDCLAUSE

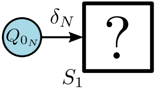
Frame Repair

Internal State

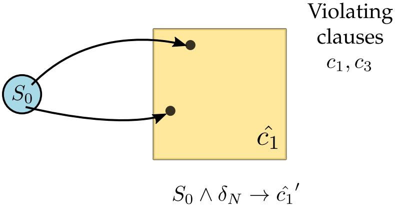


Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S

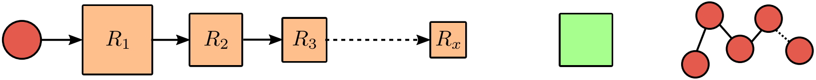


Repair R_1 to $\hat{R_1}$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R_1}'$ is valid

Frame Repair

Internal State

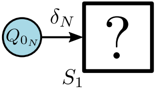
(last known) (last known) (last known)



Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

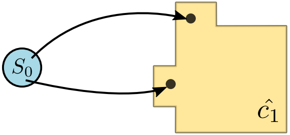
Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S

Violating clauses c_1, c_3



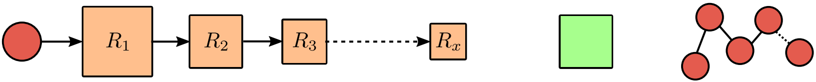
$S_0 \wedge \delta_N \rightarrow \hat{c_1}'$

Repair R_1 to $\hat{R_1}$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R_1}'$ is valid

SHRINKCLAUSE

Frame Repair

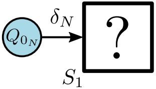
Internal State



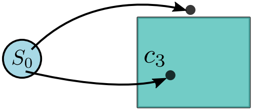
Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S



Violating clauses c_1, c_3

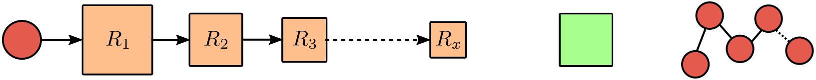
$S_0 \wedge \delta_N \not\to c_3'$

Repair R_1 to $\hat{R}_1$ s.t. $S_0 \wedge \delta_N \to \hat{R}_1{}'$ is valid

Frame Repair

Internal State

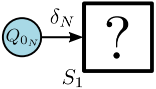
(last known) (last known) (last known)



Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

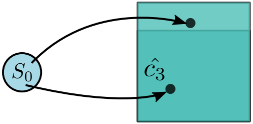
Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S

Violating clauses c_1, c_3



$S_0 \wedge \delta_N \rightarrow \hat{c_3}'$

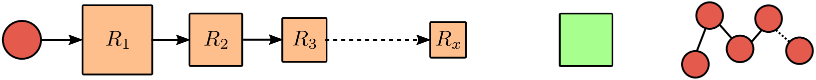
Repair R_1 to $\hat{R_1}$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R_1}'$ is valid

ExpandClause

Frame Repair

Internal State

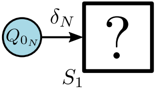
(last known) (last known) (last known)



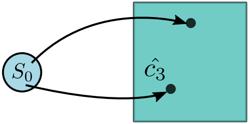
Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

Goal: Compute frame sequence S for mode N



Frame Sequence S



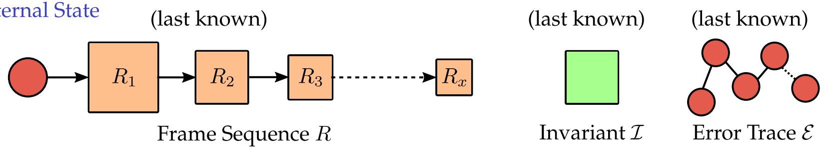
Violating clauses c_1, c_3

$S_0 \wedge \delta_N \rightarrow \hat{c_3}'$

Repair R_1 to $\hat{R_1}$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R_1}'$ is valid

Frame Repair

Internal State



Model $N = (\Sigma, Q_N, Q_{0_N}, \delta_N)$ and Safety property φ

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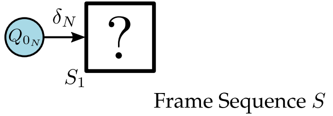

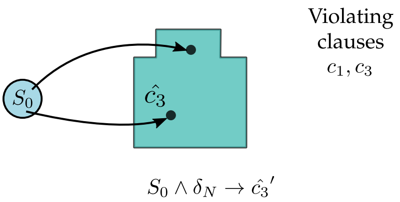

Repair R_1 to $\hat{R_1}$ s.t. $S_0 \wedge \delta_N \rightarrow \hat{R_1}'$ is valid

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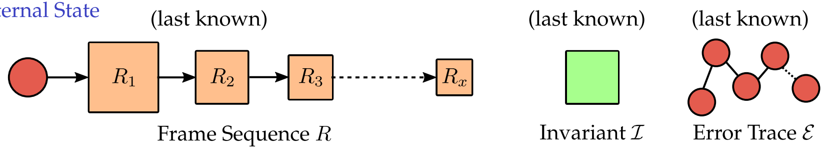

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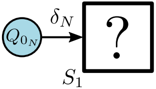
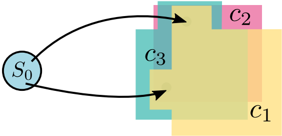


Frame Sequence S



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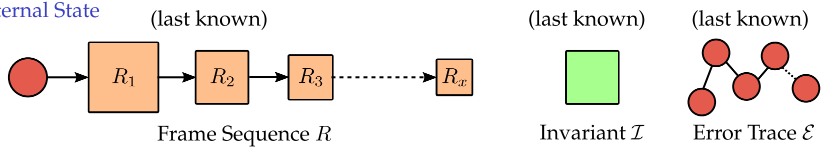

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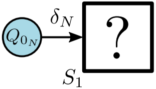

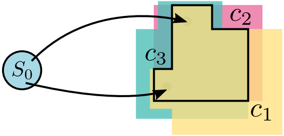

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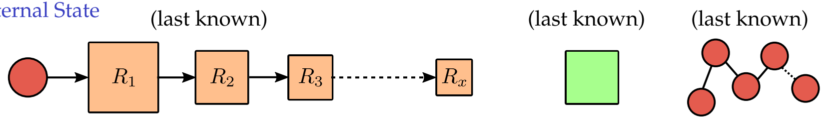

Frame Sequence R Invariant $\mathcal{I}$ Error Trace $\mathcal{E}$

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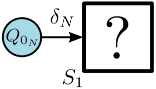

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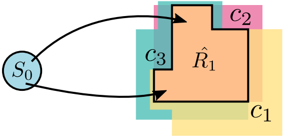

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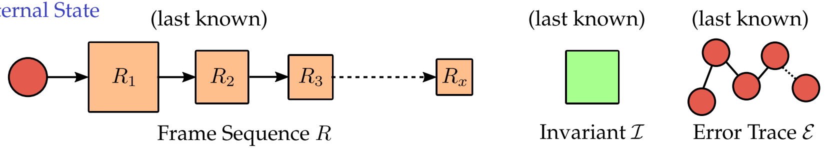

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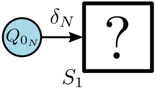

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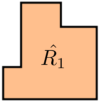

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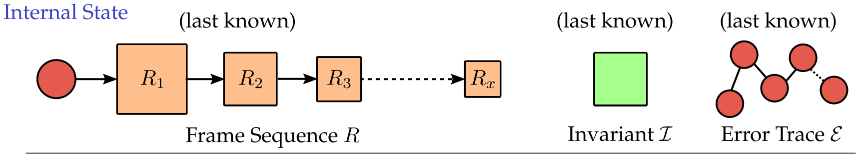

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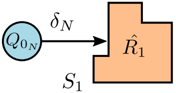
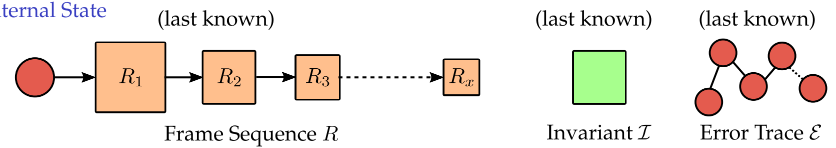


Frame Sequence S

Strengthen Frames

Internal State



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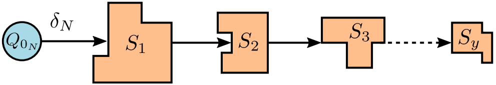
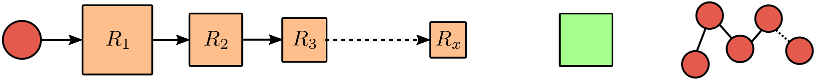


Frame Sequence S

Strengthen Frames

Internal State

(last known) (last known) (last known)



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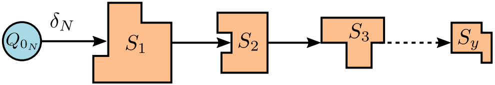
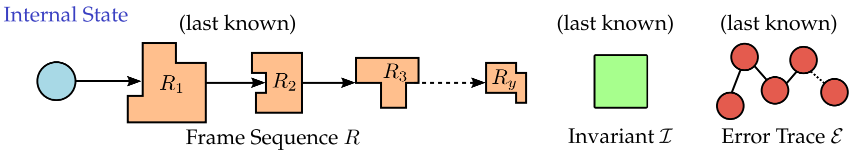


Frame Sequence S

$N \models \varphi$

Invariant: $S_{i+1} \equiv S_i$

Strengthen Frames



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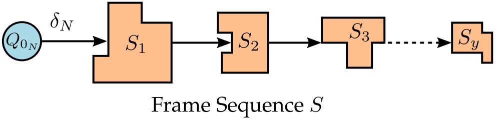

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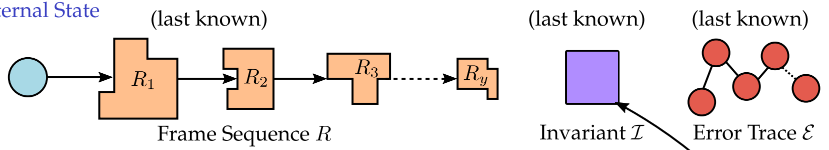
Update last known

1. Frame Sequence

Strengthen Frames

Internal State



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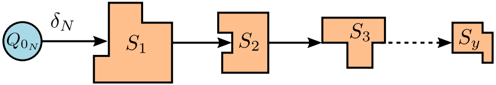

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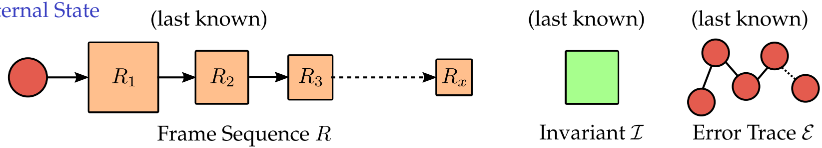
1. Frame Sequence
2. Invariant

Strengthen Frames

Internal State



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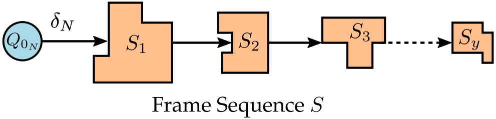
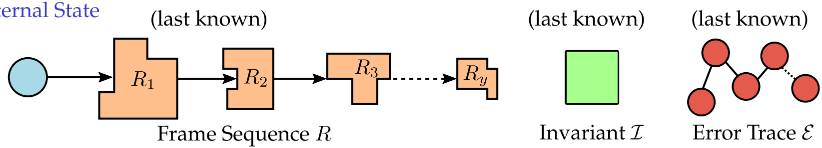


$N \not\models \varphi$

Error Trace: $\mathcal{E}_N$

Strengthen Frames

Internal State



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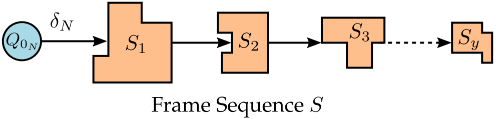

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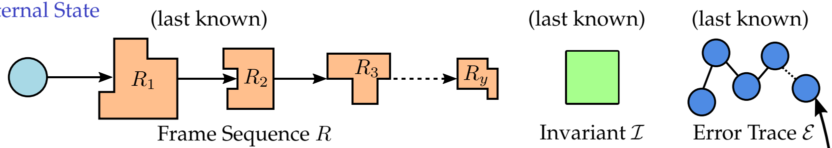
1. Frame Sequence

Strengthen Frames

Internal State



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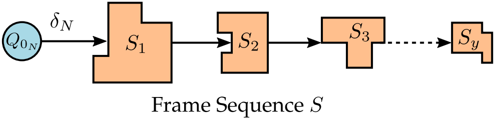

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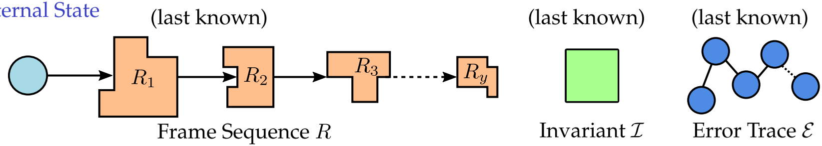
2. Error Trace

Strengthen Frames

Internal State



Ready for next model

Experiment Setup

- FuseIC3 is coded in C++ and uses MathSAT5 as SAT solver.

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- Benchmarks evaluated
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  2. Selected benchmarks from HWMCC 2015
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  3. Boeing AIR 6110 Wheel Braking System (WBS) (Bozzano et al., 2015)

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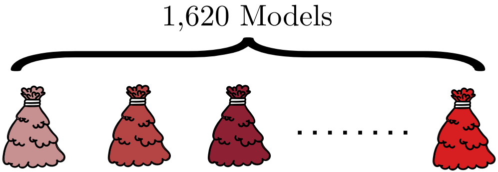
NASA ATC Benchmark



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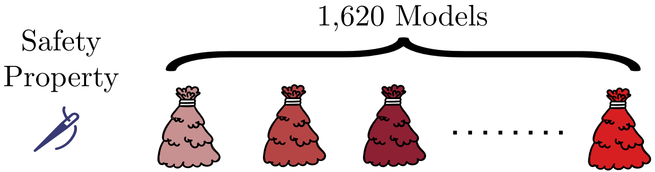

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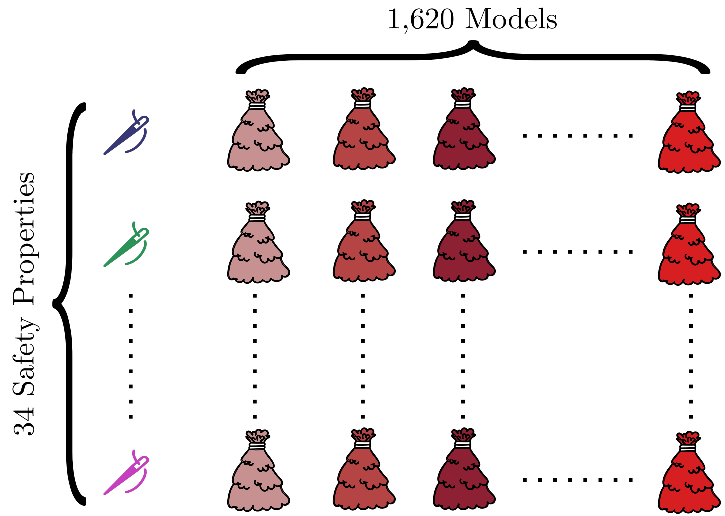

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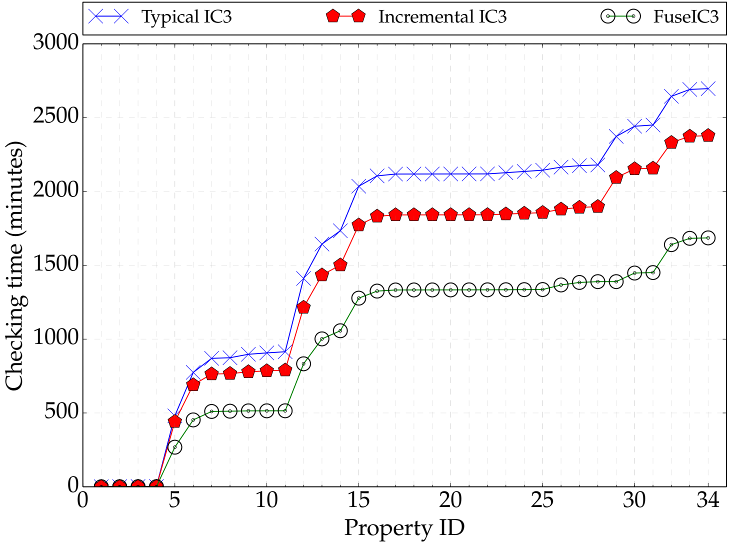

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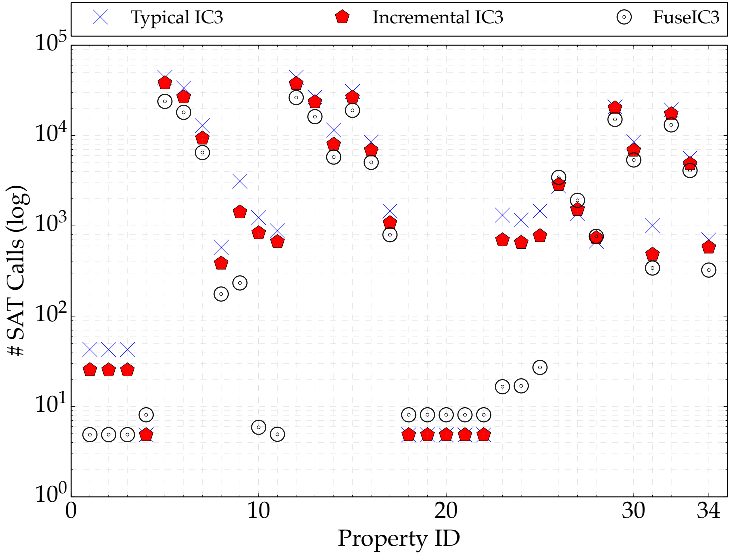

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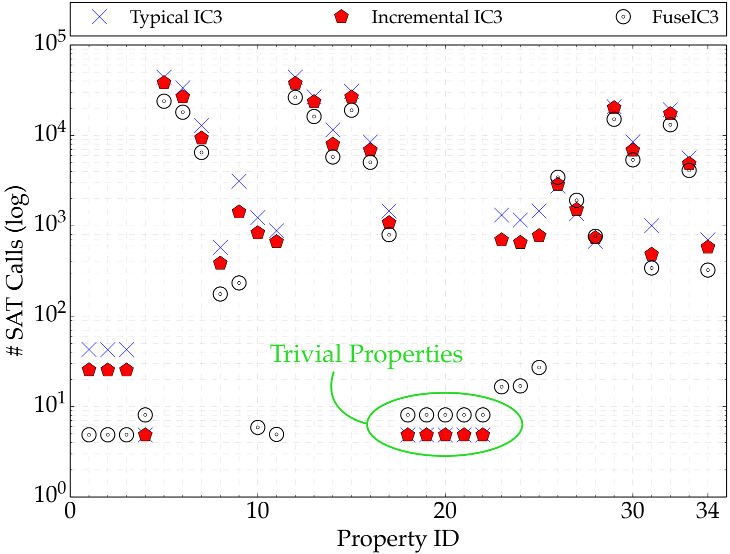

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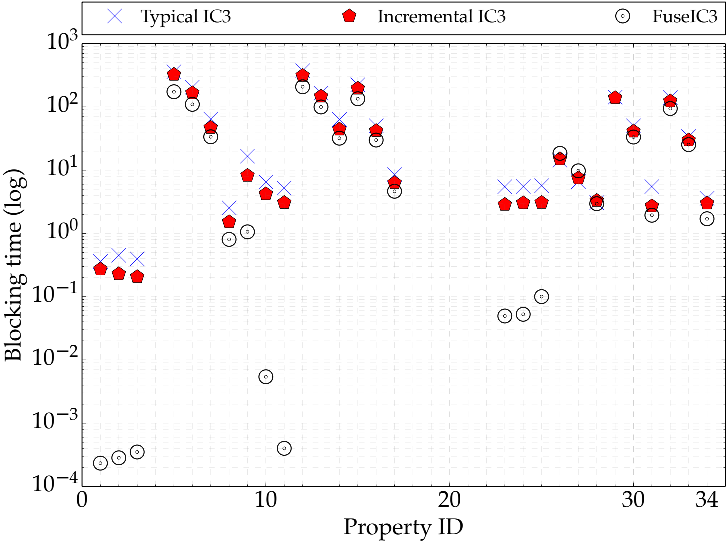
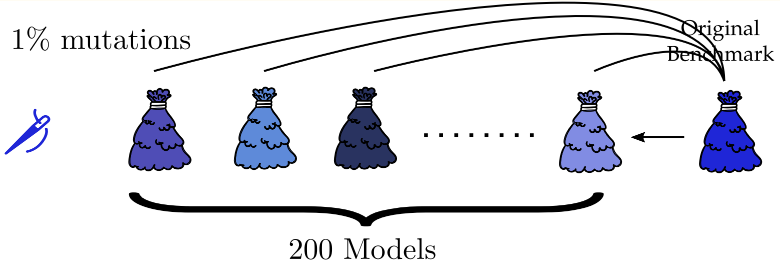


Selected HWMCC Benchmarks

Original
Benchmark

Selected HWMCC Benchmarks



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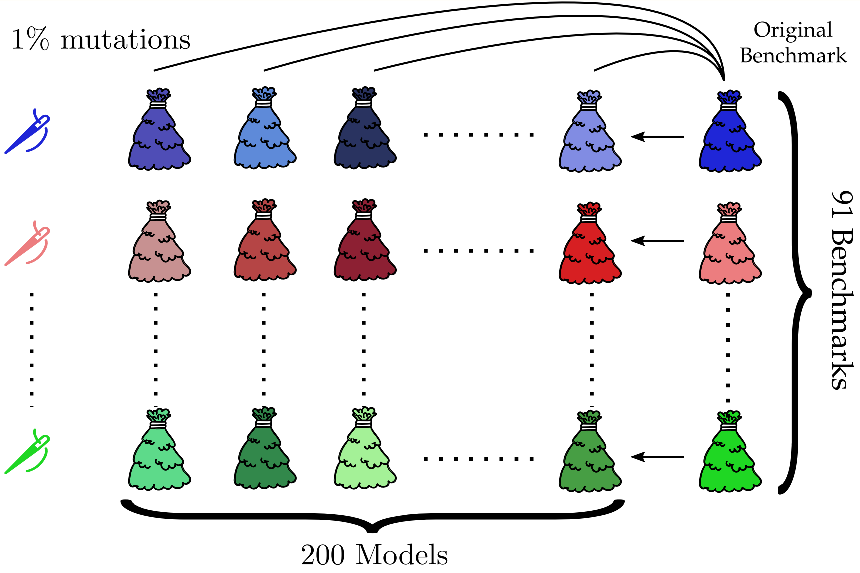

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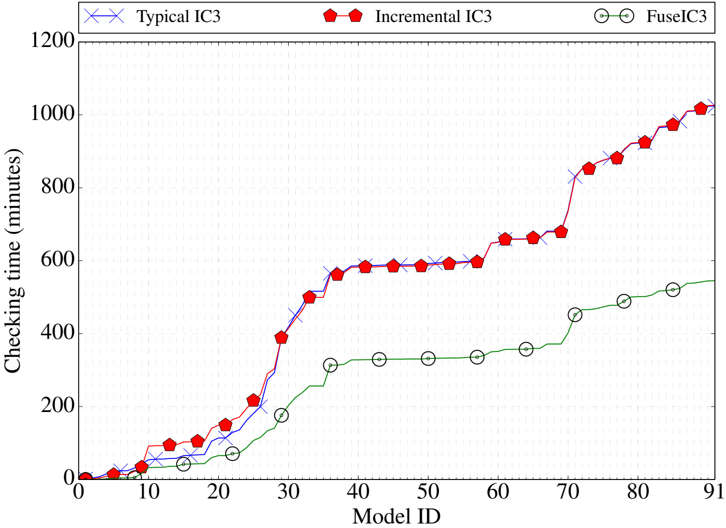

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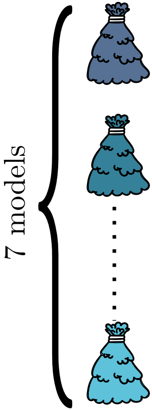

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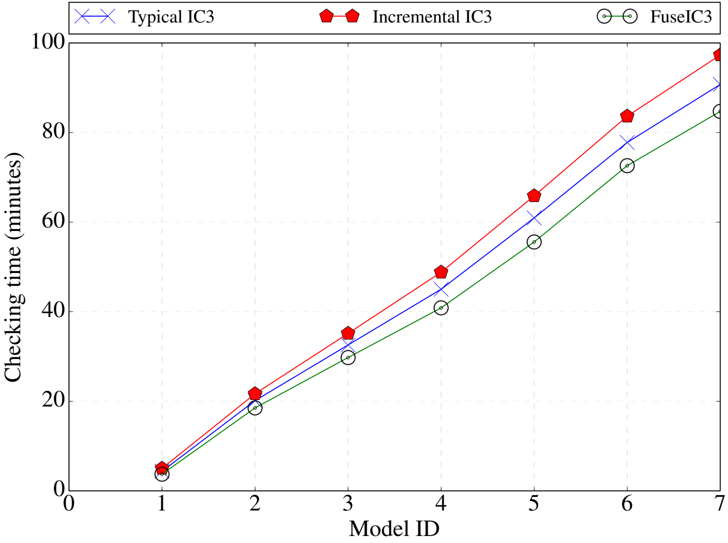

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Thank You!

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