More Scalable LTL Model Checking via Discovering Design-Space Dependencies (D^3)

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April 17, 2018

Thanks to NSF CAREER Award CNS-1552934 for supporting this work.

What is a Design Space?

Airspace Allocation

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

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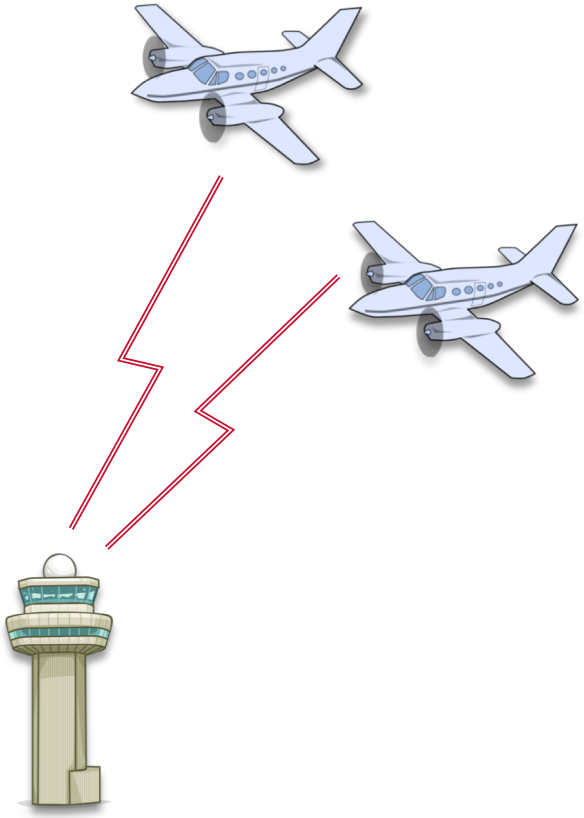

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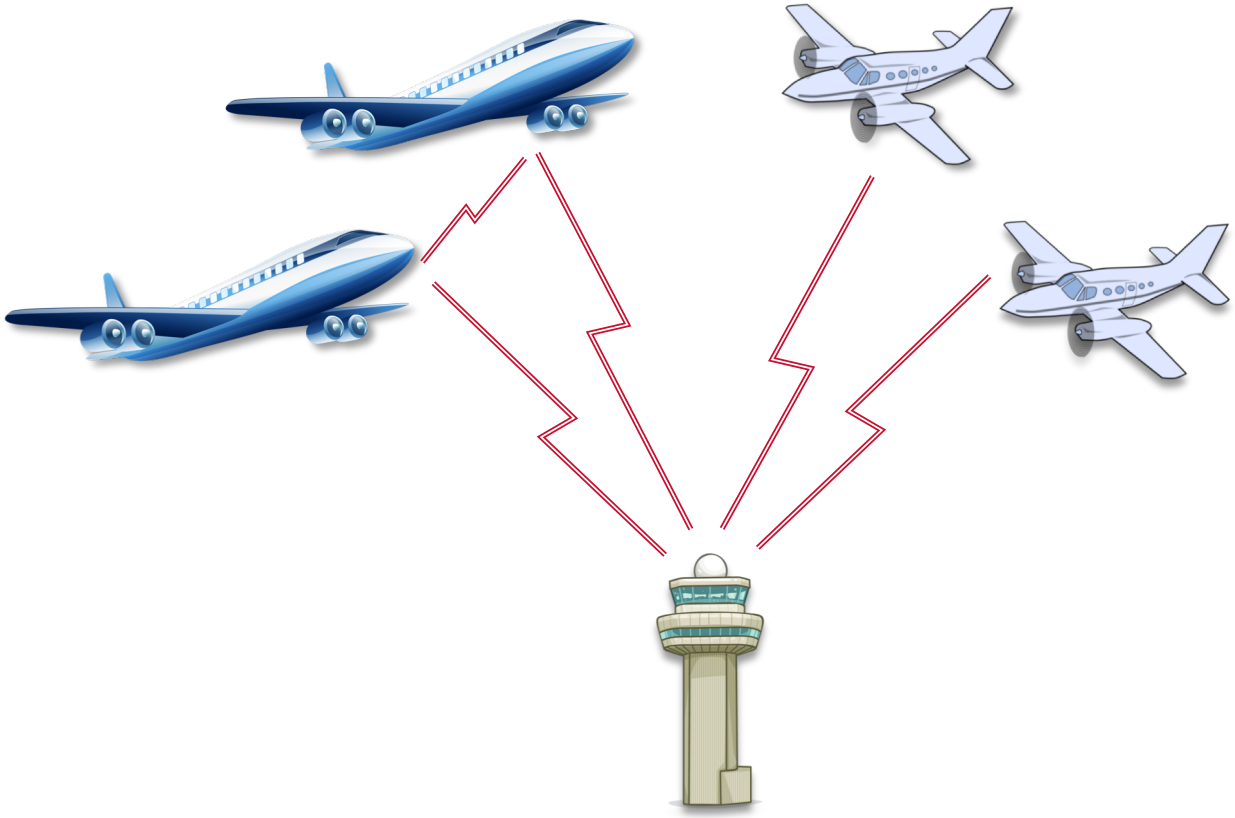

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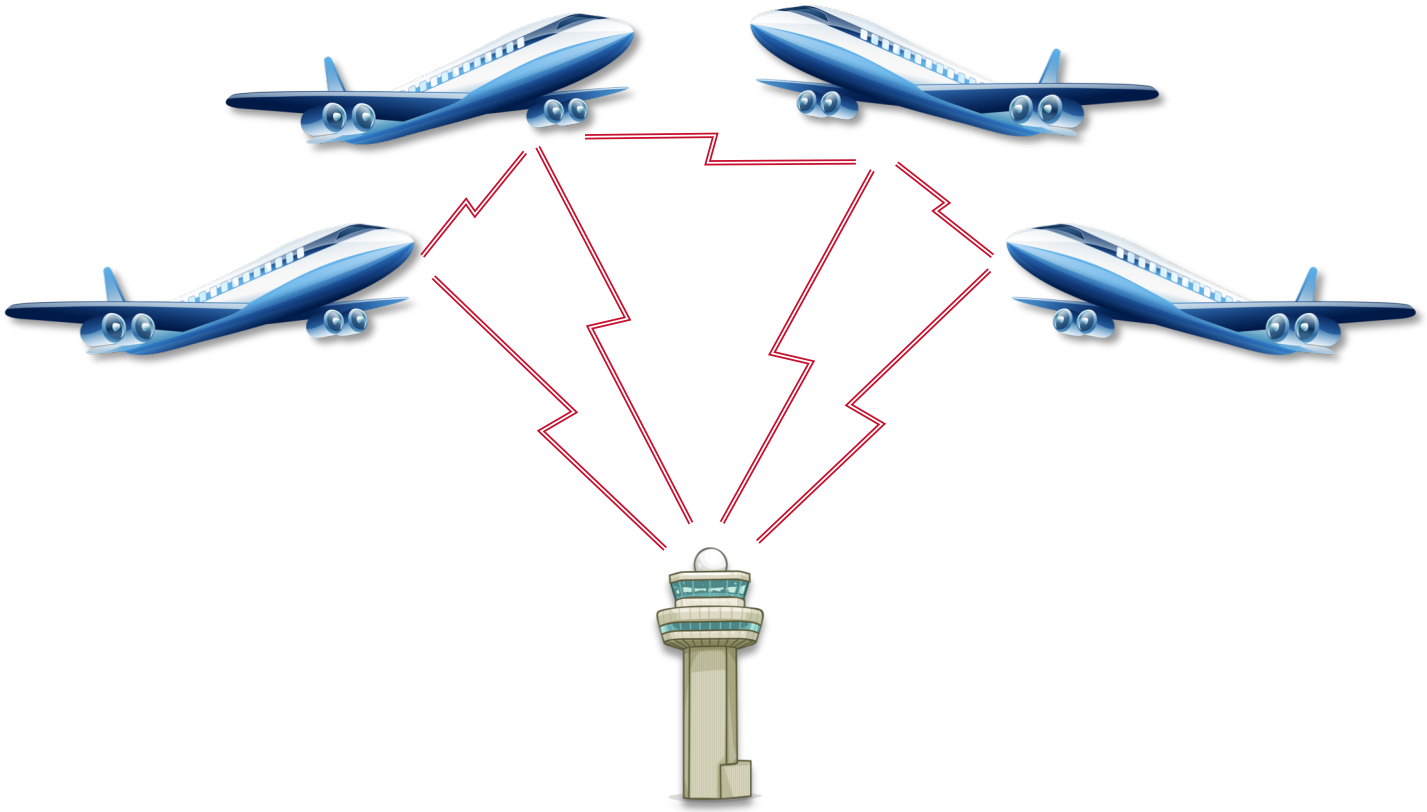

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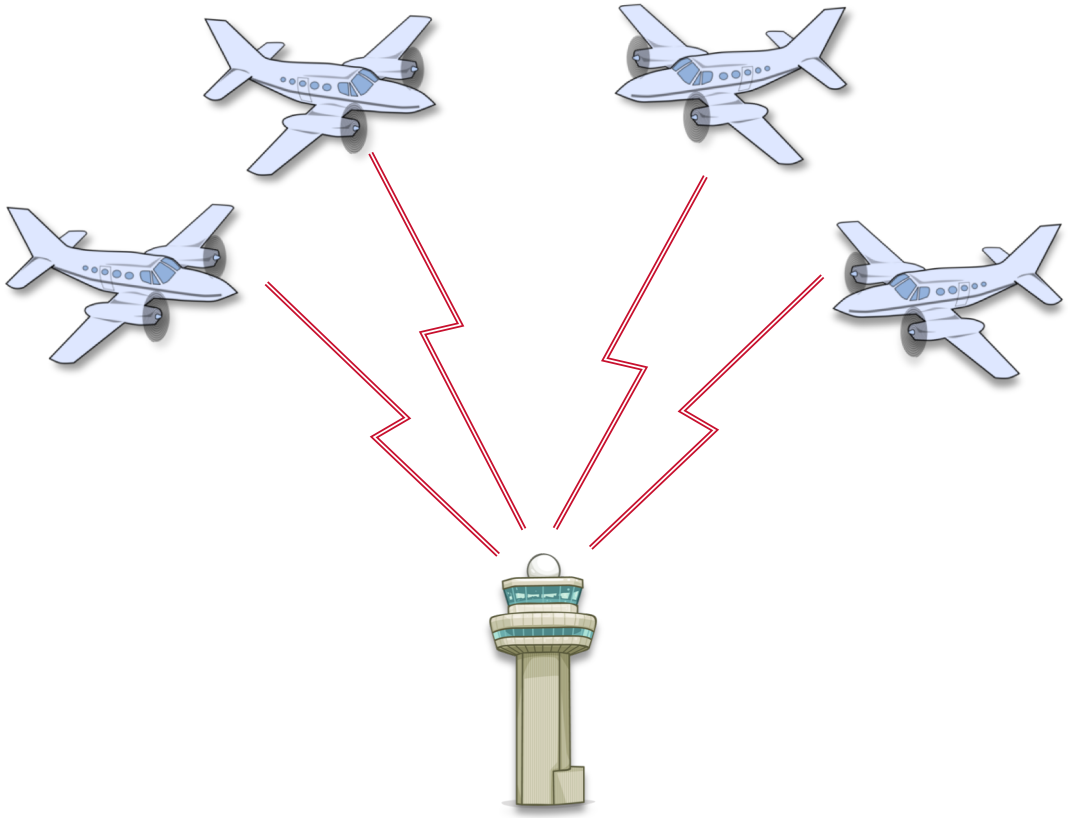

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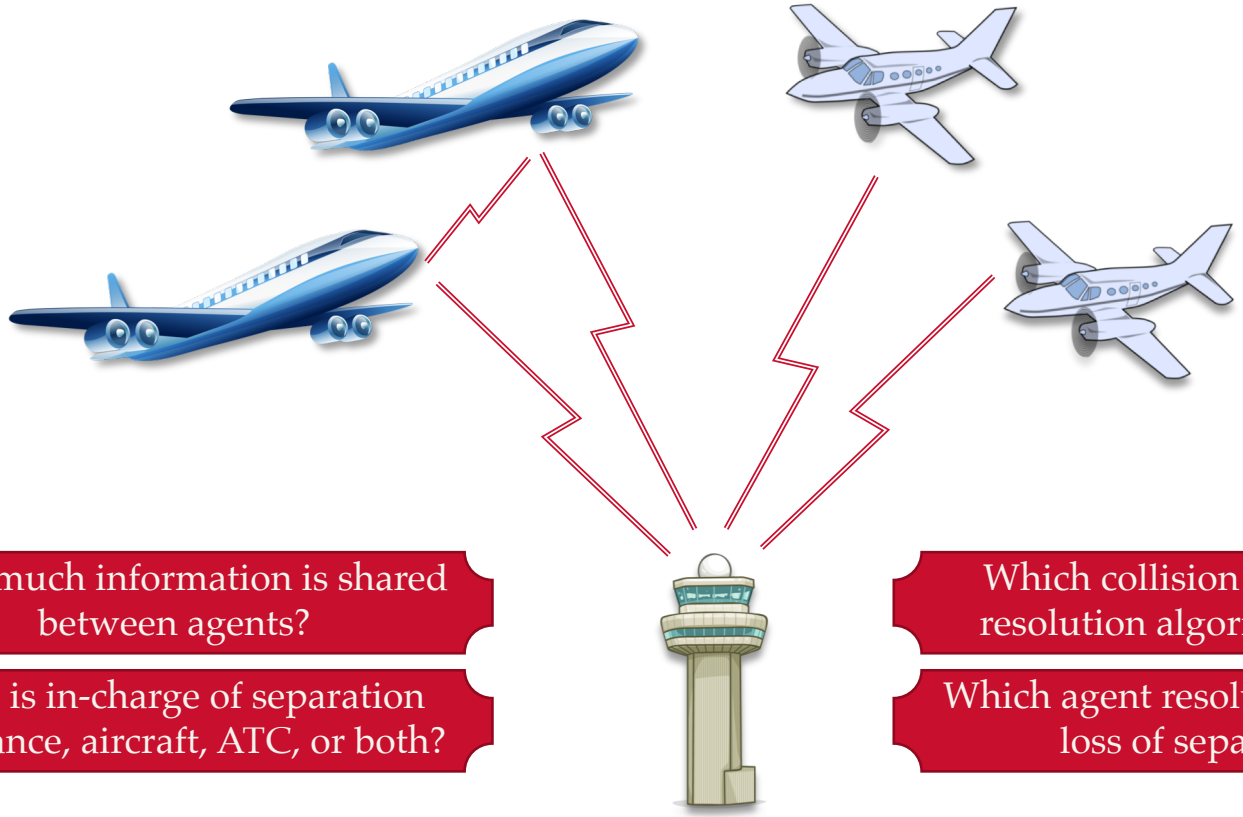

How much information is shared between agents?

Who is in-charge of separation assurance, aircraft, ATC, or both?

Which collision detection & resolution algorithm to use?

Which agent resolves a potential loss of separation?

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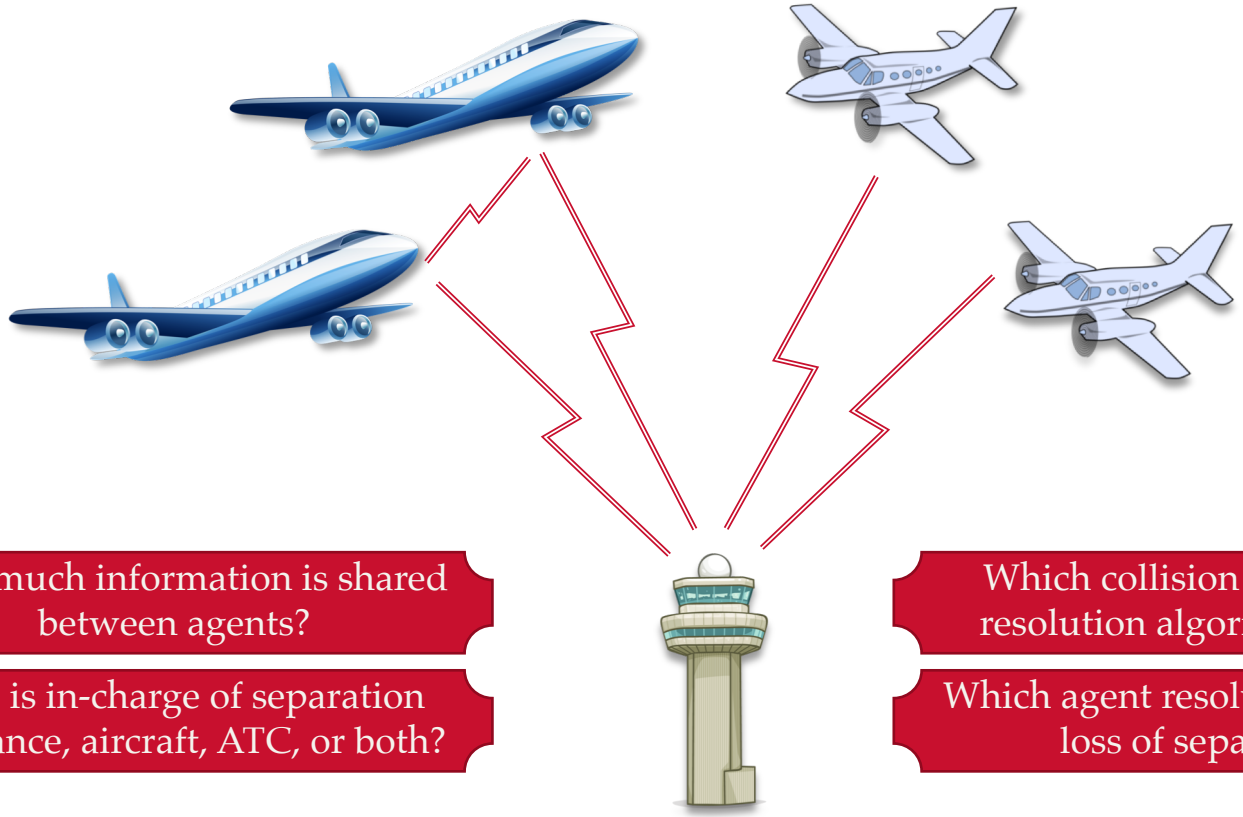

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Lots of Design Choices!

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Set of Design Choices for a System.

Design Space Analysis

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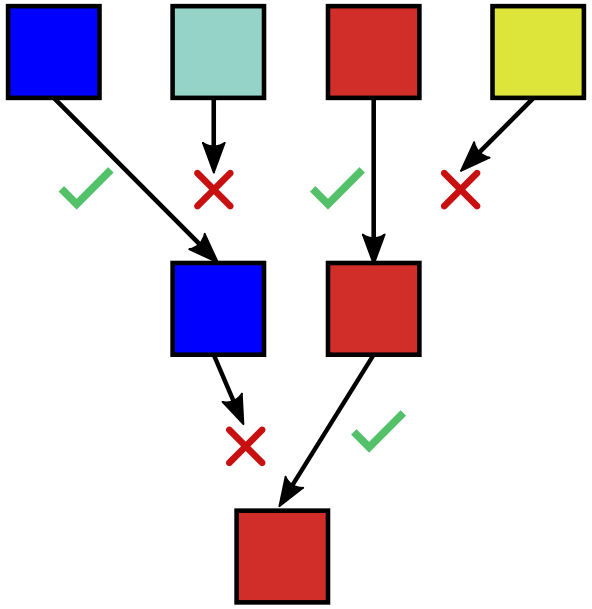

Alternative comparison via design space exploration

Design Space Analysis

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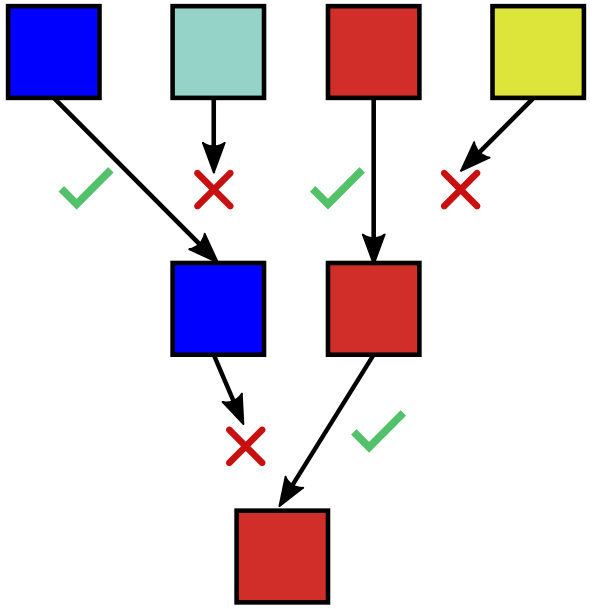

Alternative comparison via design space exploration

Model Checking!

Modeling Design Spaces

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- Classical Method
  - *every design choice leads to a separate model*

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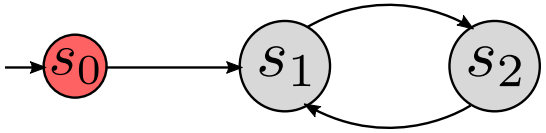

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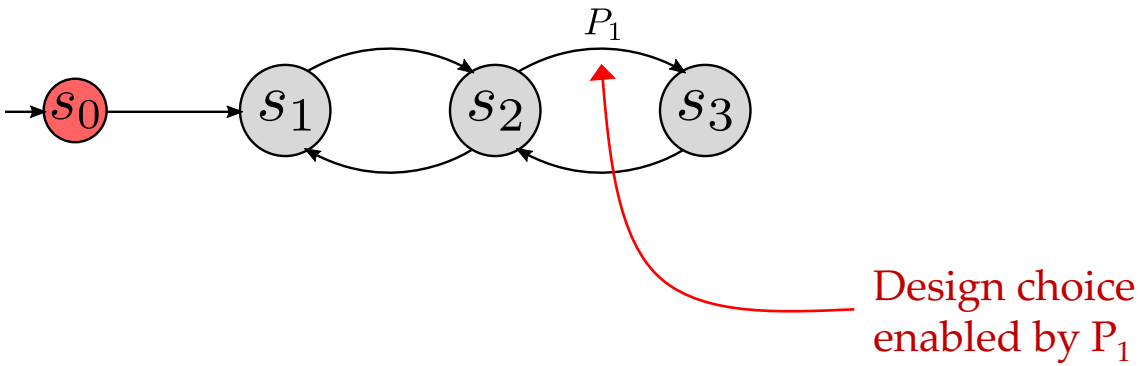

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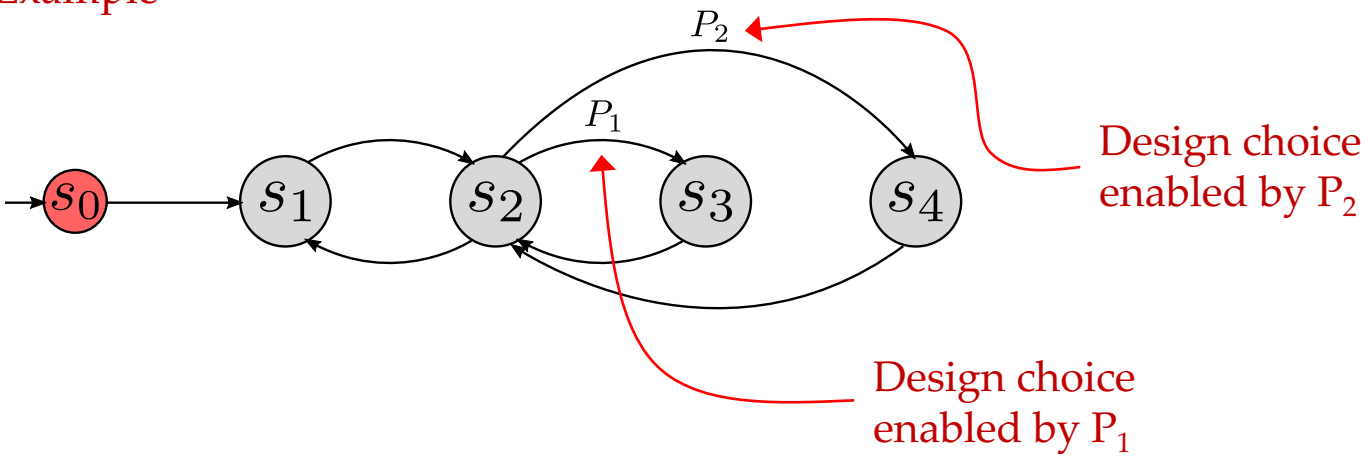

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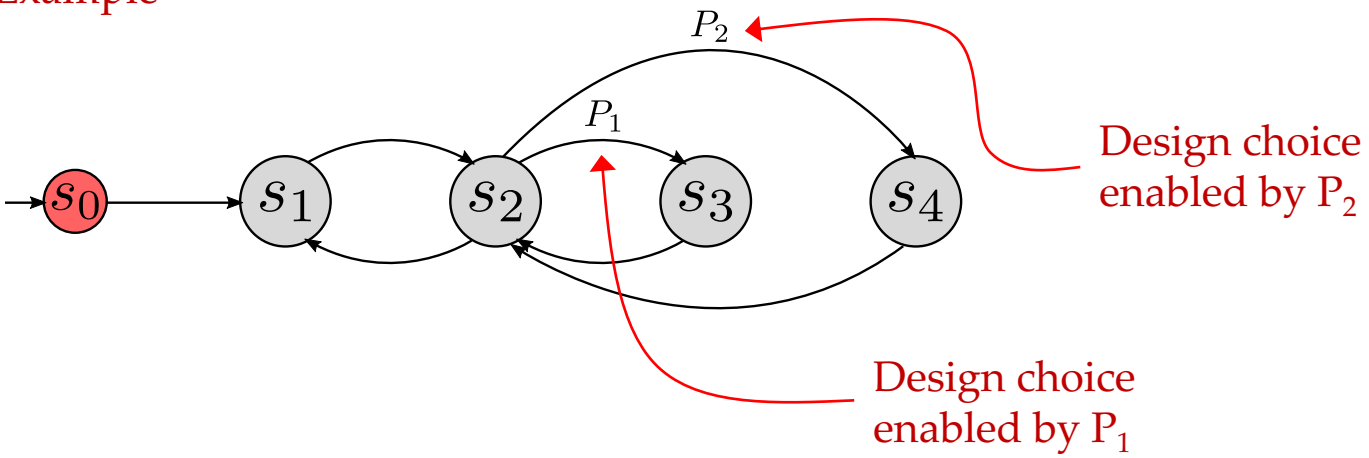
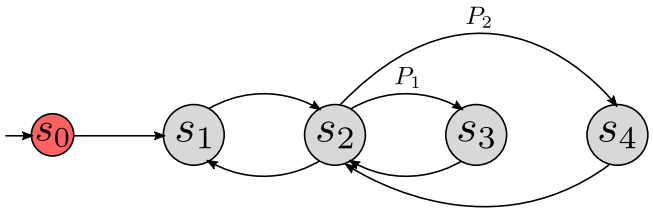


Combinatorial Transition System (CTS)

Model Checking Combinatorial Systems



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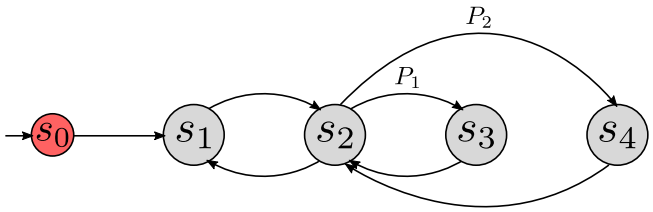

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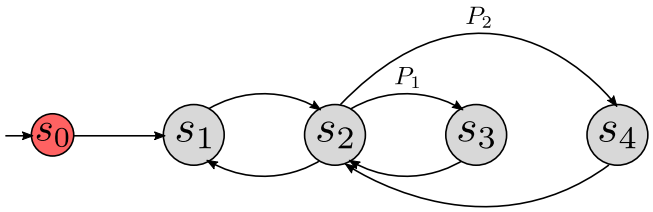

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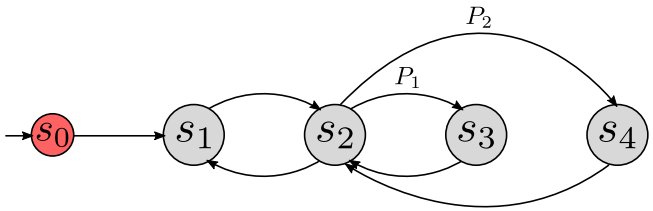

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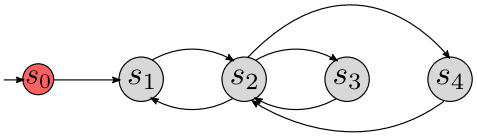
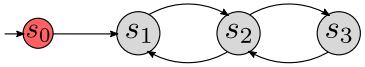
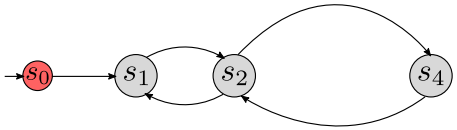


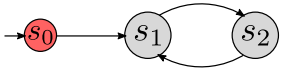
$(P_1 = \top, P_2 = \top)$



$(P_1 = \top, P_2 = \bot)$



$(P_1 = \bot, P_2 = \top)$



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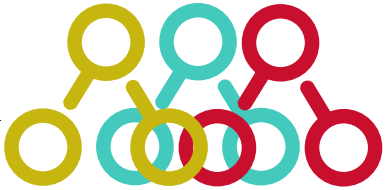
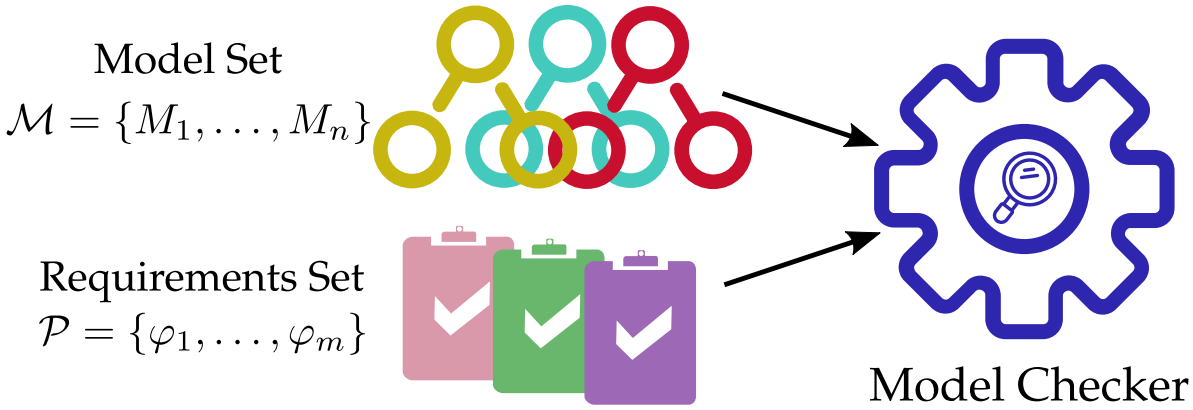
Model Checking Design Spaces

Model Set
$\mathcal{M} = \{M_1, \ldots, M_n\}$



Requirements Set
$\mathcal{P} = \{\varphi_1, \ldots, \varphi_m\}$

Model Checking Design Spaces



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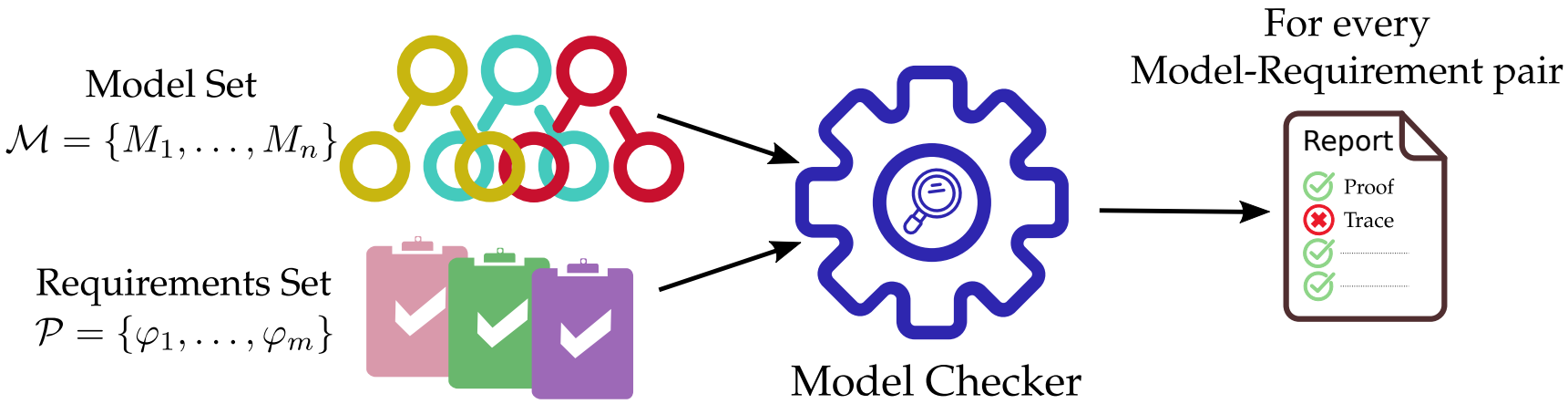

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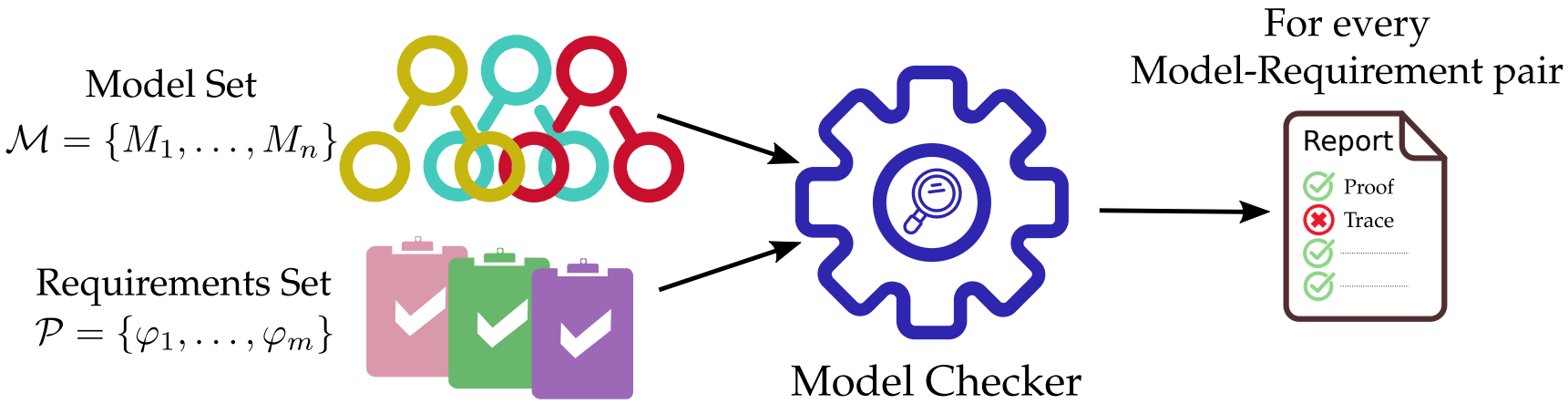


Our Goal

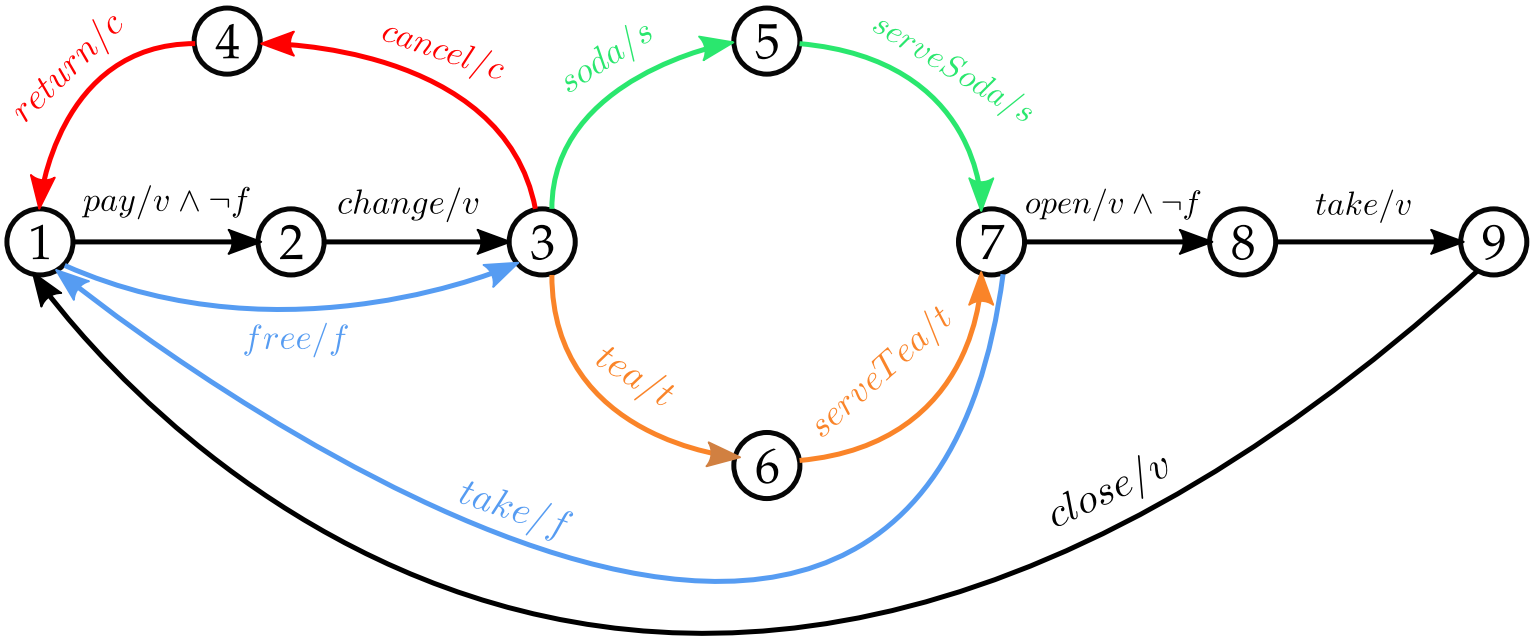
Make model-checking for design-spaces more scalable

Related Work

Related Work

1. Software Product Line verification
   (Resenmüller et al., 2010; Schirmeier et al., 2009; Classen et al., 2010, 2011, 2013; Dimovski et al., 2015)

Many Models
Many Requirements



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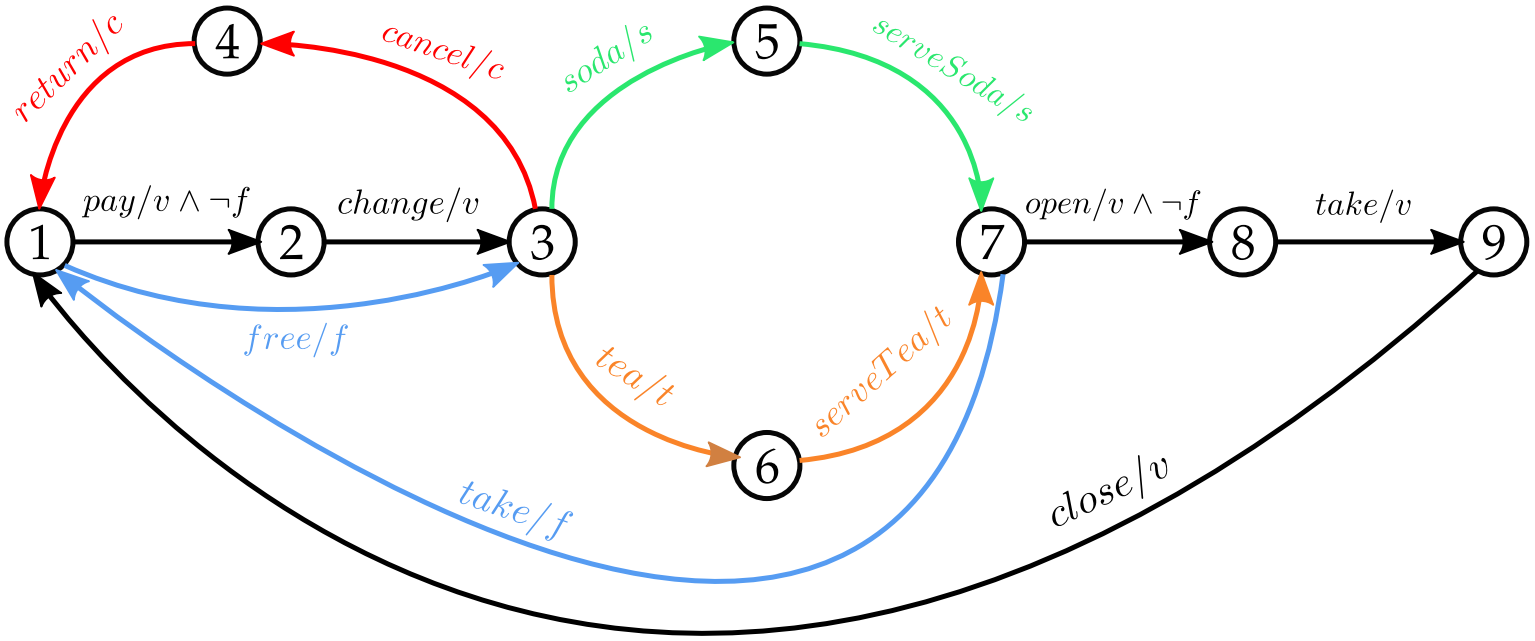
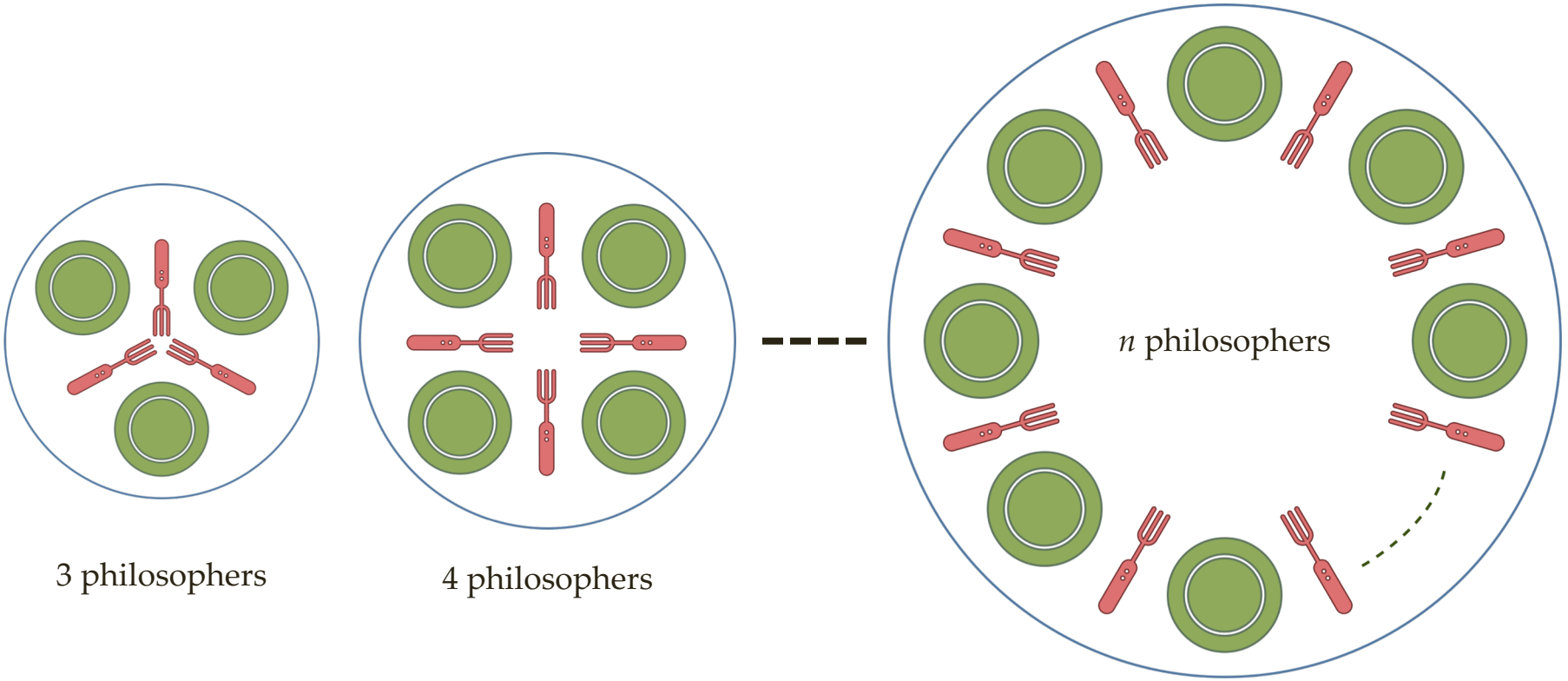


We focus on a more general approach that works with off-the-shelf model checkers

Related Work

2. Parameterized model checking (Emerson and Kahlon, 2000)

Many Models
One Requirement



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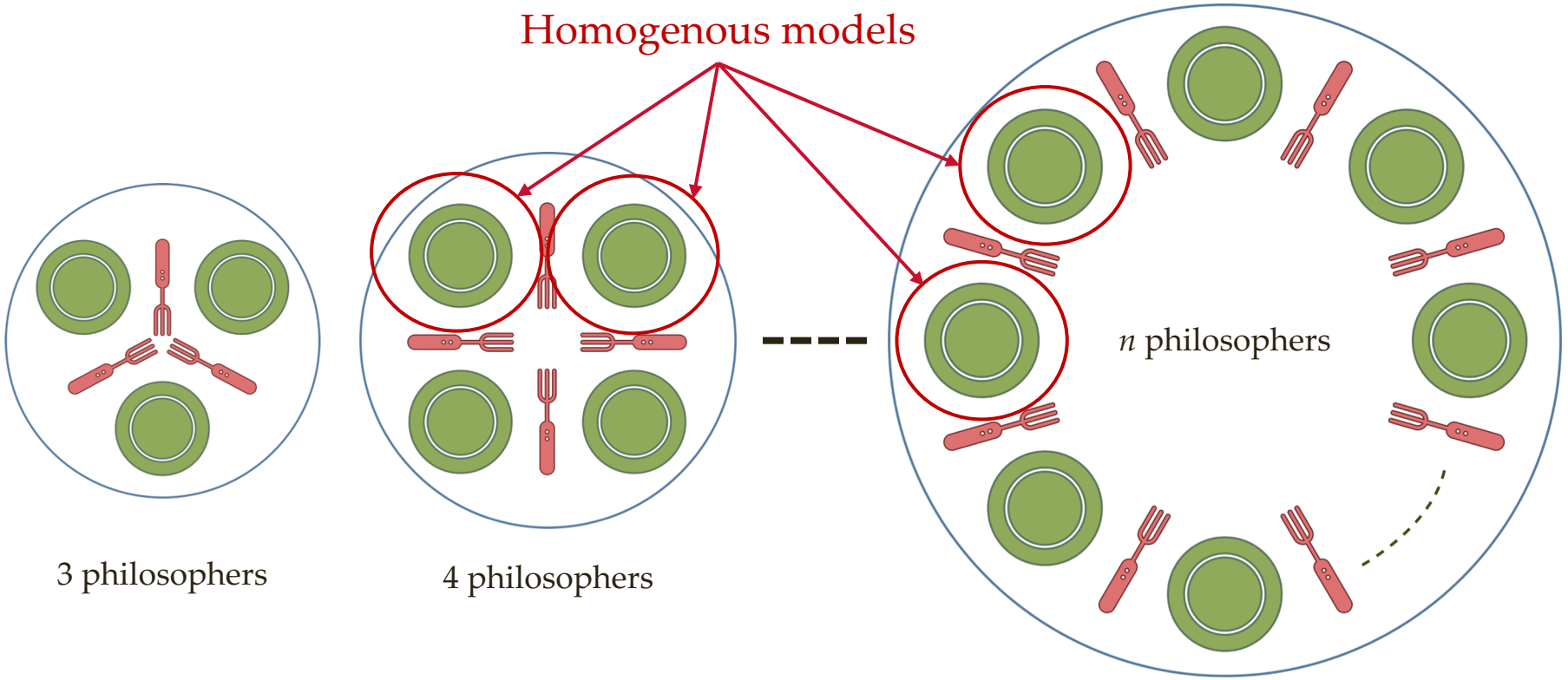

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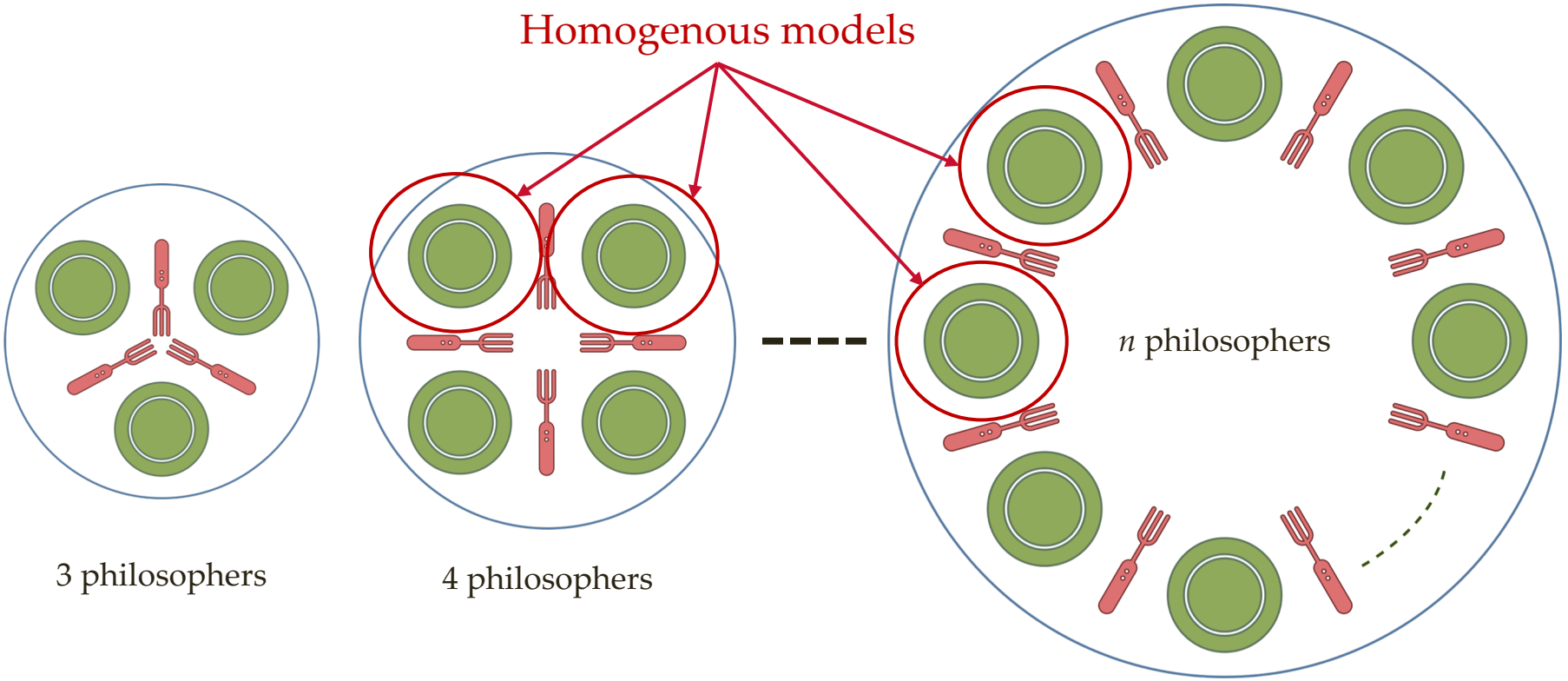

We focus on heterogenous and finite number of models

Related Work

3. Multi-property model checking

(Cabodi et al., 2010, 2011, 2017; Goldberg et al., 2018; Khasidashvili et al., 2006; Khasidashvili and Nadel, 2012; Camurati et al., 2014; Dureja and Rozier, 2017)

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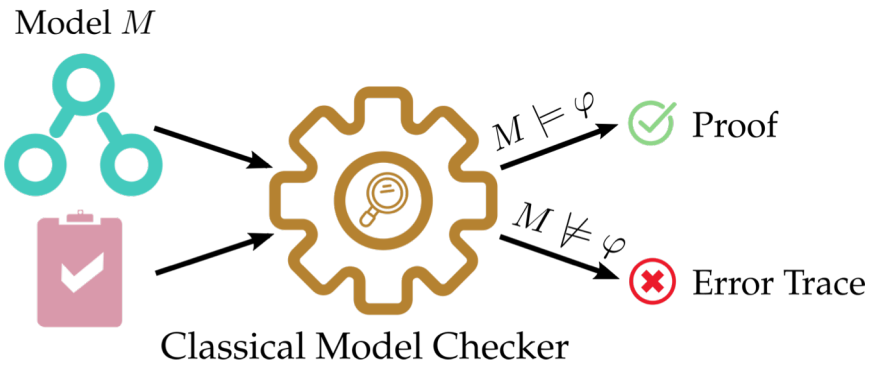
One Model
Many Requirements

Requirements

φ_1
φ_2
φ_3
φ_4
φ_5
φ_6
φ_7
φ_8



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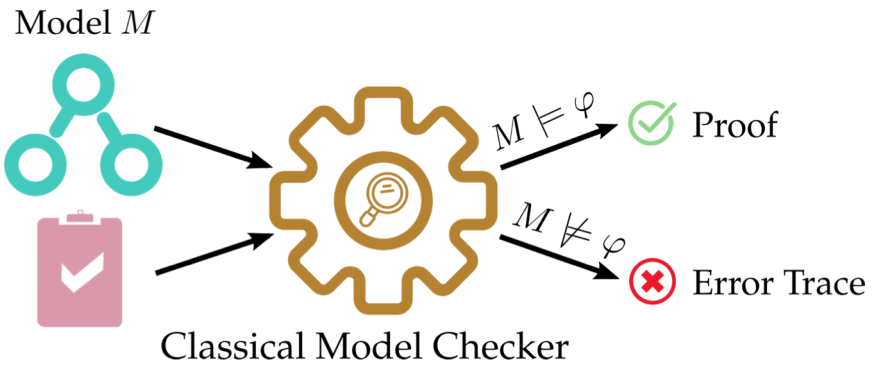

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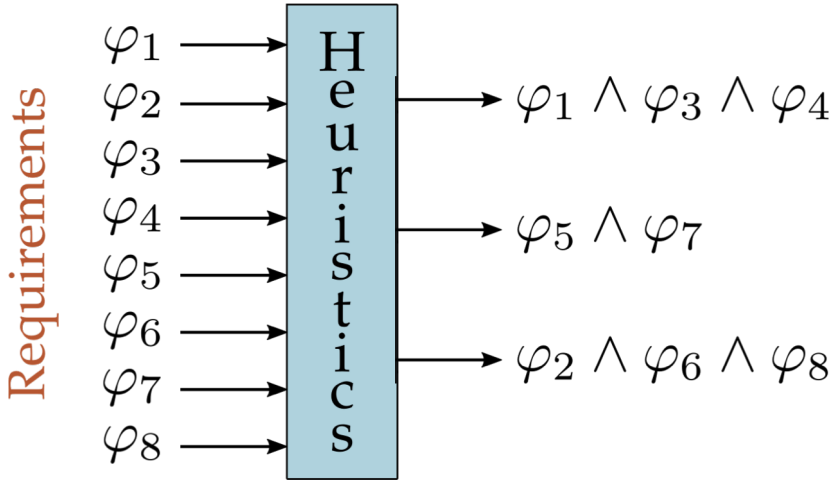

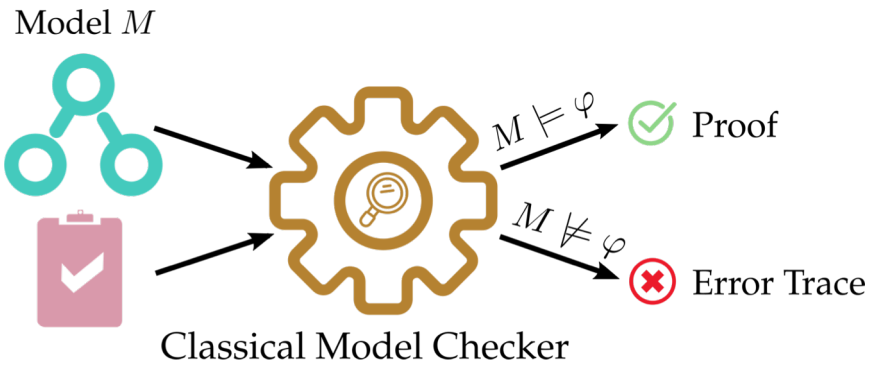

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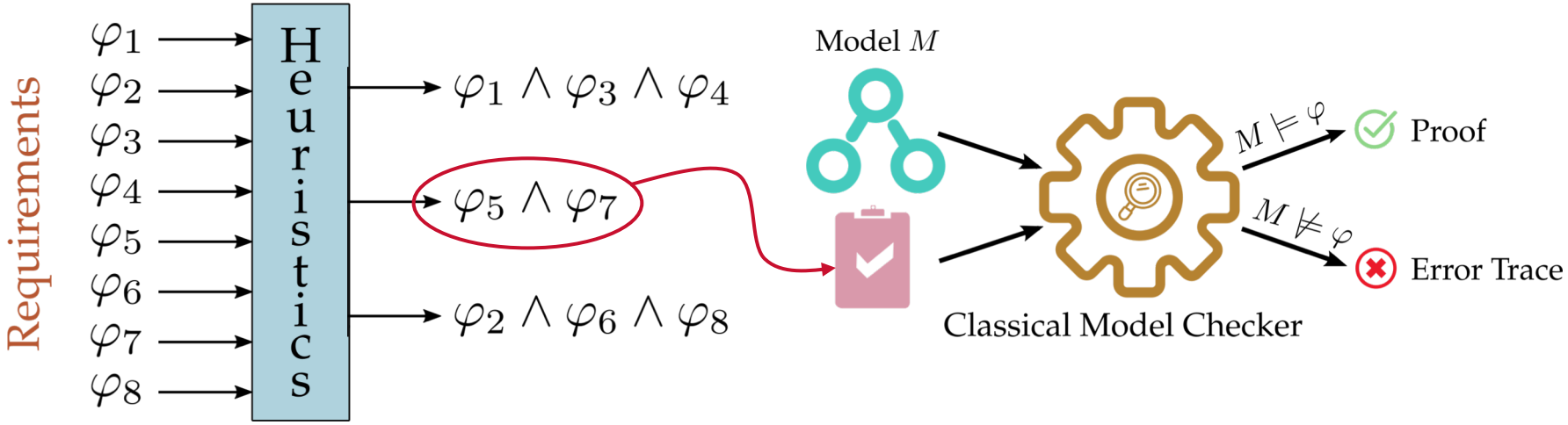

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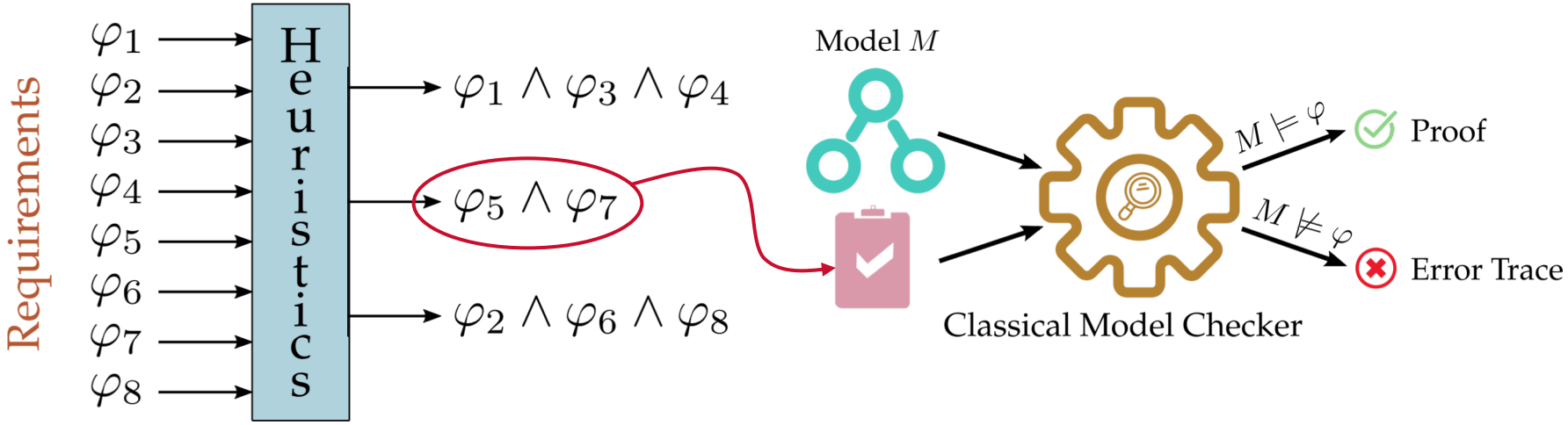

We focus on reducing the number of total model checking runs

Related Work

4. Multi-objective probabilistic model checking

(Denhert et al., 2015, 2016, Baier et al., 2014, Etessami et al., 2007, Forejt et al., 2011, Kwiatkowska et al., 2013, Quatmann et al., 2016)

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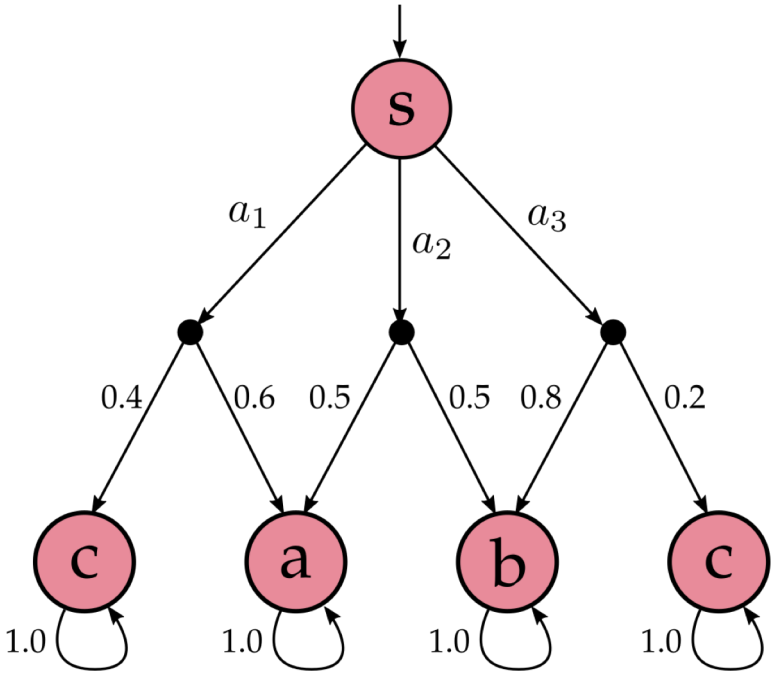

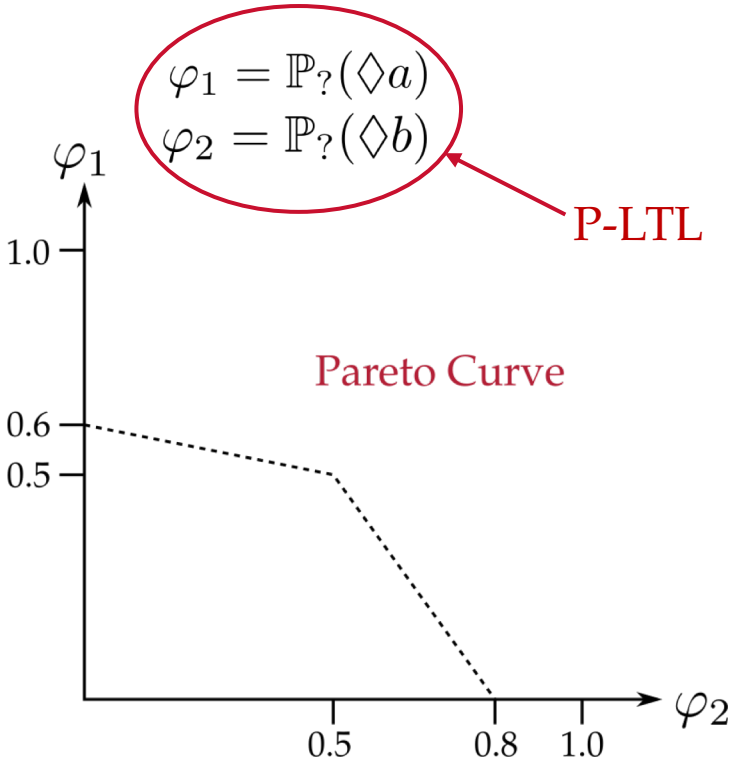

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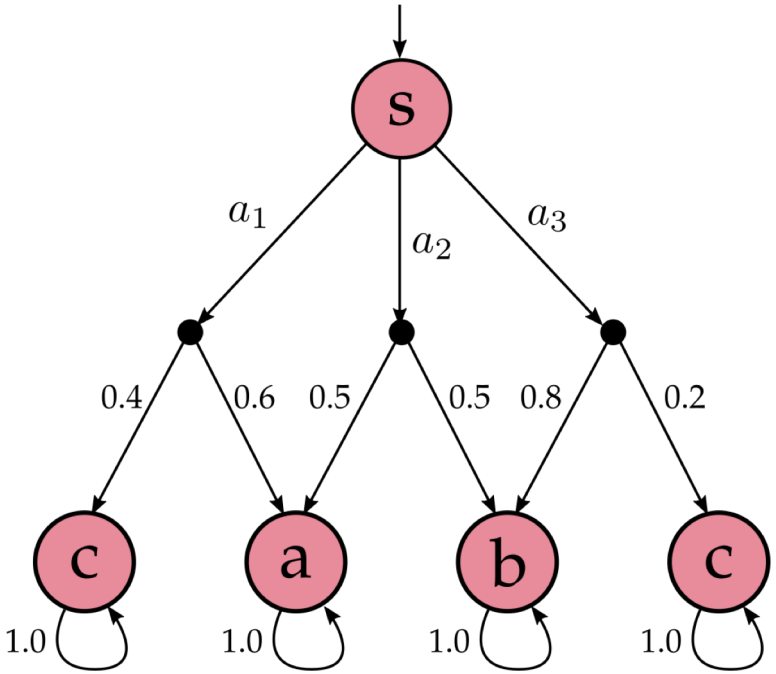
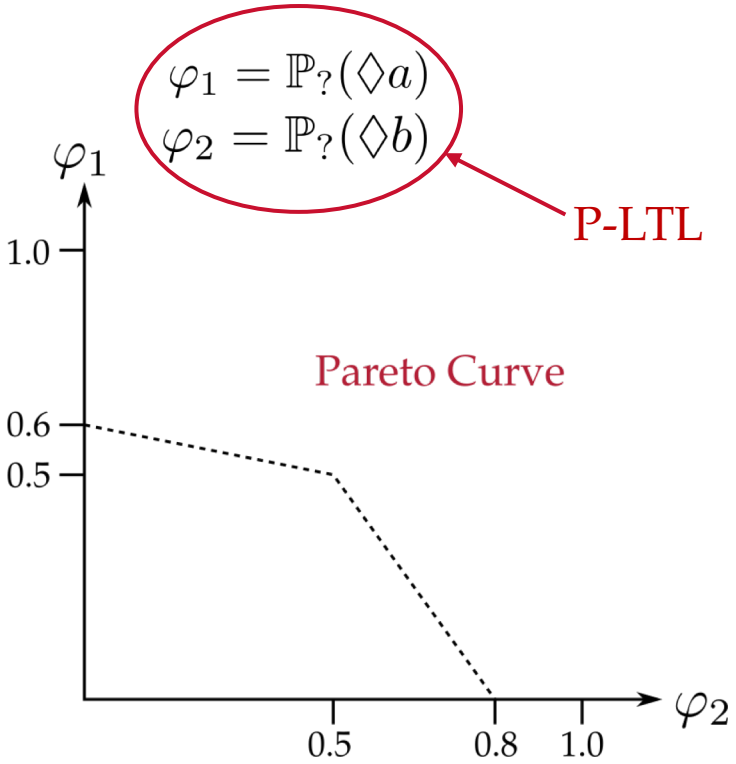
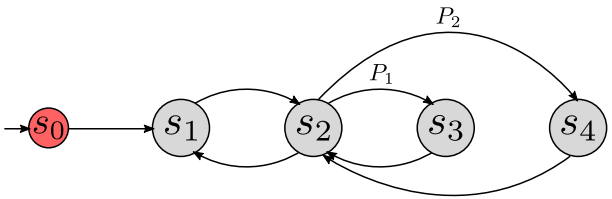




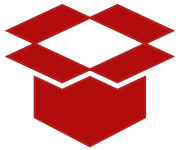
We focus on LTL/Invariant model checking with Boolean result.

Discover Design-Space Dependencies (D^3)

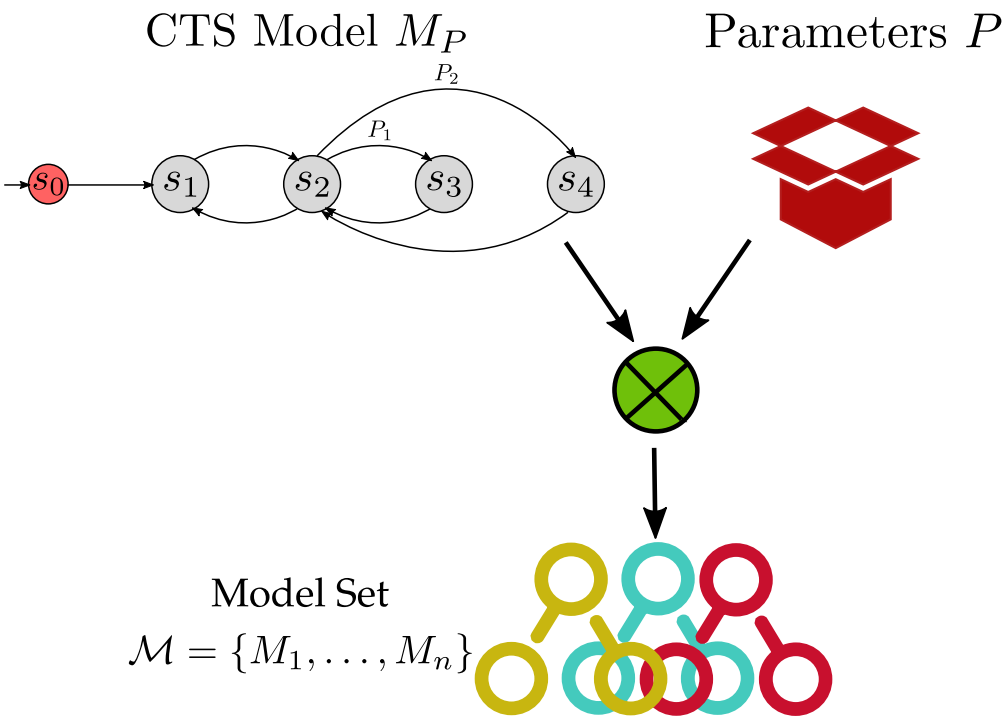
CTS Model M_P



Parameters P



Discover Design-Space Dependencies (D^3)



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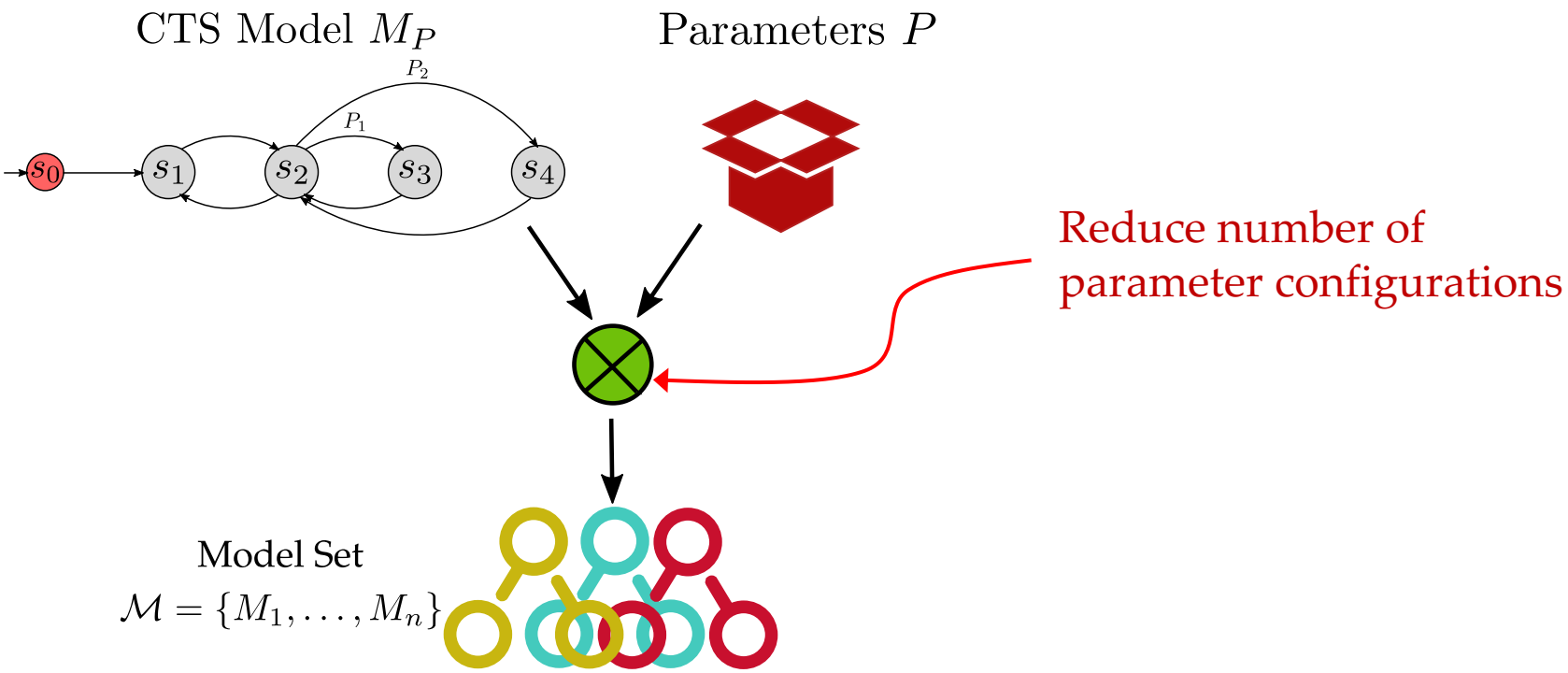

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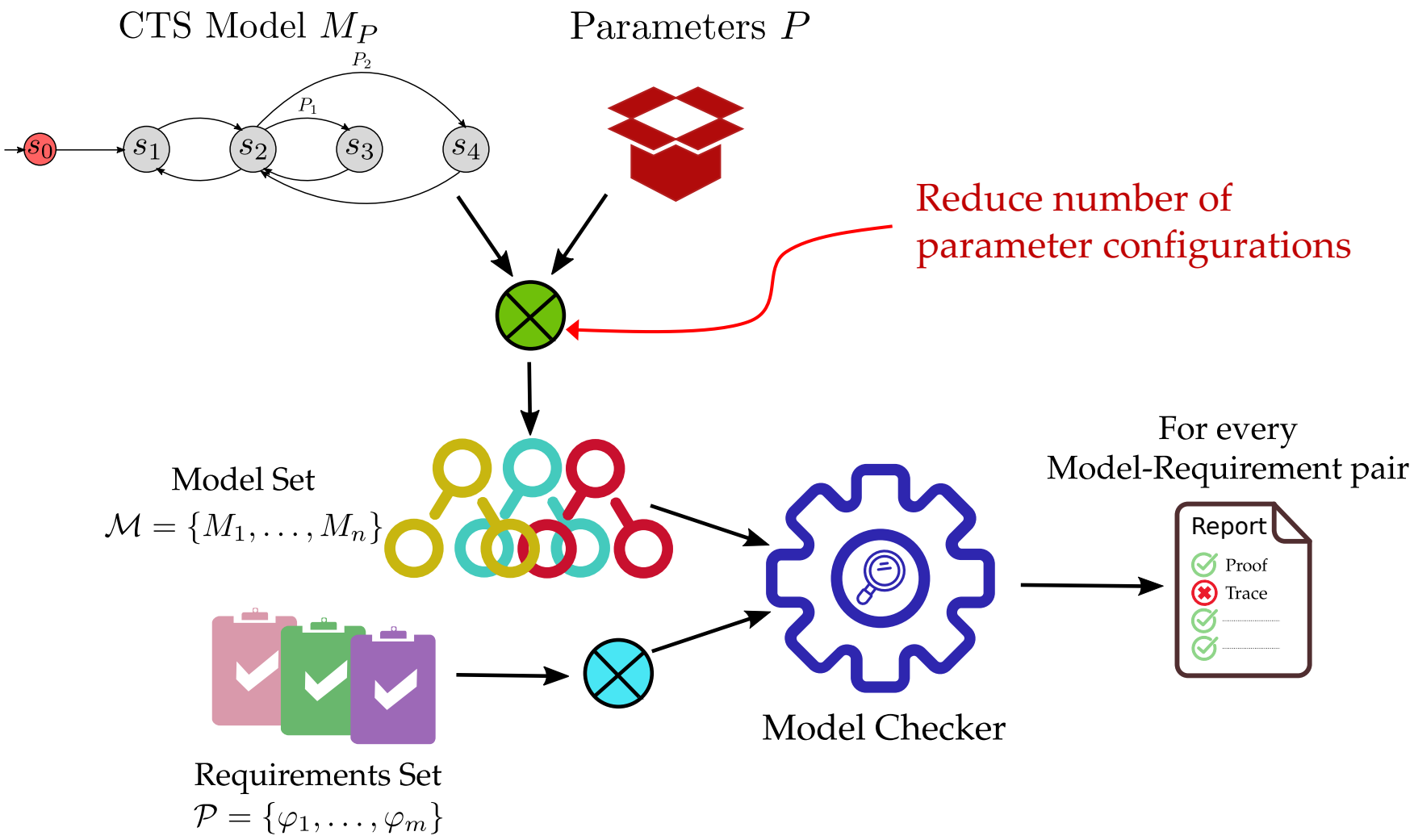

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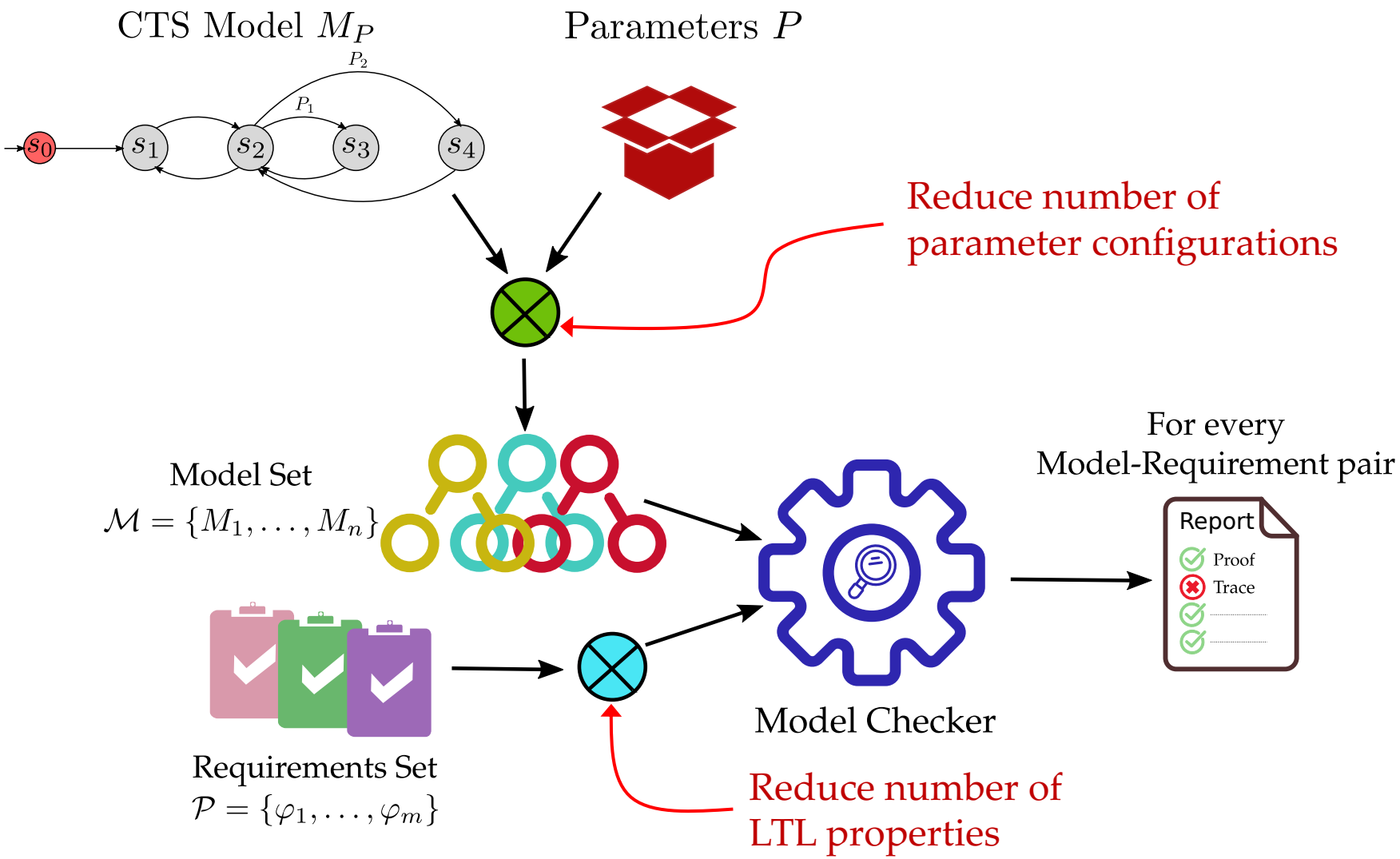
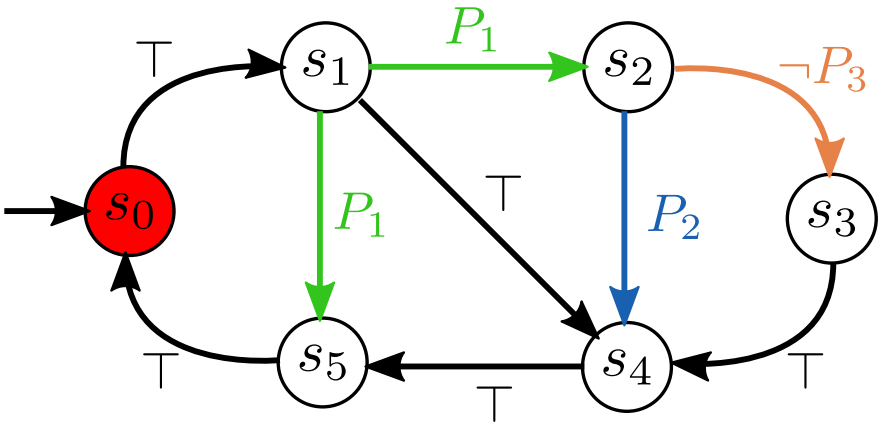


Parameter Configurations

Parameter Configurations

Motivating Example

M_P

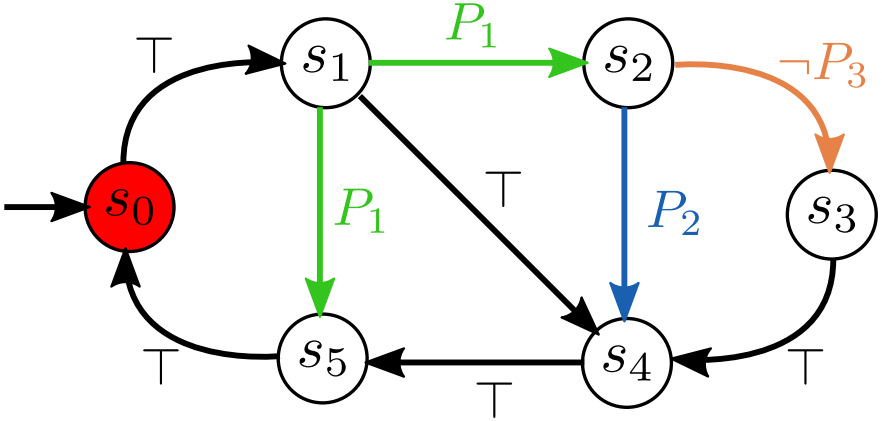


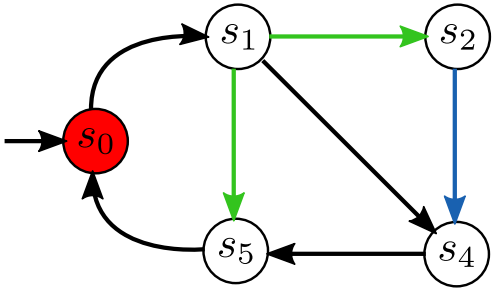
Boolean parameters P_1, P_2, P_3

Parameter Configurations

Motivating Example

M_P





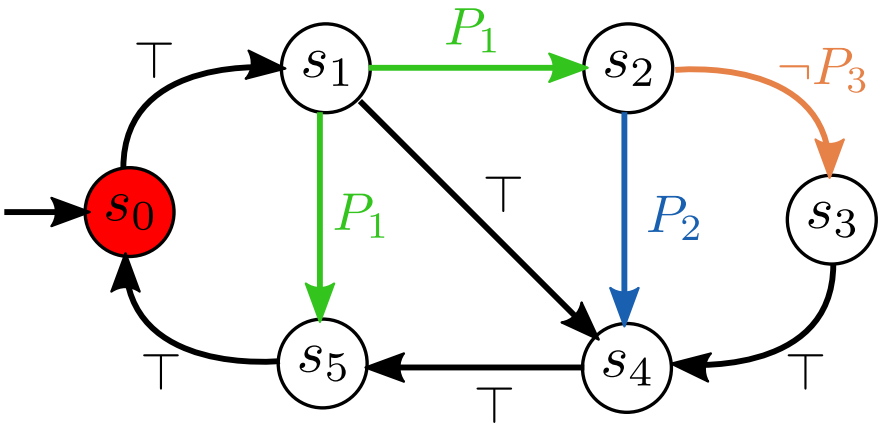
$(P_1 = \top, P_2 = \top, P_3 = \top)$

Boolean parameters P_1, P_2, P_3

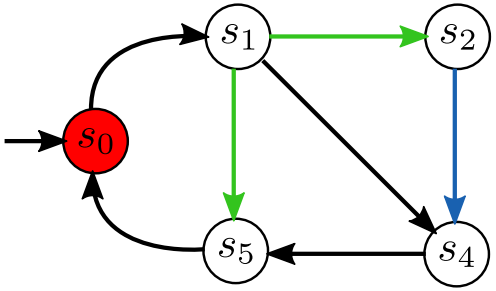
Parameter Configurations

Motivating Example

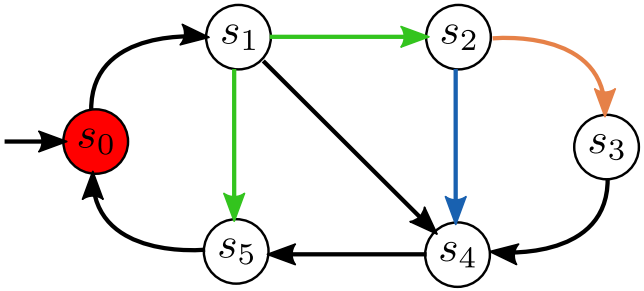
M_P



Boolean parameters P_1, P_2, P_3



$(P_1 = \top, P_2 = \top, P_3 = \top)$

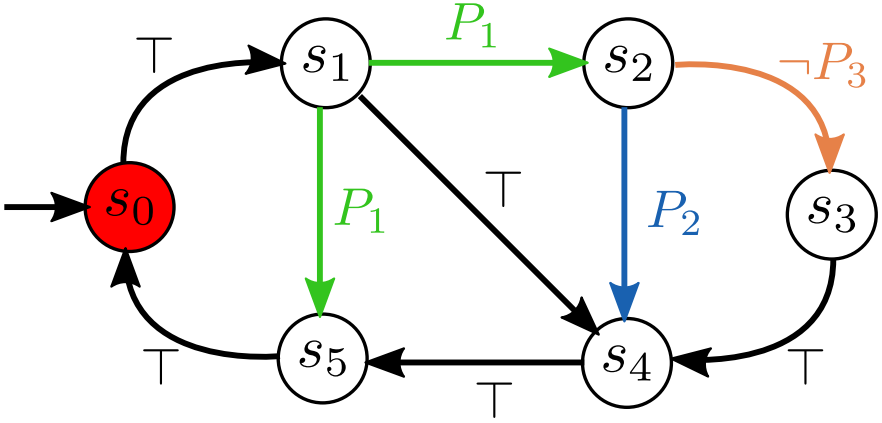


$(P_1 = \top, P_2 = \top, P_3 = \bot)$

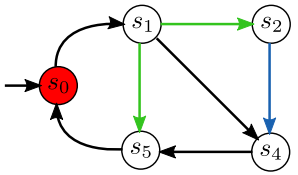
Parameter Configurations

Motivating Example

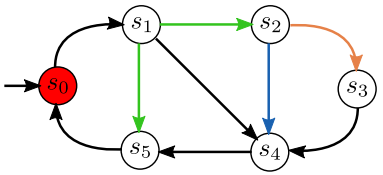
M_P



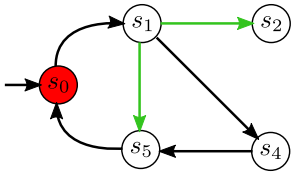
Boolean parameters P_1, P_2, P_3



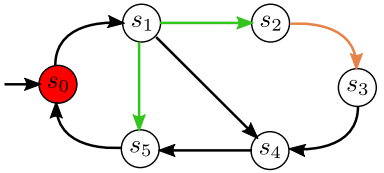
$(P_1 = \top, P_2 = \top, P_3 = \top)$



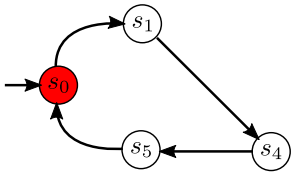
$(P_1 = \top, P_2 = \top, P_3 = \bot)$



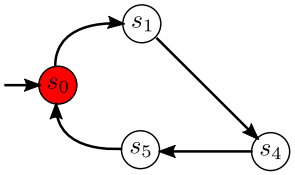
$(P_1 = \top, P_2 = \bot, P_3 = \top)$



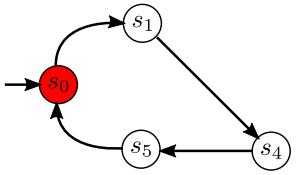
$(P_1 = \top, P_2 = \bot, P_3 = \bot)$



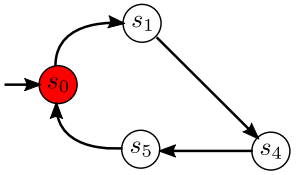
$(P_1 = \bot, P_2 = \top, P_3 = \top)$



$(P_1 = \bot, P_2 = \top, P_3 = \bot)$



$(P_1 = \bot, P_2 = \bot, P_3 = \top)$

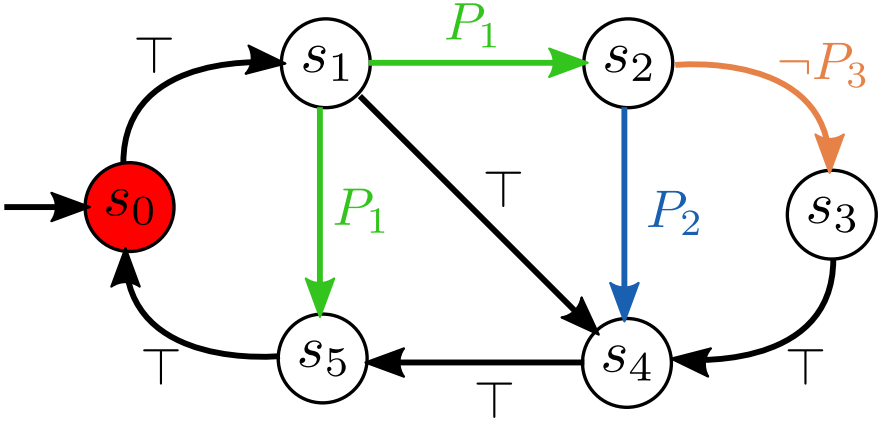


$(P_1 = \bot, P_2 = \bot, P_3 = \bot)$

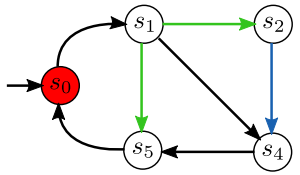
Parameter Configurations

Motivating Example

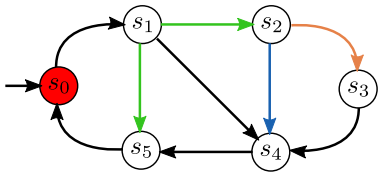
M_P



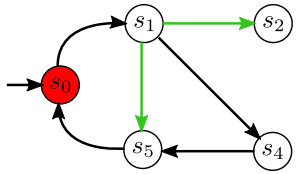
Boolean parameters P_1, P_2, P_3



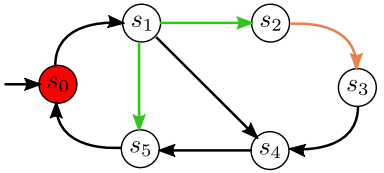
$(P_1 = \top, P_2 = \top, P_3 = \top)$



$(P_1 = \top, P_2 = \top, P_3 = \bot)$

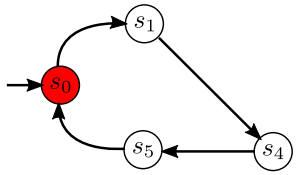


$(P_1 = \top, P_2 = \bot, P_3 = \top)$

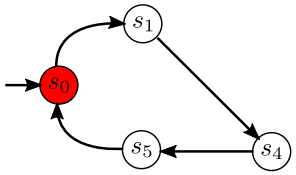


$(P_1 = \top, P_2 = \bot, P_3 = \bot)$

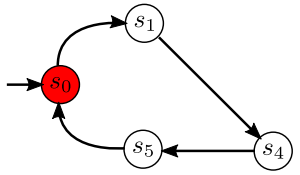
Same Models



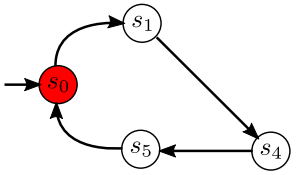
$(P_1 = \bot, P_2 = \top, P_3 = \top)$



$(P_1 = \bot, P_2 = \top, P_3 = \bot)$



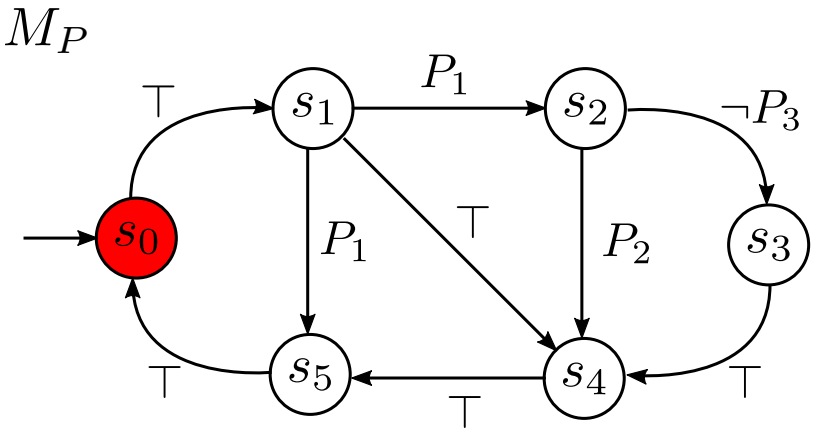
$(P_1 = \bot, P_2 = \bot, P_3 = \top)$



$(P_1 = \bot, P_2 = \bot, P_3 = \bot)$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check

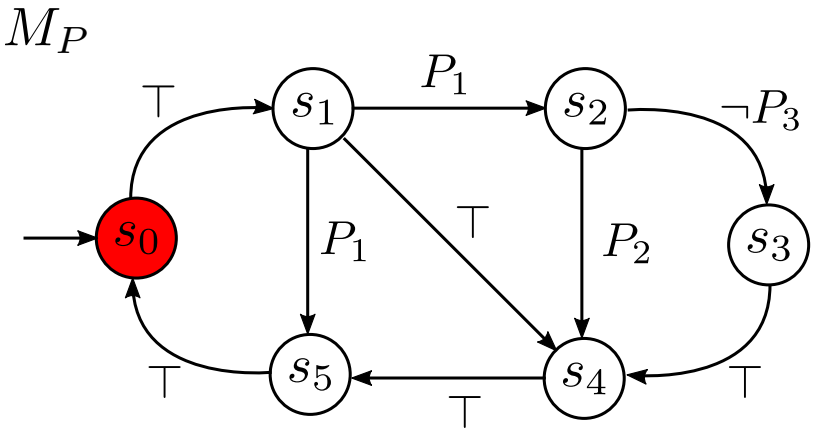


Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



FINDUP

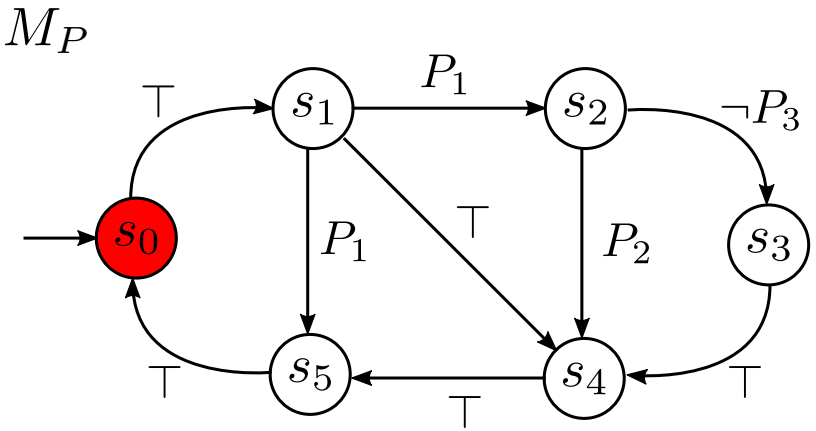
(finds reachable unset parameters)

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



FINDUP

(finds reachable unset parameters)

Configuration

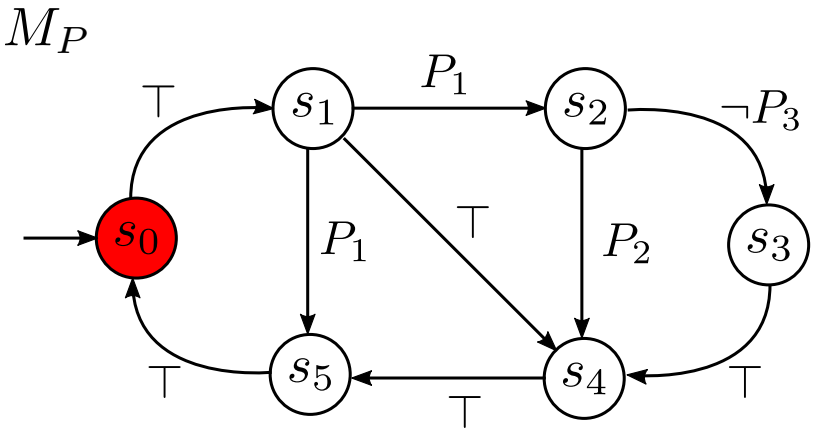
$\hat{c} =$ initially empty

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



Parameter Configurations

?

FindUP

(finds reachable unset parameters)

Configuration

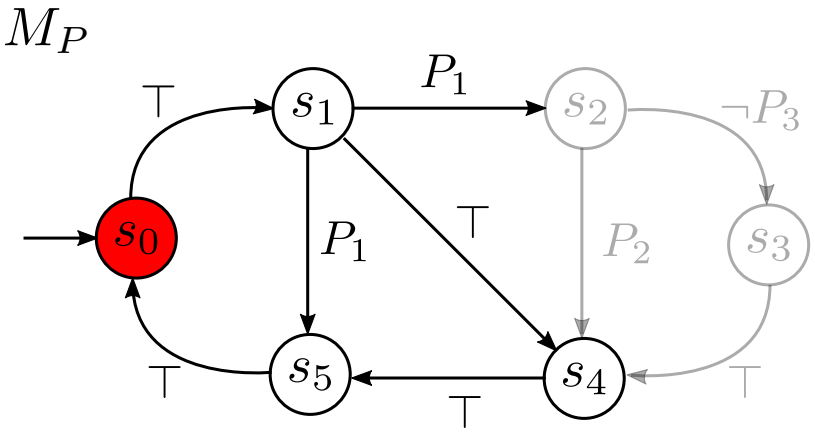
$\hat{c} =$ initially empty

Unset Parameters

$P_u = \text{FindUP}(M_P, \hat{c})$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



Parameter Configurations

?

FindUP

(finds reachable unset parameters)

Configuration

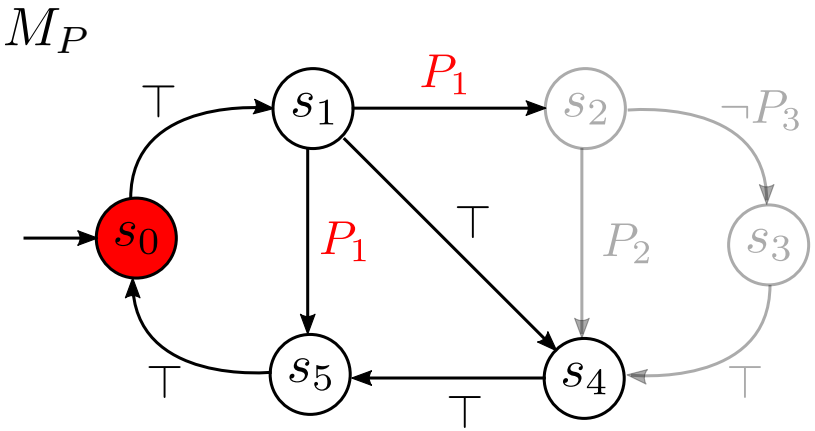
$\hat{c} =$ initially empty

Unset Parameters

$P_u = \text{FindUP}(M_P, \hat{c})$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



Parameter Configurations

?

FindUP

(finds reachable unset parameters)

Configuration

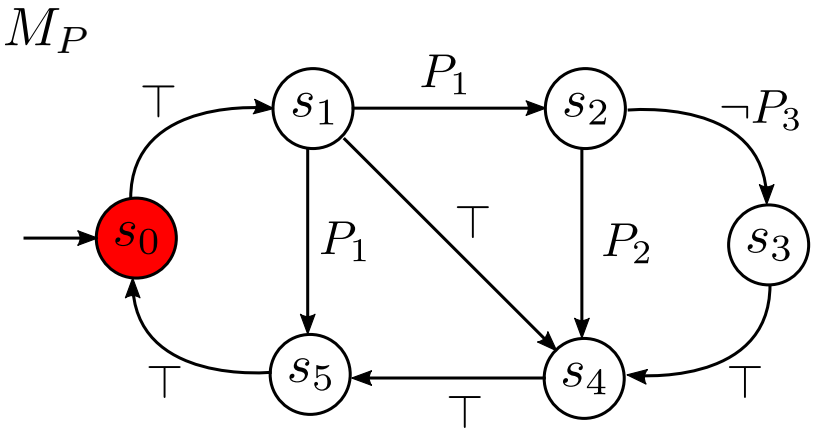
$\hat{c} =$ initially empty

Unset Parameters

$$P_u = \text{FindUP}(M_P, \hat{c})$$
$$= (P_1)$$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = (P_1)$

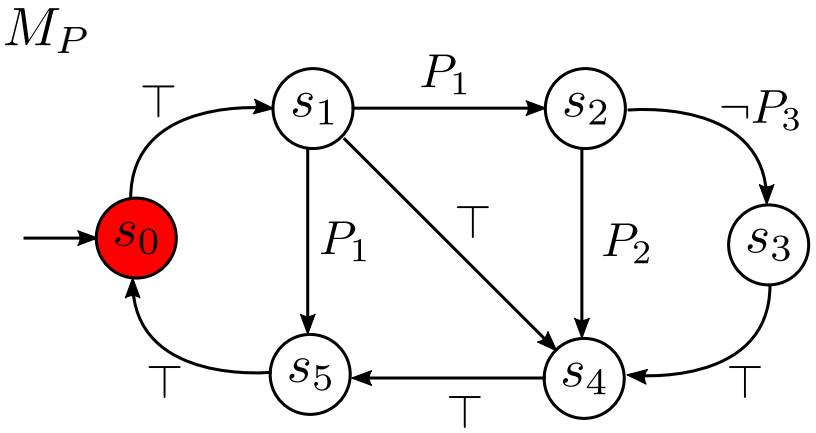
$\hat{c} =$ initially empty

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = (P_1)$

$\hat{c} =$ initially empty

GENPC

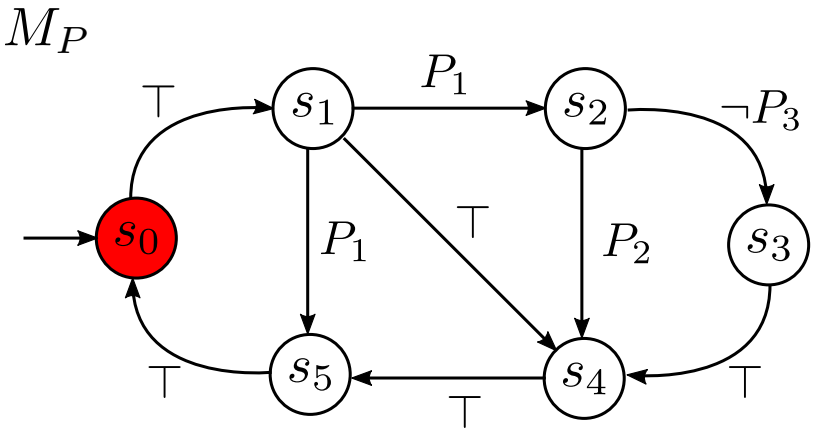
(recursively generate parameter configurations)

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = (P_1)$

$\hat{c} =$ initially empty

GenPC

(recursively generate parameter configurations)

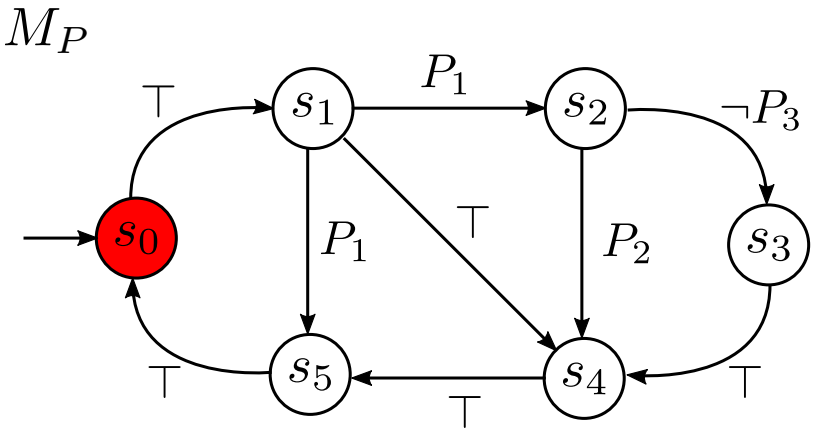
Parameter Configurations

?

Call GenPC$(M_P, P_u, \hat{c})$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



Parameter Configurations

?

$P_u = (P_1)$

$\hat{c} =$ initially empty

GENPC

(recursively generate parameter configurations)

Call GENPC$(M_P, P_u, \hat{c})$

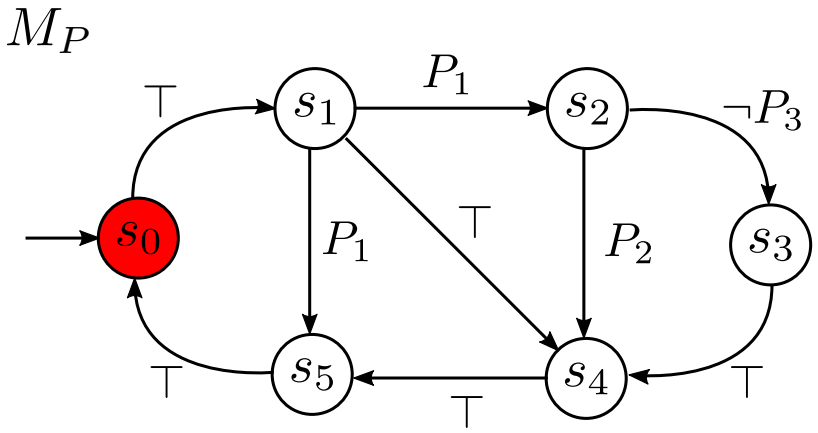
$p =$ dequeue from P_u

$= P_1$

$P_u =$ empty

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = (P_1)$

$\hat{c} =$ initially empty

GENPC

(recursively generate parameter configurations)

Parameter Configurations

?

Call GENPC$(M_P, P_u, \hat{c})$

$p =$ dequeue from P_u

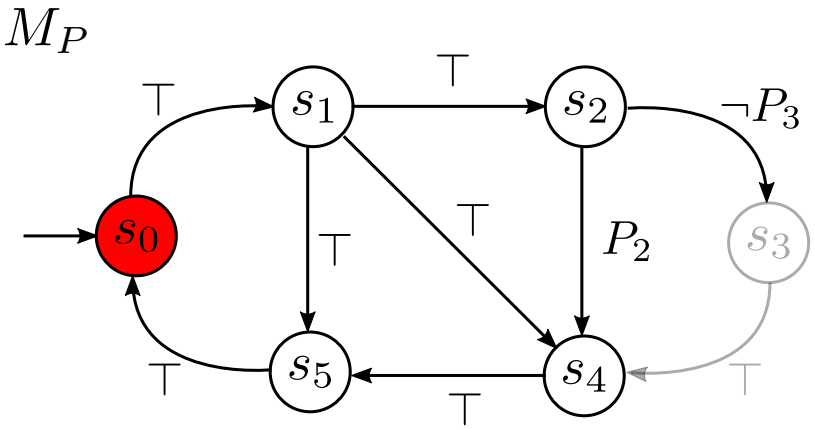
$= P_1$

$P_u =$ empty

$\hat{c} = (P_1 = \top)$ and $\hat{c} = (P_1 = \bot)$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = \text{empty}$

$\hat{c} = (P_1 = \top)$

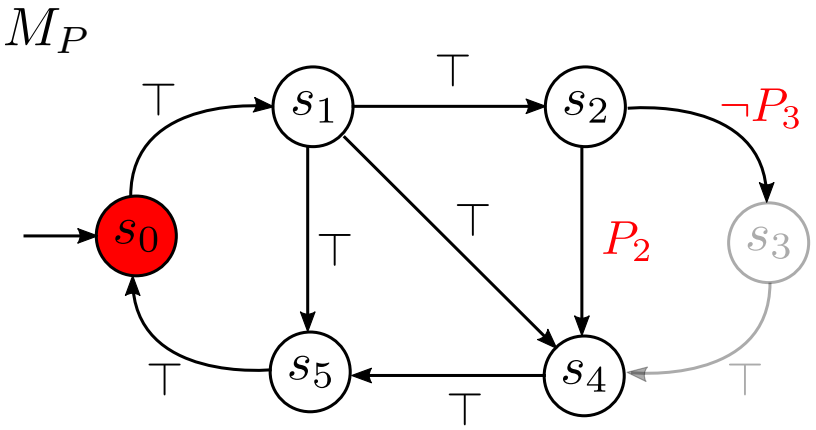
$P_u = \textsc{FindUP}(M_P, \hat{c})$

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = \text{empty}$

$\hat{c} = (P_1 = \top)$

$P_u = \textsc{FindUP}(M_P, \hat{c})$

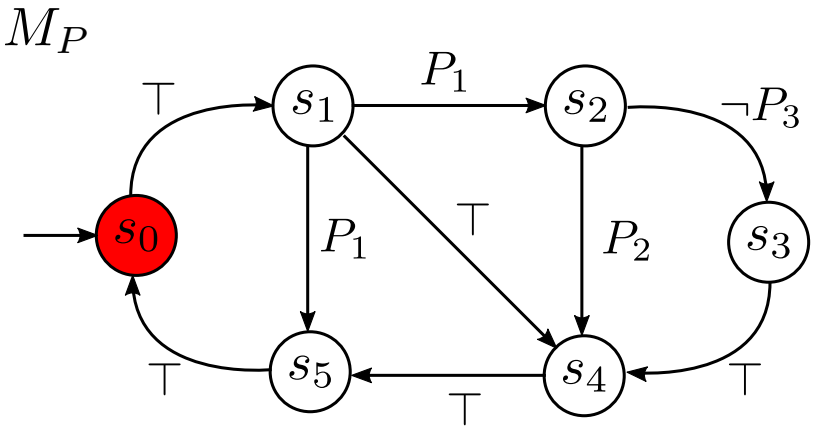
$= (P_2, P_3)$

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = (P_2, P_3)$

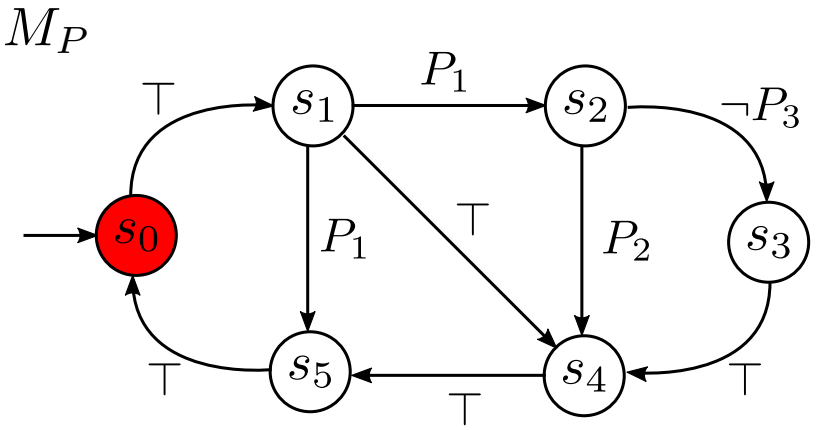
$\hat{c} = (P_1 = \top)$

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = (P_2, P_3)$

$\hat{c} = (P_1 = \top)$

Call GenPC$(M_P, P_u, \hat{c})$

$p =$ dequeue from P_u

$= P_2$

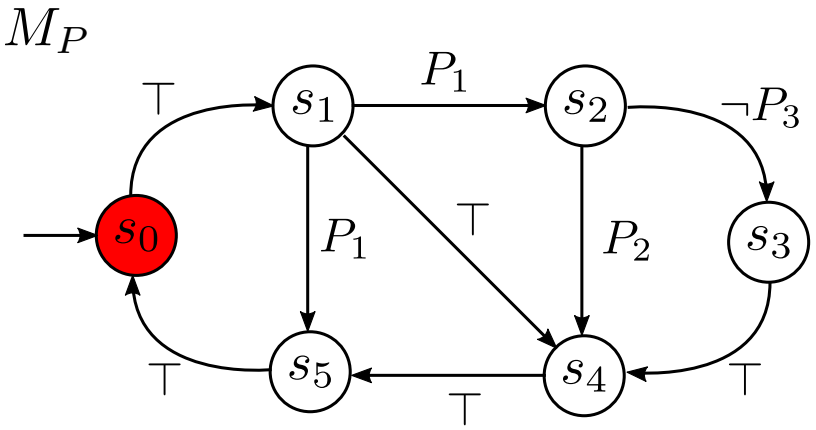
$P_u = (P_3)$

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



Parameter Configurations

?

$P_u = (P_2, P_3)$

$\hat{c} = (P_1 = \top)$

Call GenPC$(M_P, P_u, \hat{c})$

p = dequeue from P_u

$= P_2$

$P_u = (P_3)$

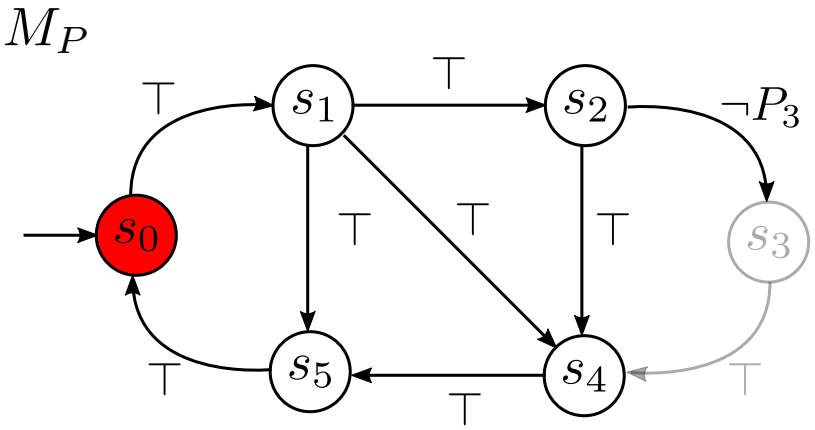
$\hat{c} = (P_1 = \top, P_2 = \top)$

and

$\hat{c} = (P_1 = \top, P_2 = \bot)$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$$P_u = (P_3)$$
$$\hat{c} = (P_1 = \top, P_2 = \top)$$

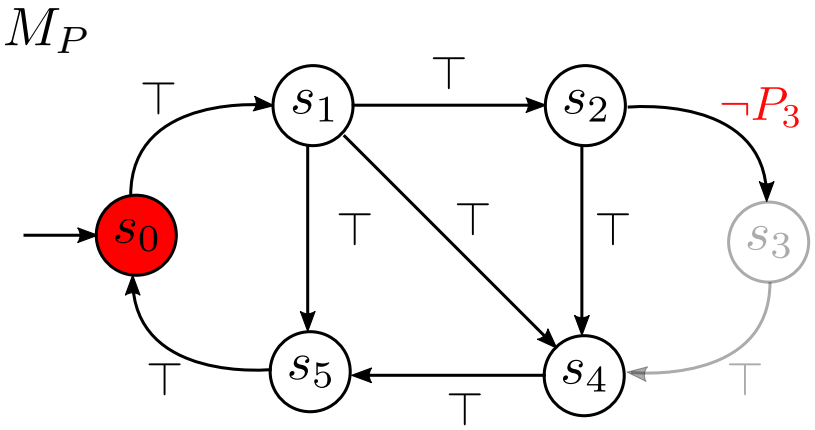
$$P_u = \textsc{FindUP}(M_P, \hat{c})$$

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$$P_u = (P_3)$$
$$\hat{c} = (P_1 = \top, P_2 = \top)$$

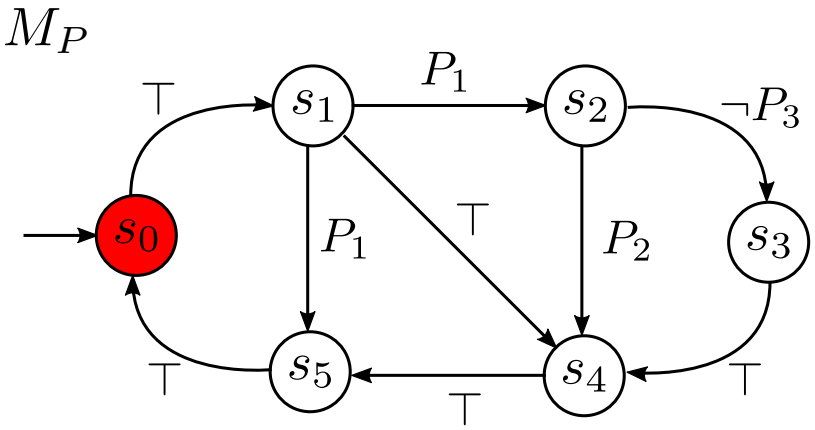
$$P_u = \textsc{FindUP}(M_P, \hat{c})$$
$$= (P_3)$$

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



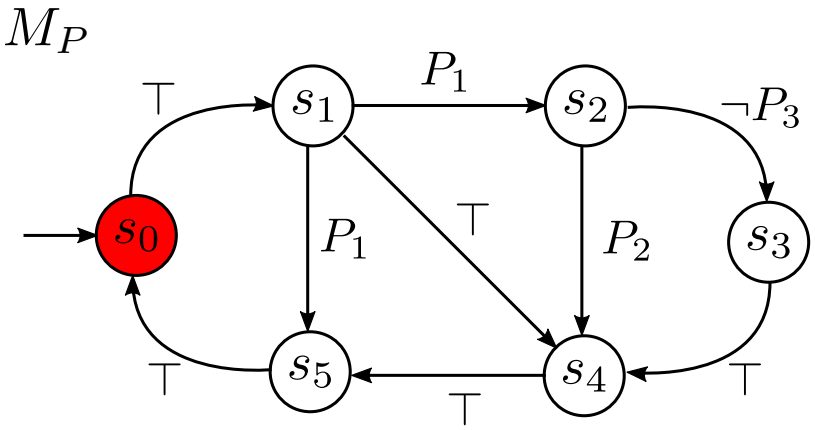
$$P_u = (P_3)$$
$$\hat{c} = (P_1 = \top, P_2 = \top)$$

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = (P_3)$

$\hat{c} = (P_1 = \top, P_2 = \top)$

Call GenPC$(M_P, P_u, \hat{c})$

p = dequeue from P_u
$= P_3$

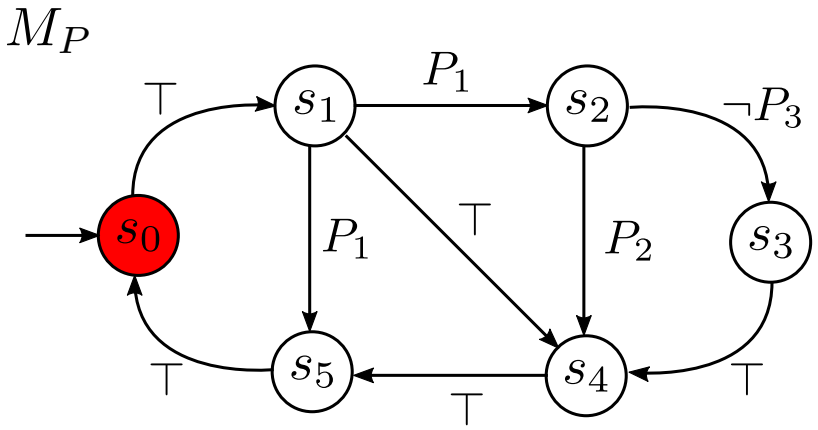
P_u = empty

Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



Parameter Configurations

?

$P_u = (P_3)$

$\hat{c} = (P_1 = \top, P_2 = \top)$

Call GenPC$(M_P, P_u, \hat{c})$

p = dequeue from P_u
$= P_3$

P_u = empty

$\hat{c} = (P_1 = \top, P_2 = \top, P_3 = \top)$

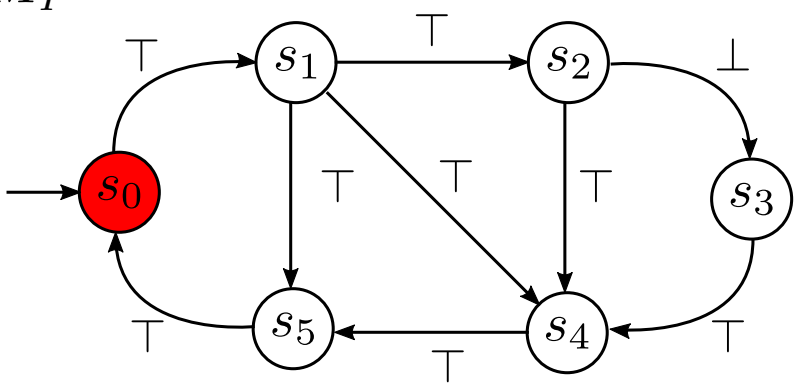
and

$\hat{c} = (P_1 = \top, P_2 = \top, P_3 = \bot)$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check

M_P



$P_u = \text{empty}$

$\hat{c} = (P_1 = \top, P_2 = \top, P_3 = \top)$

$P_u = \textsc{FindUP}(M_P, \hat{c})$

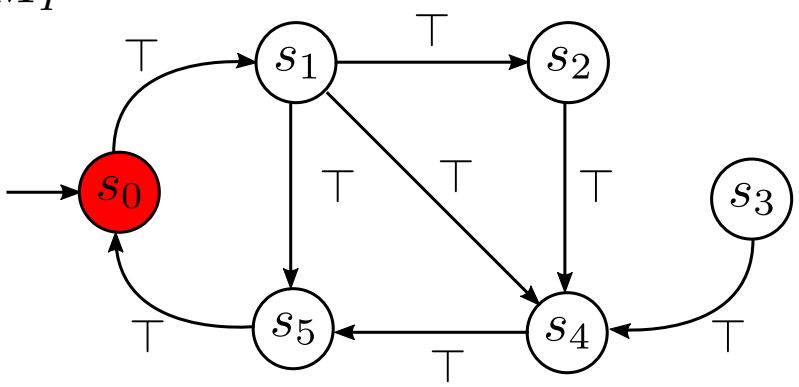
Parameter Configurations

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check

M_P



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$= \text{empty}$

Parameter Configurations

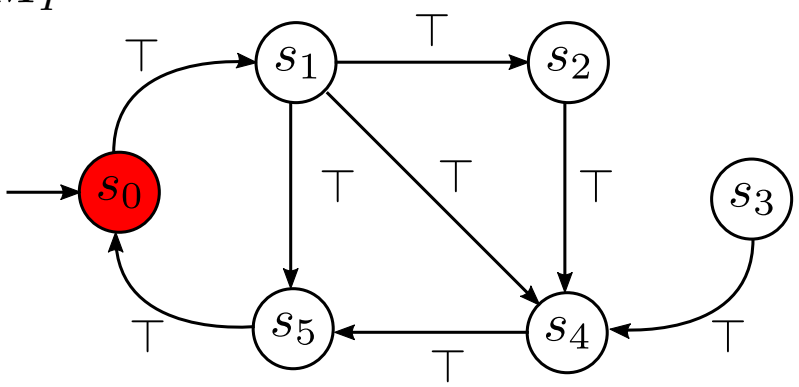
$(P_1 = \top, P_2 = \top, P_3 = \top)$

?

Parameter Configurations

Goal: Reduce the number of parameter configurations to check

M_P



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Parameter Configurations

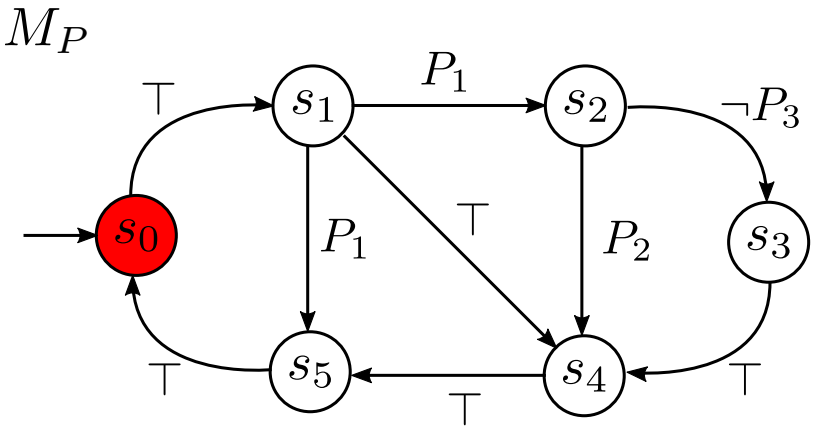
$(P_1 = \top, P_2 = \top, P_3 = \top)$

?

Configuration Found!

Parameter Configurations

Goal: Reduce the number of parameter configurations to check



$P_u = \text{empty}$

$\hat{c} = (P_1 = \top, P_2 = \top, P_3 = \bot)$

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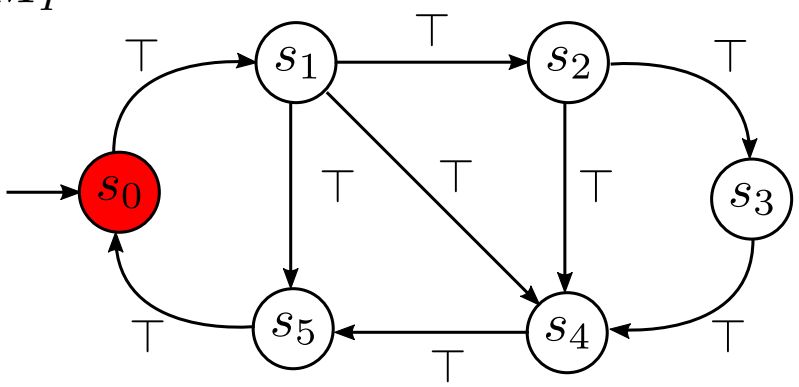
Parameter Configurations

$(P_1 = \top, P_2 = \top, P_3 = \top)$

Parameter Configurations

Goal: Reduce the number of parameter configurations to check

M_P



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Configuration Found!

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Parameter Configurations

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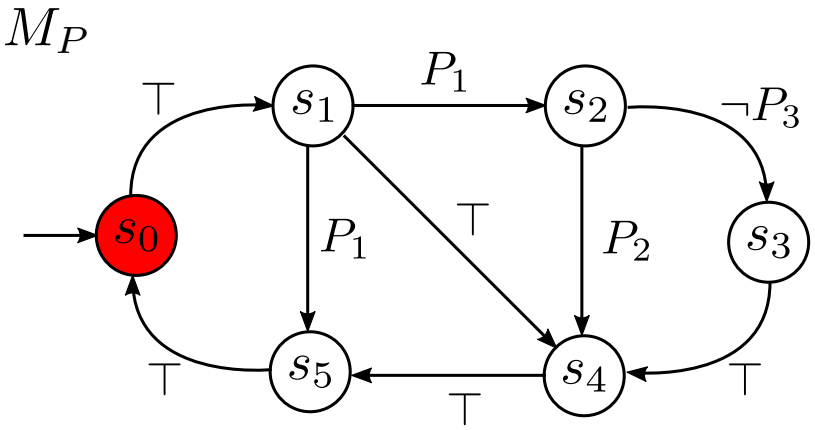

Parameter Configurations

$(P_1 = \top, P_2 = \top, P_3 = \top)$
$(P_1 = \top, P_2 = \top, P_3 = \bot)$
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$(P_1 = \top, P_2 = \bot, P_3 = \bot)$

Parameter Configurations

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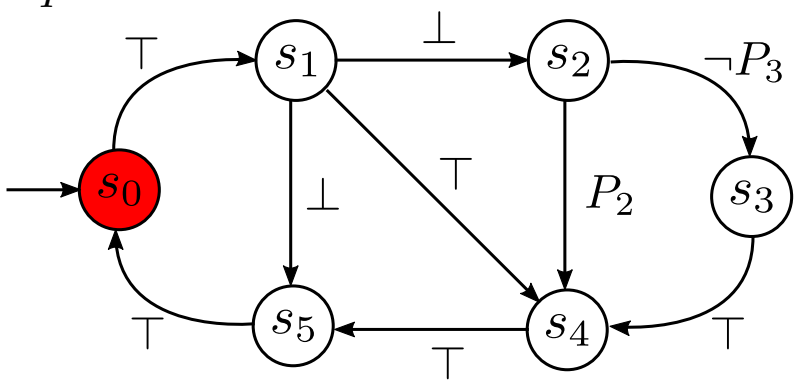
M_P



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Parameter Configurations

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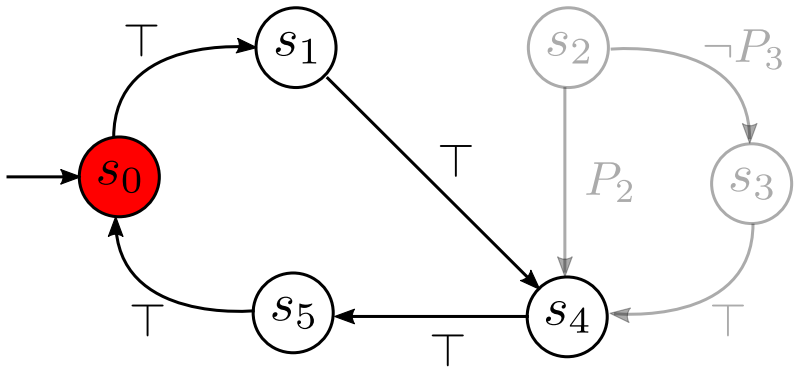

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Parameter Configurations

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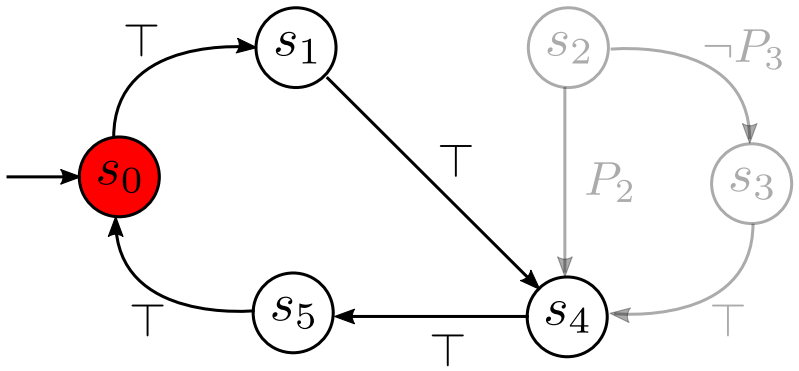

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$(P_1 = \top, P_2 = \bot, P_3 = \bot)$

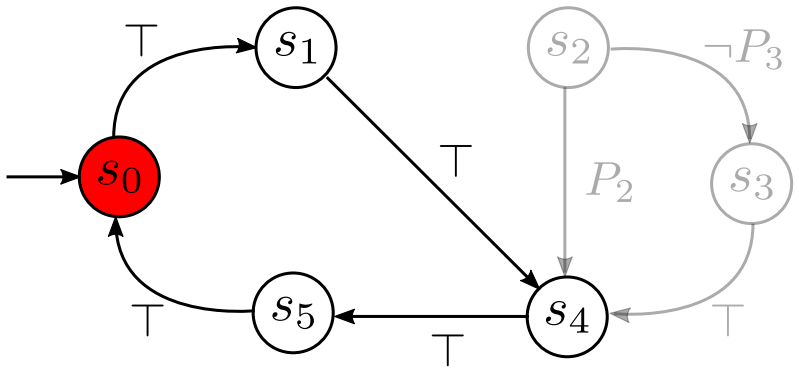
$(P_1 = \bot)$

Configuration Found!

Parameter Configurations

Goal: Reduce the number of parameter configurations to check

M_P



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$(P_1 = \top, P_2 = \top, P_3 = \bot)$

$(P_1 = \top, P_2 = \bot, P_3 = \top)$

$(P_1 = \top, P_2 = \bot, P_3 = \bot)$

$(P_1 = \bot)$

Configuration Found!

Minimal Guarantee

LTL Properties

LTL Properties

Motivating Example

Given: Model M over variables p and q

$$\varphi_1 = \Box q$$
$$\varphi_2 = \Box(p \wedge q)$$

LTL Properties

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Given: Model M over variables p and q

$$\varphi_1 = \Box q$$
$$\varphi_2 = \Box(p \wedge q)$$

$$M \models \varphi_2 \text{ then } M \models \varphi_1$$

LTL Properties

Motivating Example

Given: Model M over variables p and q

$$\varphi_1 = \Box q$$
$$\varphi_2 = \Box(p \wedge q)$$

$$M \models \varphi_2 \text{ then } M \models \varphi_1 \; (M \not\models \varphi_1 \text{ then } M \not\models \varphi_2)$$

LTL Properties

Motivating Example

Given: Model M over variables p and q

$$\varphi_1 = \Box q$$
$$\varphi_2 = \Box(p \wedge q)$$

$M \models \varphi_2$ then $M \models \varphi_1$ ($M \not\models \varphi_1$ then $M \not\models \varphi_2$)

φ_1 and φ_2 are dependent

LTL Properties

Motivating Example

Given: Model M over variables p and q

$$\varphi_1 = \Box q$$
$$\varphi_2 = \Box(p \wedge q)$$

$M \models \varphi_2$ then $M \models \varphi_1$ ($M \not\models \varphi_1$ then $M \not\models \varphi_2$)

φ_1 and φ_2 are dependent

$$\varphi_3 = \Box(p \vee q)$$

LTL Properties

Motivating Example

Given: Model M over variables p and q

$\varphi_1 = \Box q$

$\varphi_2 = \Box(p \wedge q)$

$M \models \varphi_2$ then $M \models \varphi_1$ ($M \not\models \varphi_1$ then $M \not\models \varphi_2$)

φ_1 and φ_2 are dependent

$\varphi_3 = \Box(p \vee q)$

$M \models \varphi_2$ then $M \models \varphi_3$

LTL Properties

Motivating Example

Given: Model M over variables p and q

$\varphi_1 = \Box q$

$\varphi_2 = \Box(p \wedge q)$

$M \models \varphi_2$ then $M \models \varphi_1$ ($M \not\models \varphi_1$ then $M \not\models \varphi_2$)

φ_1 and φ_2 are dependent

$\varphi_3 = \Box(p \vee q)$

$M \models \varphi_2$ then $M \models \varphi_3$

φ_2 and φ_3 are dependent

LTL Properties

Motivating Example

Given: Model M over variables p and q

$\varphi_1 = \Box q$

$\varphi_2 = \Box(p \wedge q)$

$M \models \varphi_2$ then $M \models \varphi_1$ ($M \not\models \varphi_1$ then $M \not\models \varphi_2$)

φ_1 and φ_2 are dependent

$\varphi_3 = \Box(p \vee q)$

$M \models \varphi_2$ then $M \models \varphi_3$

φ_2 and φ_3 are dependent

Knowing dependencies *at design-time* is hard!

LTL Properties

Motivating Example

Given: Model M over variables p and q

$\varphi_1 = \Box q$

$\varphi_2 = \Box(p \wedge q)$

$M \models \varphi_2$ then $M \models \varphi_1$ ($M \not\models \varphi_1$ then $M \not\models \varphi_2$)

φ_1 and φ_2 are dependent

$\varphi_3 = \Box(p \vee q)$

$M \models \varphi_2$ then $M \models \varphi_3$

φ_2 and φ_3 are dependent

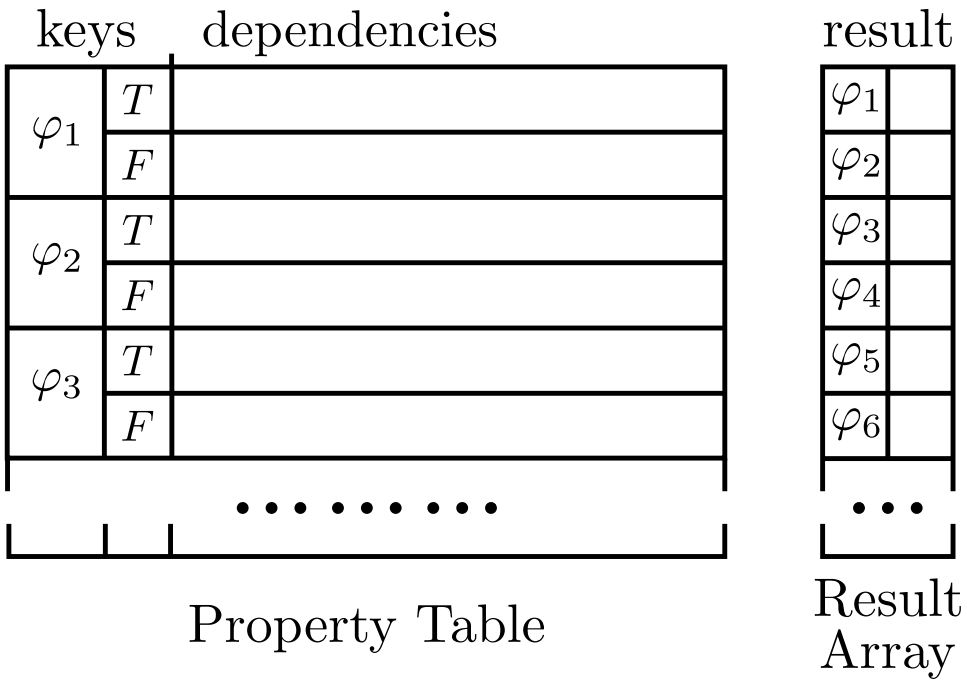
Knowing dependencies *at design-time* is hard!

We use LTL Satisfiability Checking

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



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Goal: Reduce the number of LTL properties to check

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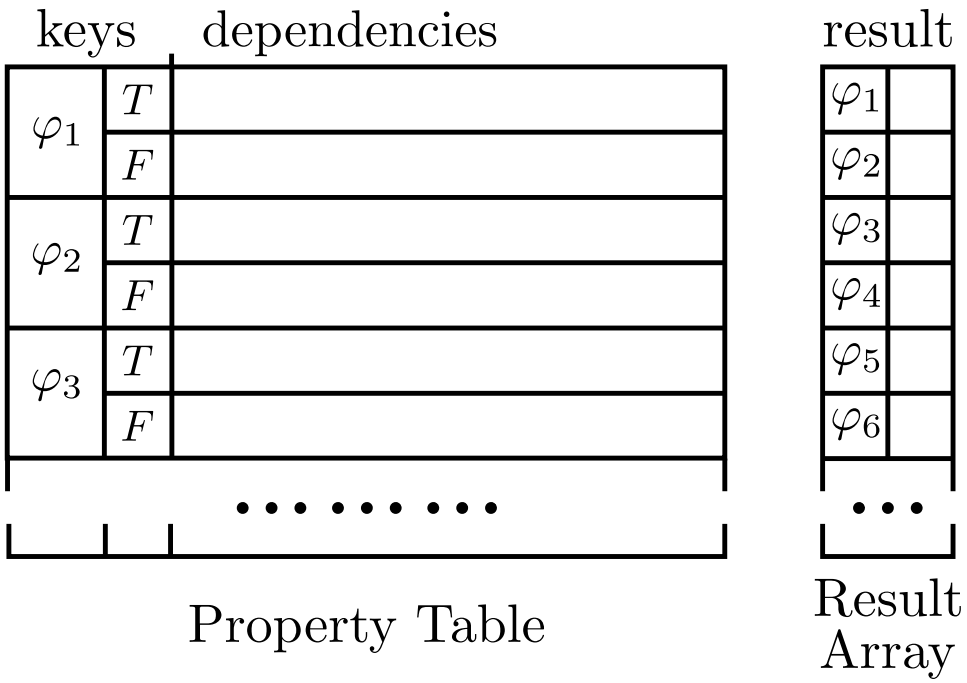

CheckRP

(checks reduced number or properties)

LTL Properties

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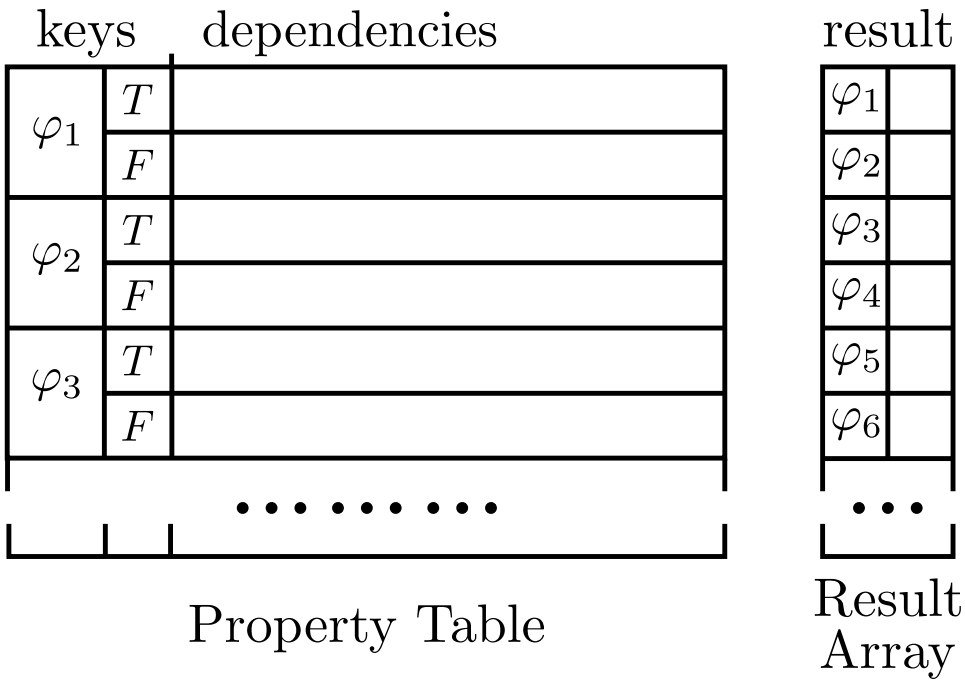
$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

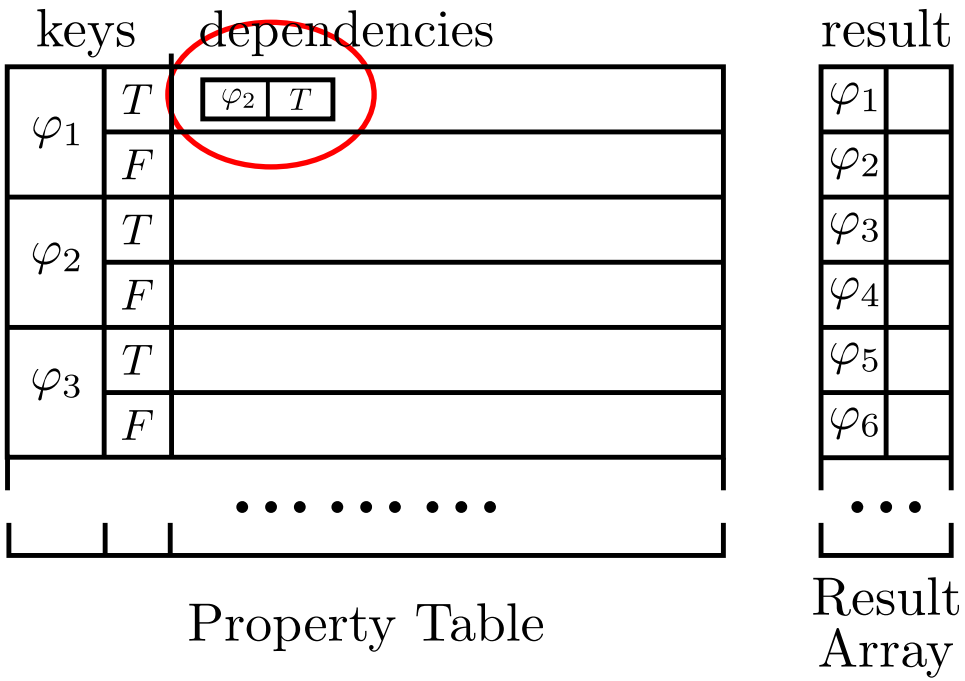
(checks reduced number or properties)

Is $(\varphi_1 \rightarrow \varphi_2)$ satisfiable?

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

(checks reduced number or properties)

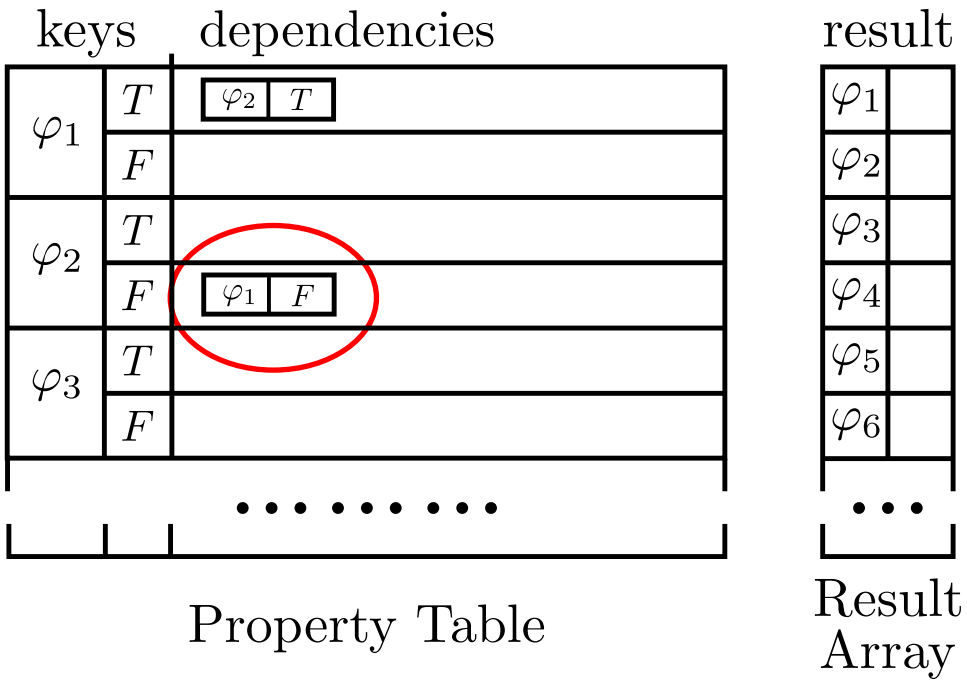
Is $(\varphi_1 \rightarrow \varphi_2)$ satisfiable?

Yes!

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

(checks reduced number or properties)

Is $(\varphi_1 \rightarrow \varphi_2)$ satisfiable?

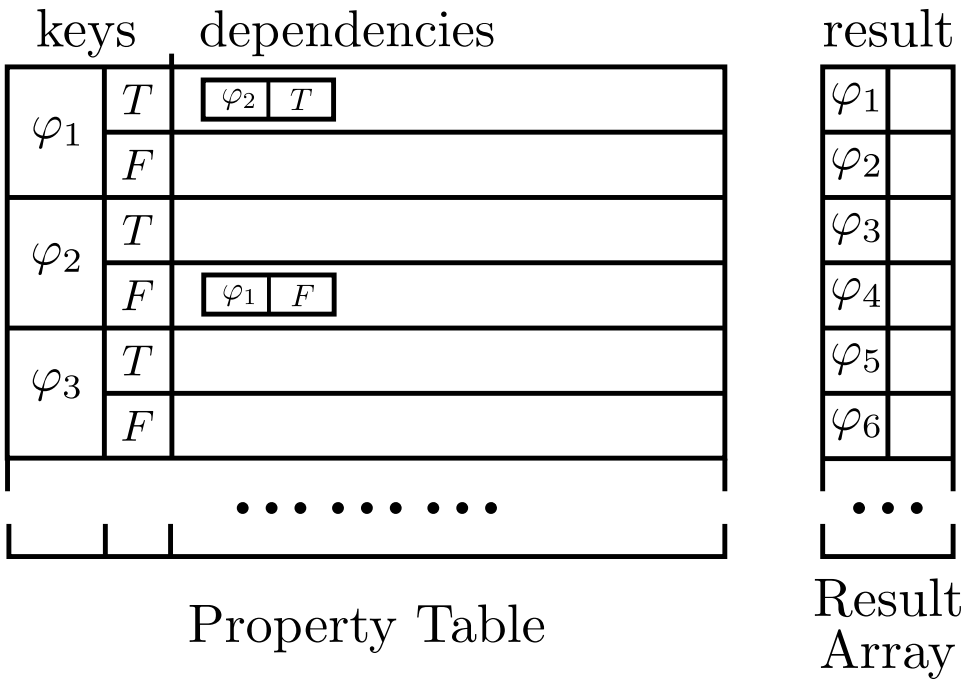
Yes!

$(\neg\varphi_2 \rightarrow \neg\varphi_1)$ also satisfiable.

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

(checks reduced number or properties)

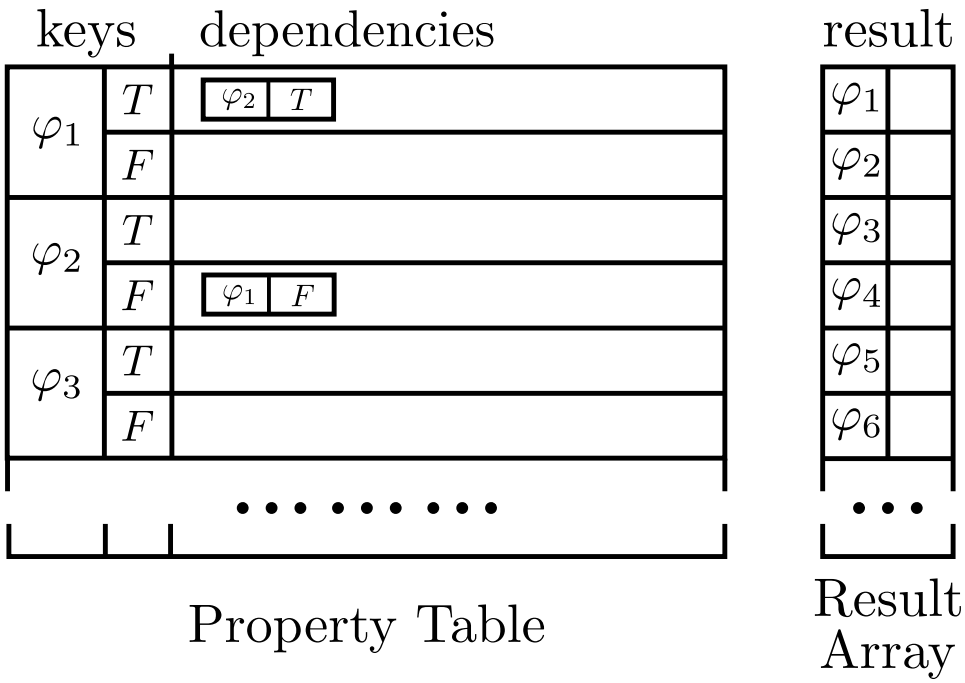
$\varphi_1 \rightarrow \varphi_2$
$\neg\varphi_1 \rightarrow \varphi_2$
$\neg\varphi_1 \rightarrow \neg\varphi_2$
$\varphi_1 \rightarrow \neg\varphi_2$

\+ contra-positives

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

(checks reduced number or properties)

$\varphi_1 \rightarrow \varphi_2$

$\neg\varphi_1 \rightarrow \varphi_2$

$\neg\varphi_1 \rightarrow \neg\varphi_2$

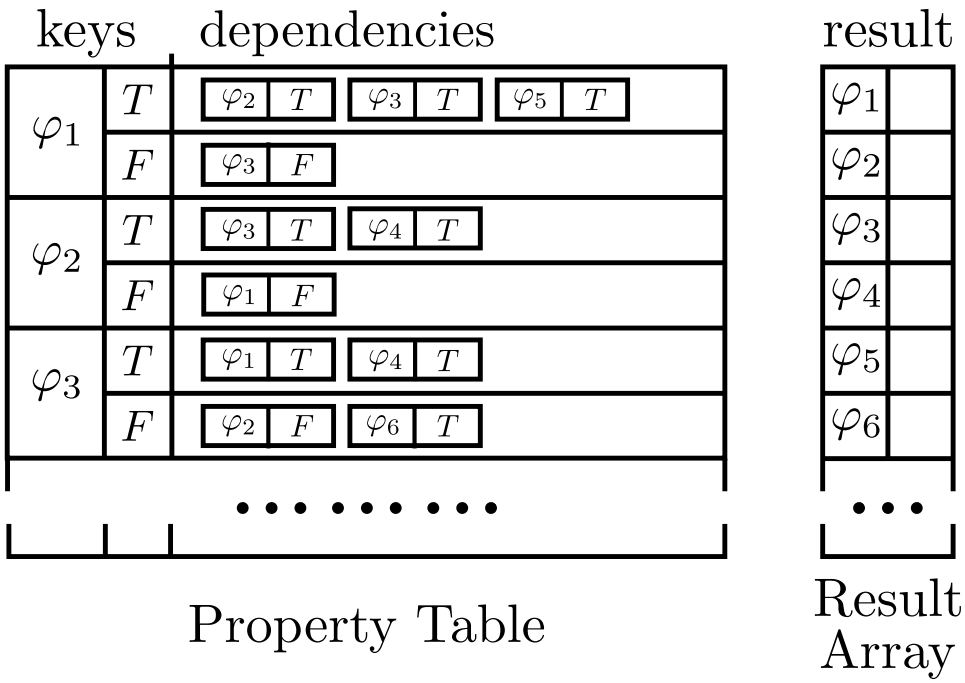
Interesting

$\varphi_1 \rightarrow \neg\varphi_2$

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

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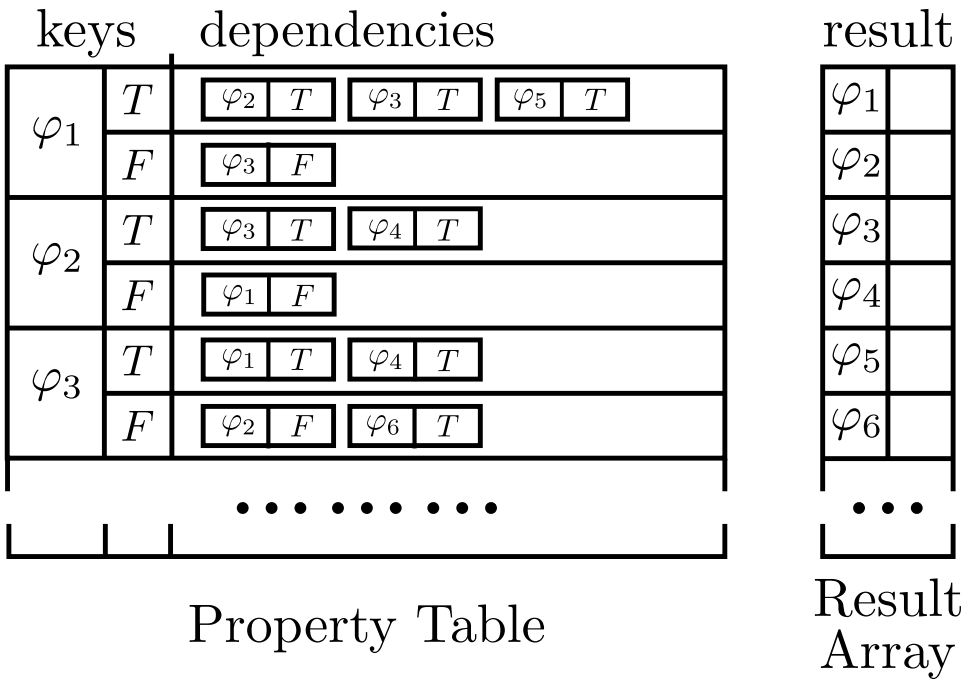
$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

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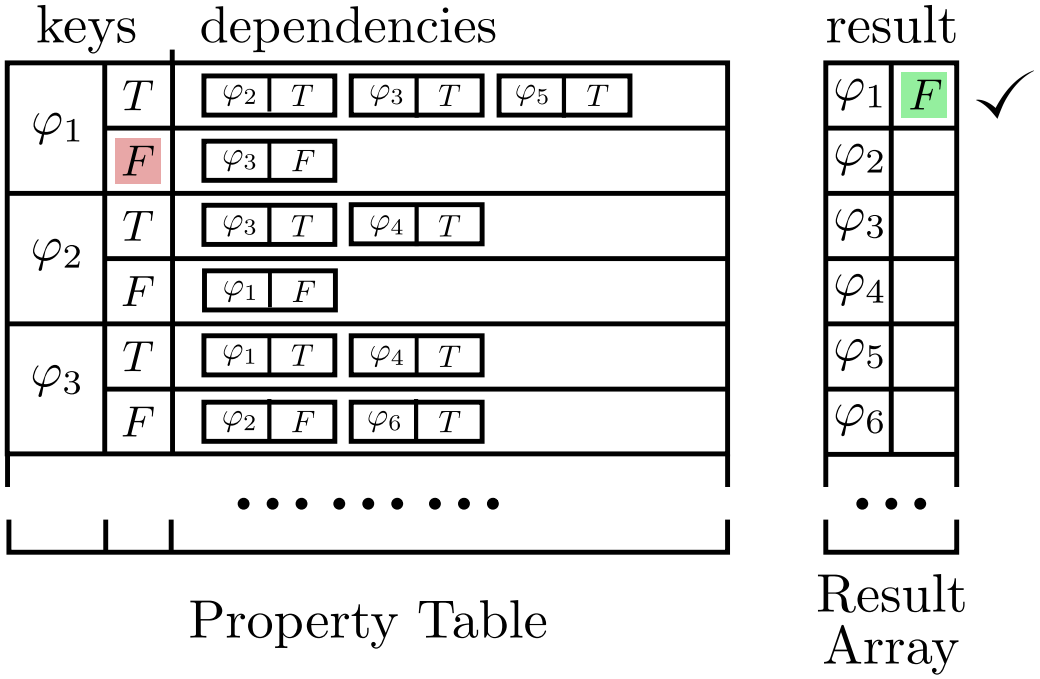
Check if $\forall \varphi \in \mathcal{P}$

$M \models ? \varphi$

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP

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Check if $\forall \varphi \in \mathcal{P}$

$M \models ? \varphi$

$M \not\models \varphi_1$

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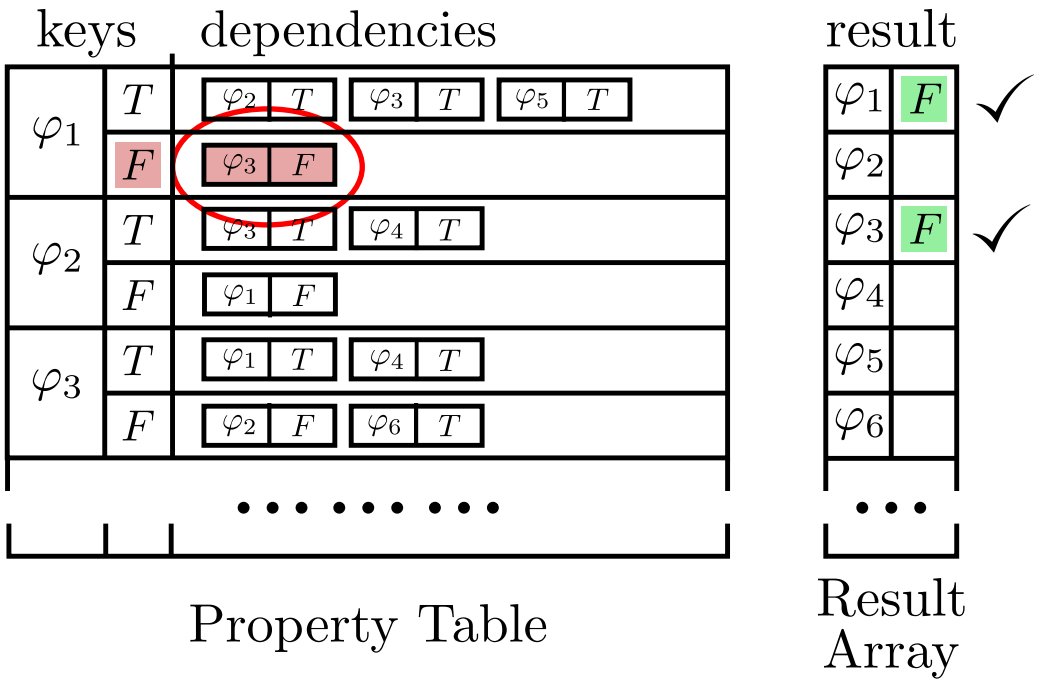
$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CheckRP
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Check if $\forall \varphi \in \mathcal{P}$
$M \models ? \varphi$

$M \not\models \varphi_1$

$M \not\models \varphi_3$

LTL Properties

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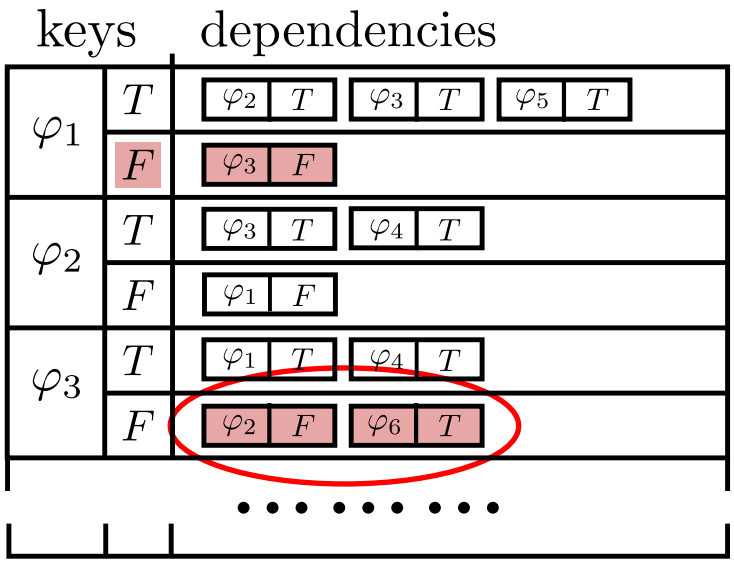
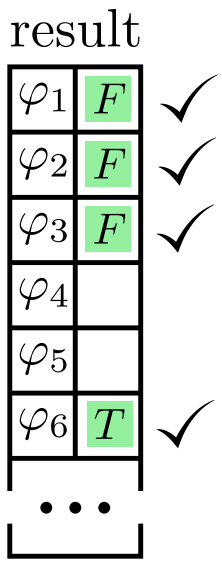
$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



Property Table



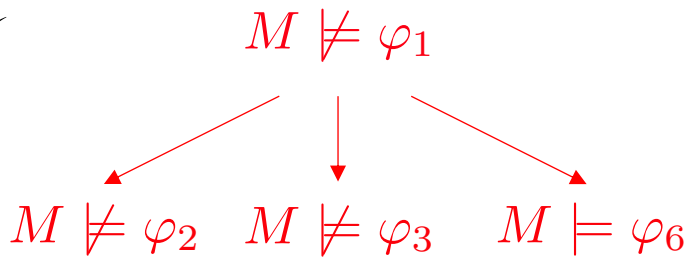
Result Array

CheckRP

(checks reduced number or properties)

Check if $\forall \varphi \in \mathcal{P}$

$M \models_? \varphi$



LTL Properties

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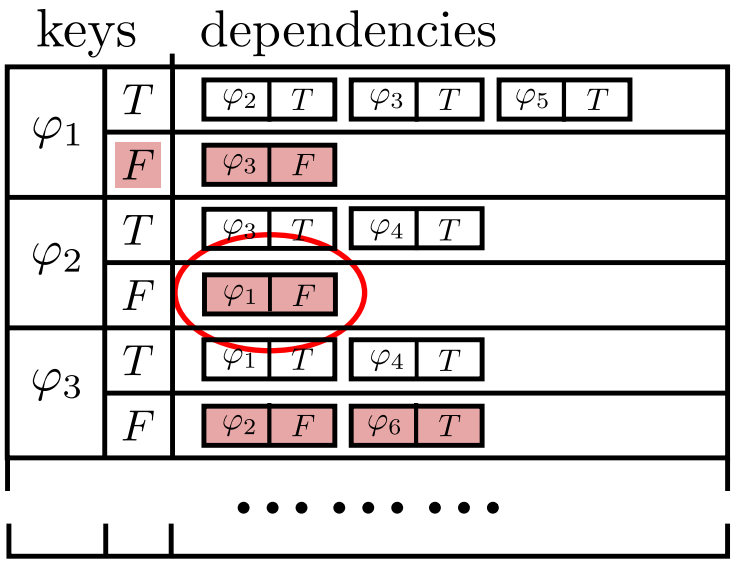
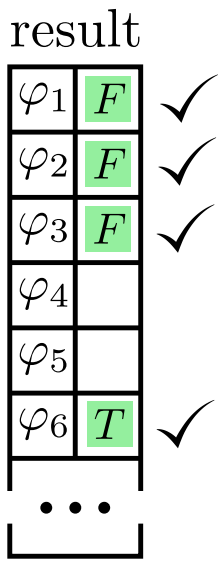


Property Table

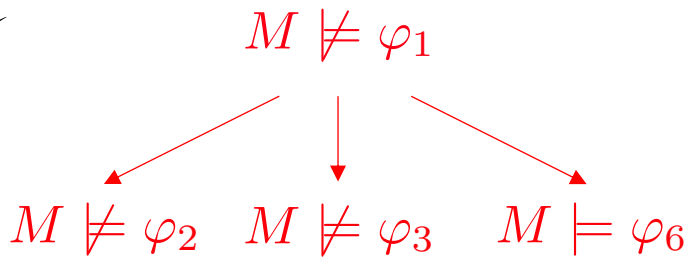


Result Array

CHECKRP

(checks reduced number or properties)

Check if $\forall \varphi \in \mathcal{P}$ $M \models_? \varphi$

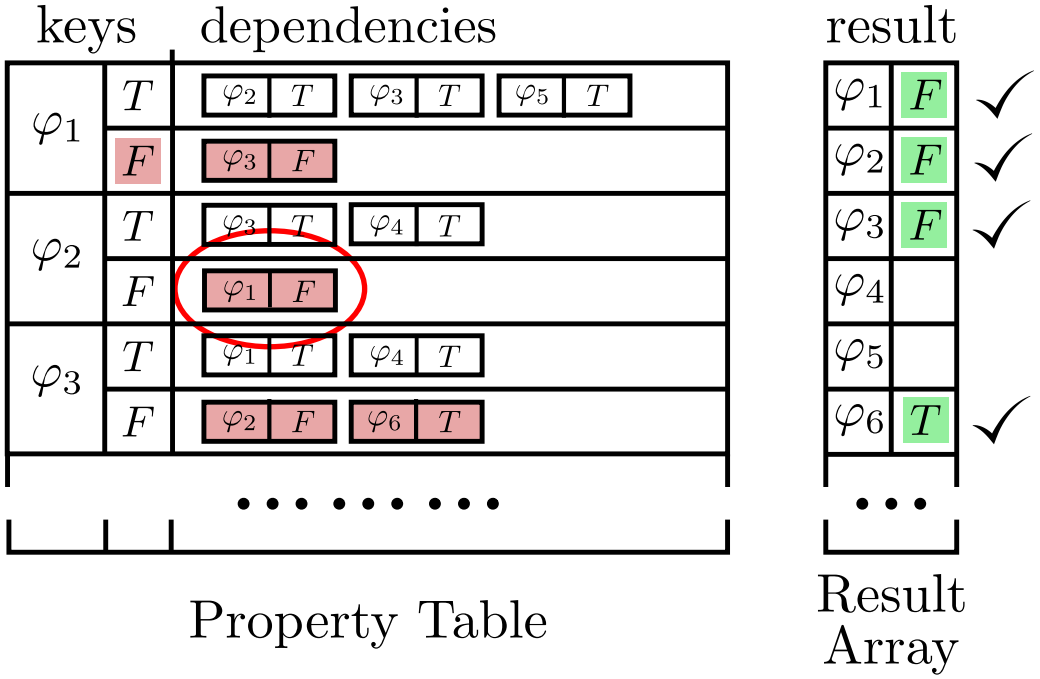


Self Validating!

LTL Properties

Goal: Reduce the number of LTL properties to check

$\mathcal{P} = \{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$



CHECKRP
(checks reduced number or properties)

Heuristics

H1: Maximum Dependence

H2: Property Grouping

Experiment Setup

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- D^3 is implemented as a preprocessing script in ~2,000 lines of Python.

Source code available at

`http://temporallogic.org/research/TACAS18`

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Experiment Setup

- D^3 is implemented as a preprocessing script in ~2,000 lines of Python.
- We use NUXMV as the interfaced state-of-the-art model checker
- Benchmarks Evaluated
  - NASA NextGen Air Traffic Control (ATC) System (Gario et al., 2016)
  - BOEING AIR 6110 Wheel Braking (WBS) System (Bozzano et al., 2015)

Source code available at

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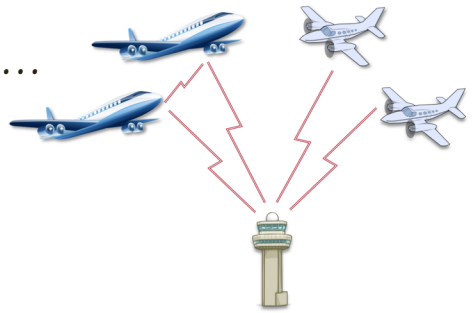
NASA ATC Benchmark

NASA ATC Benchmark

- Large design-space with 1,620 design choices
  different types of aircraft, varying levels of information sharing, …



NASA ATC Benchmark

- Large design-space with 1,620 design choices
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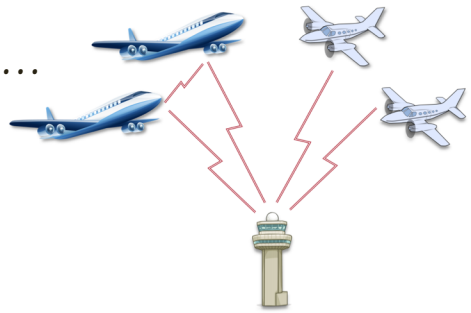
- 191 LTL properties (liveness + safety) per model



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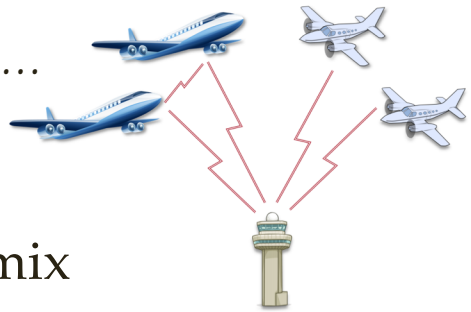

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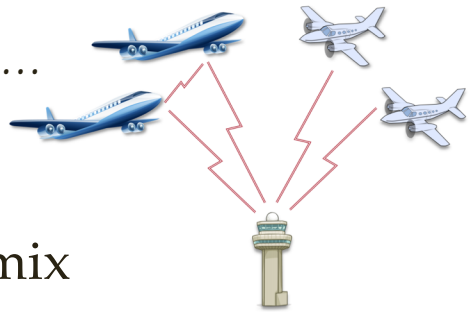

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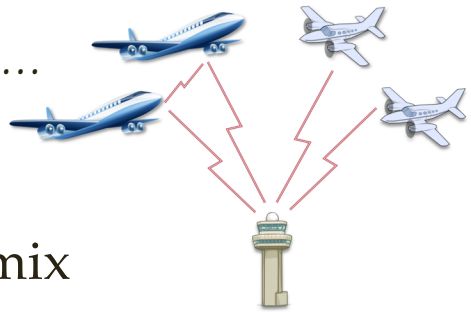

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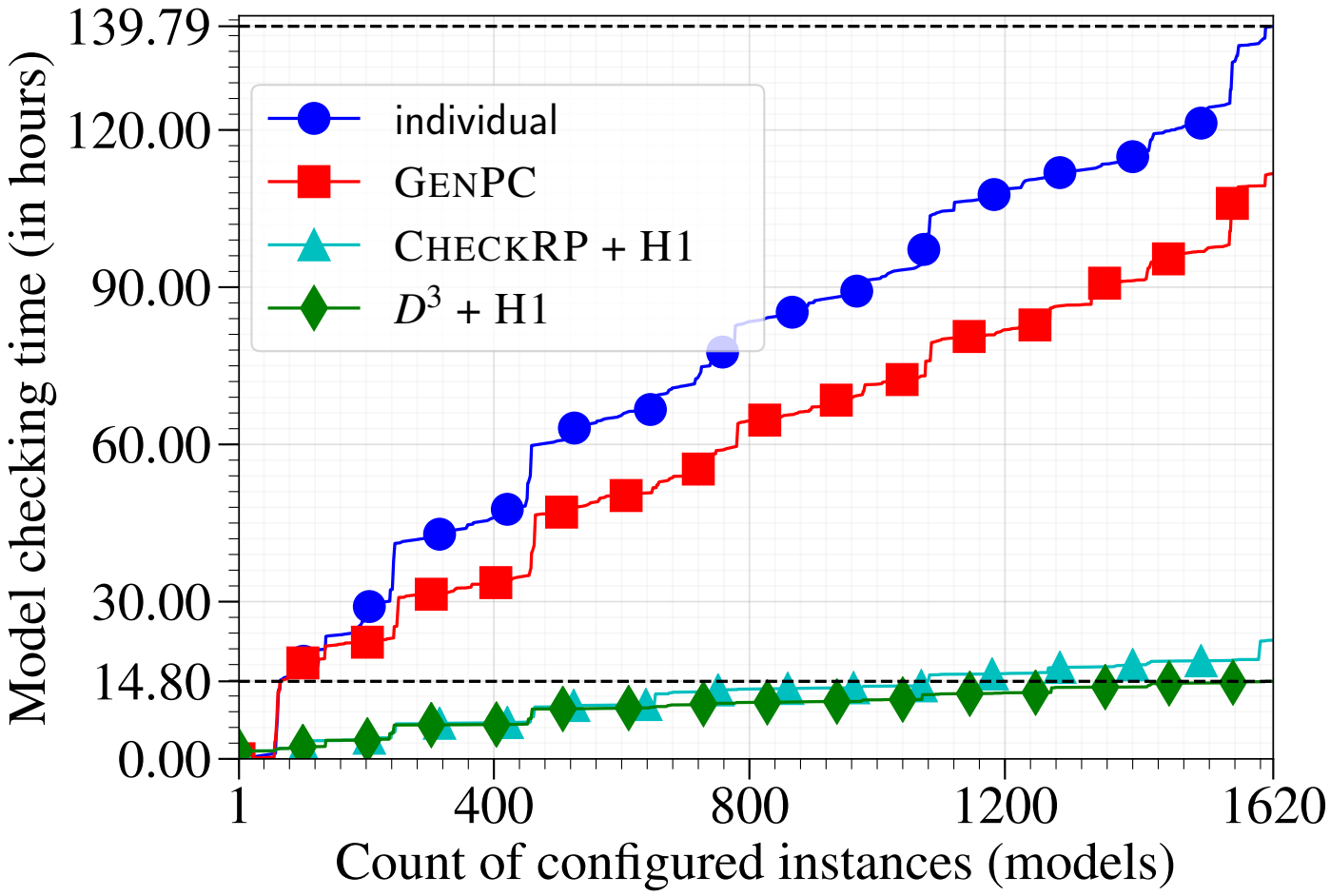

UNSAT properties

9.0x speedup

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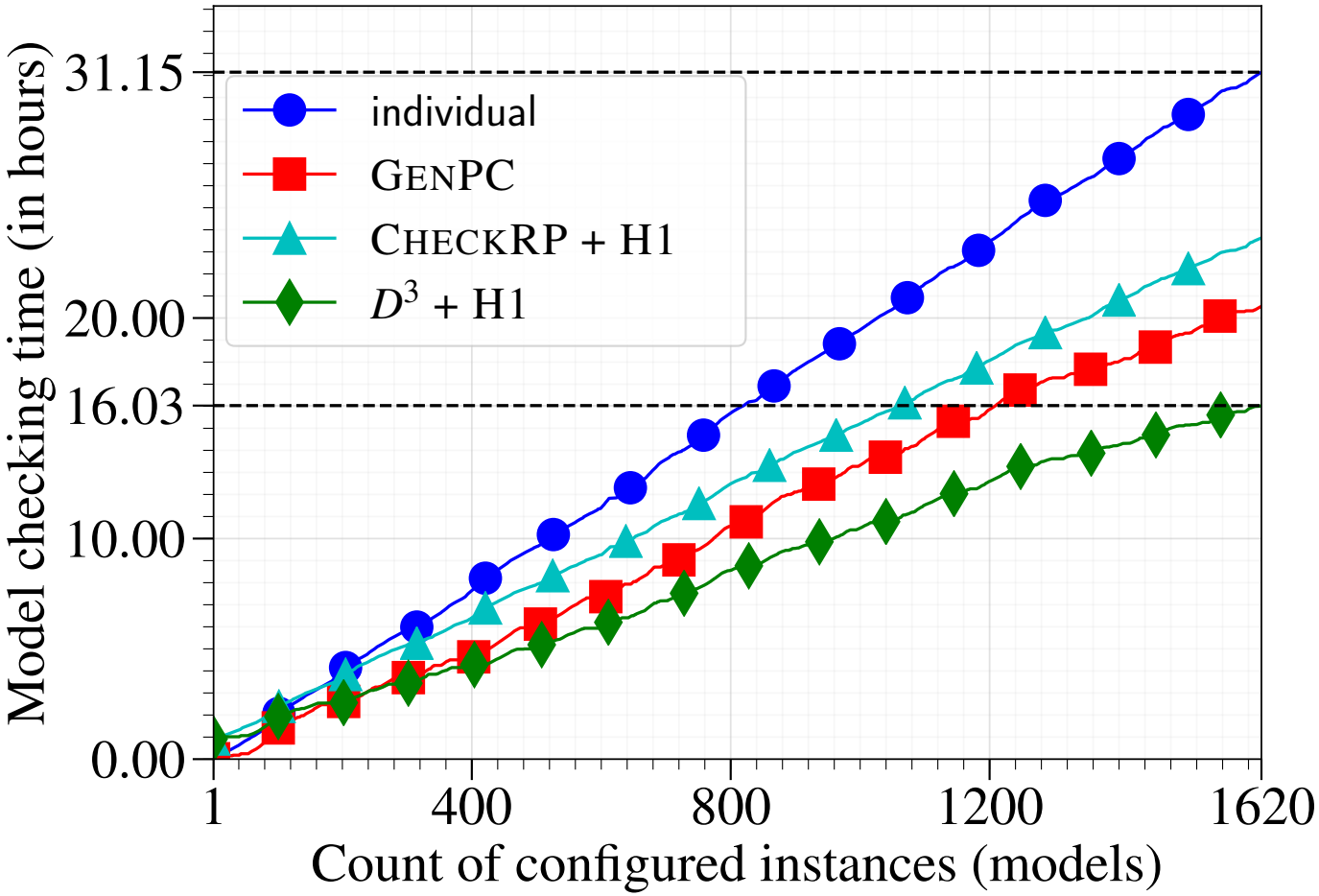
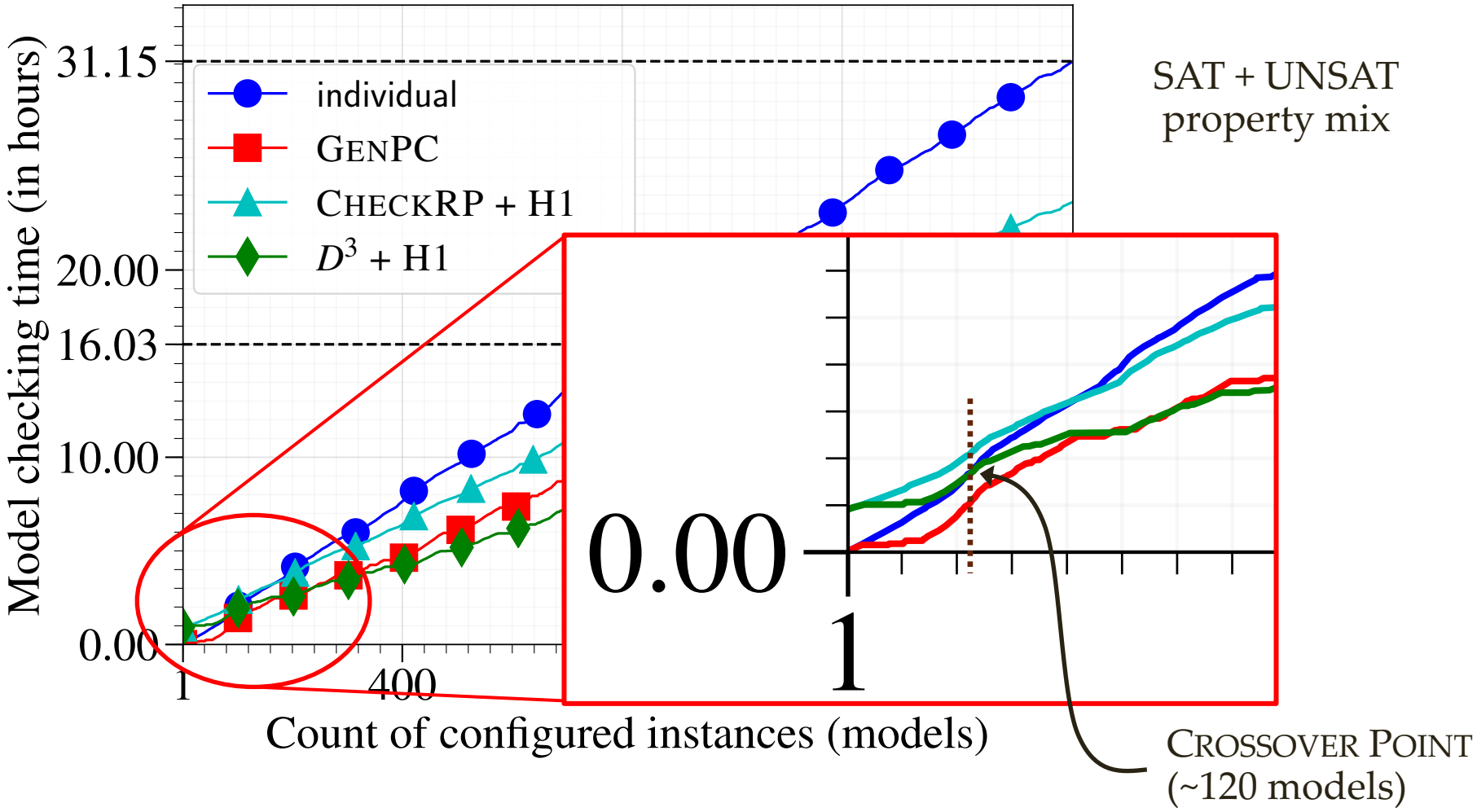


SAT + UNSAT property mix

1.9x speedup

NASA ATC Benchmark



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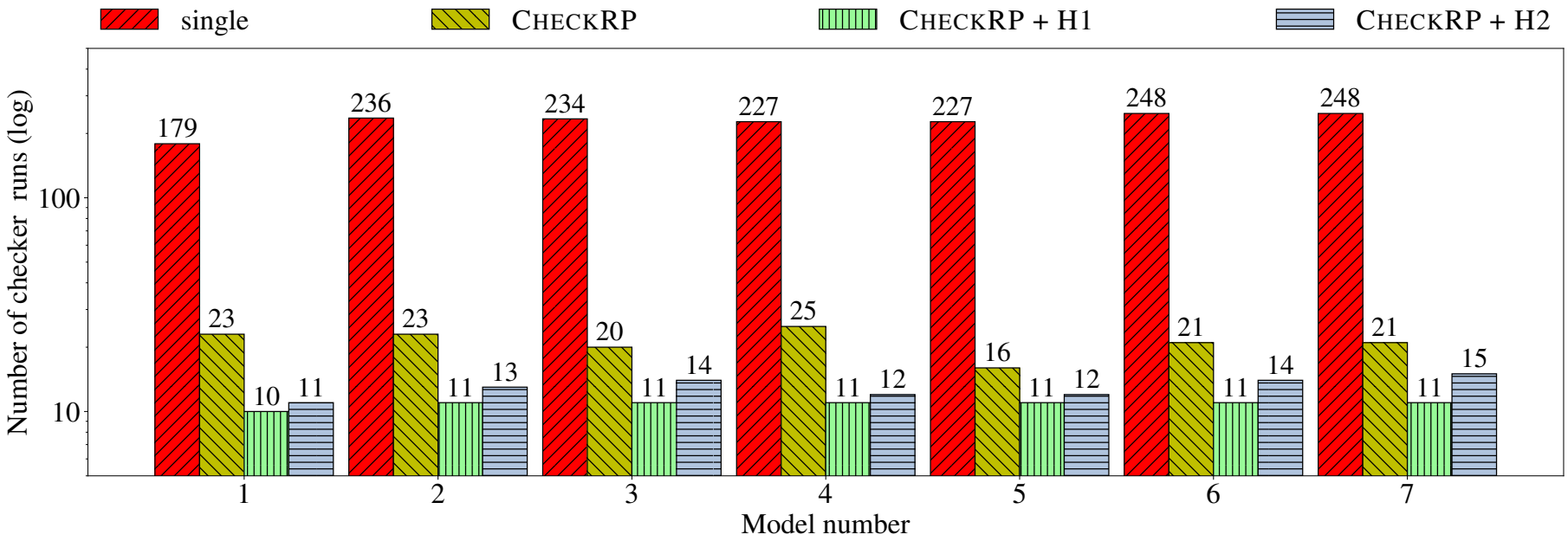

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Thank You!

`http://temporallogic.org/research/TACAS18`