Falsification of Cyber-Physical Systems with Robustness-Guided Black-Box Checking

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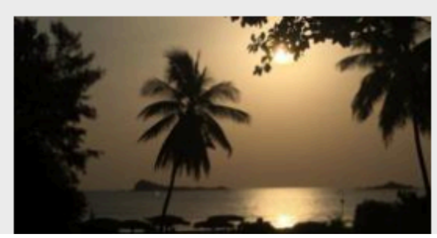

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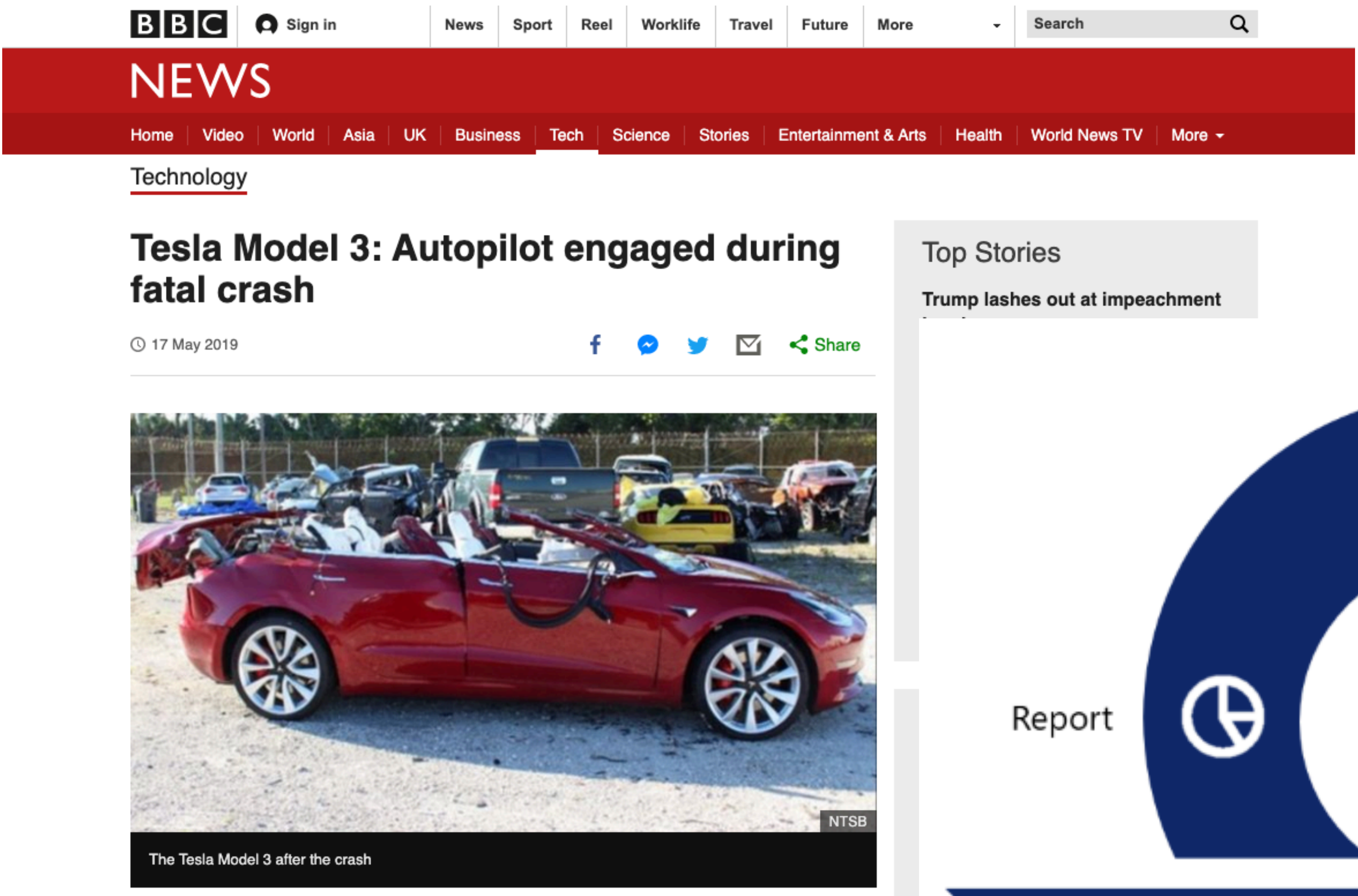

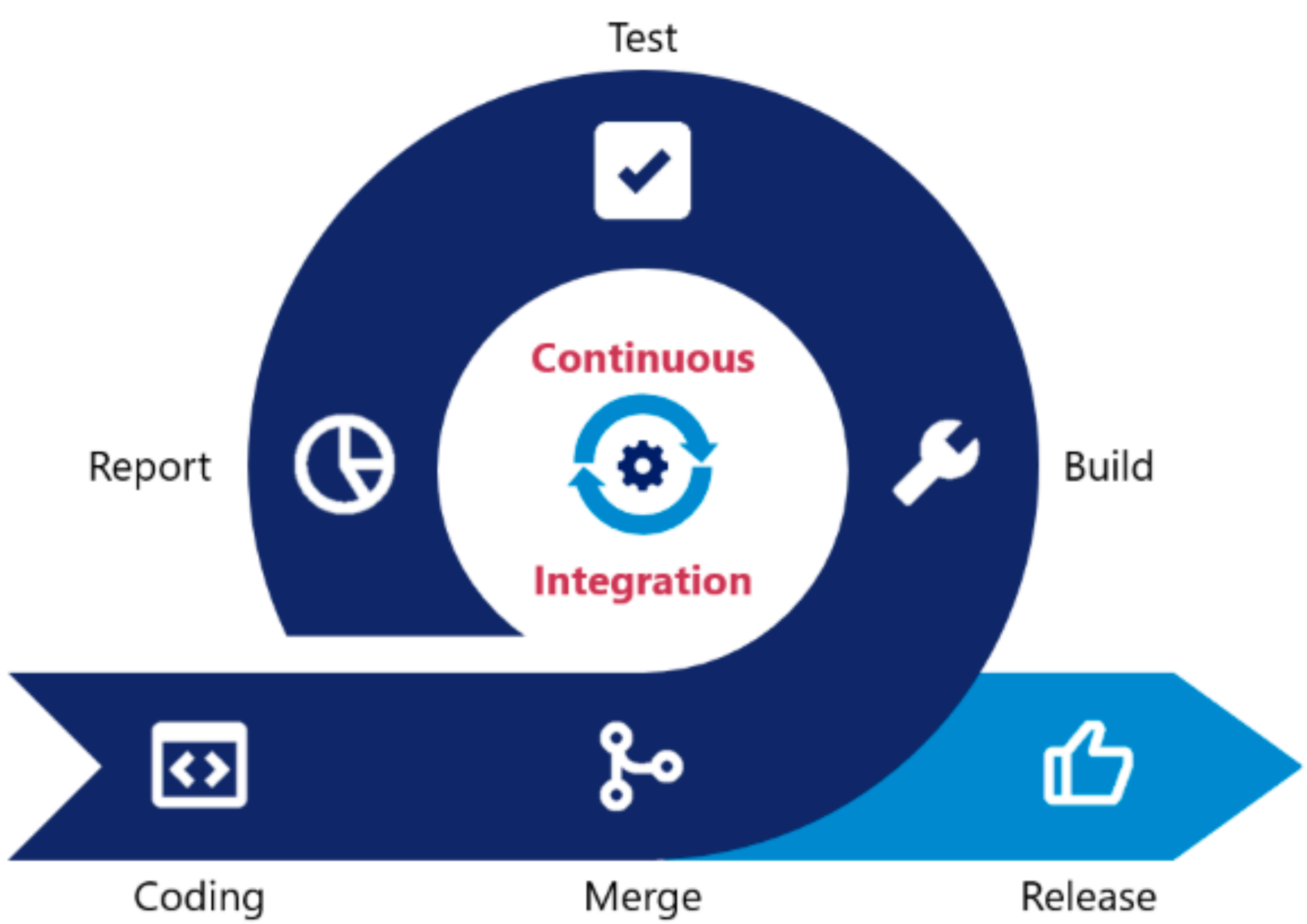

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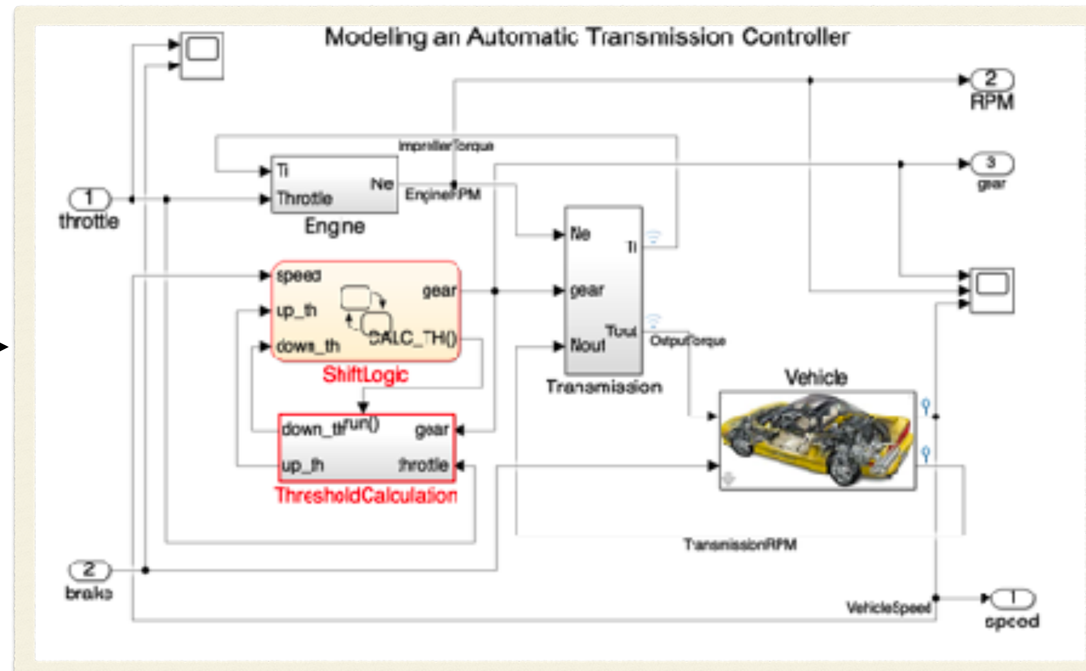
Falsification: Robustness + Optimization

$\mathscr{M}$



Robustness Monitor
Spec: φ in STL
(signal temporal logic)

Optimizer
(Minimize Robustness)

M. Waga (NII)

Falsification: Robustness + Optimization

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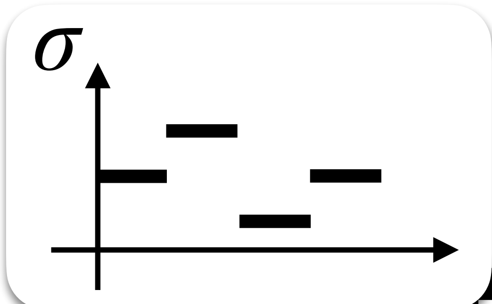

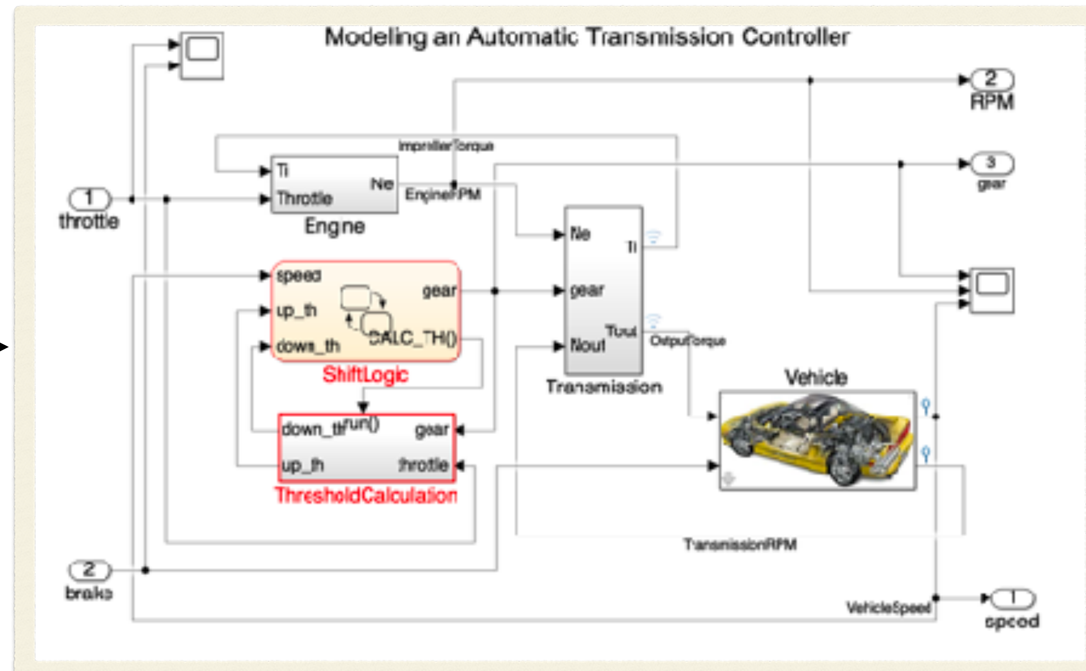

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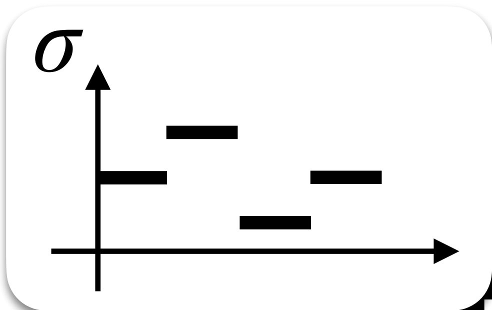

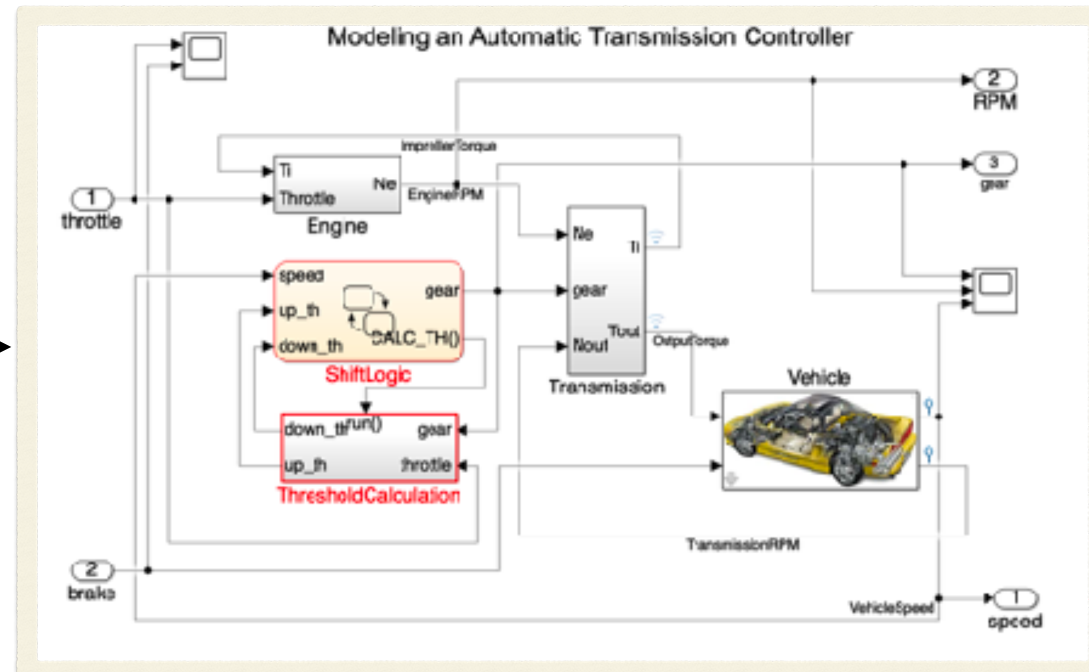

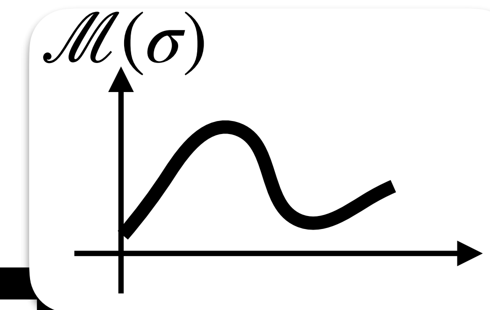

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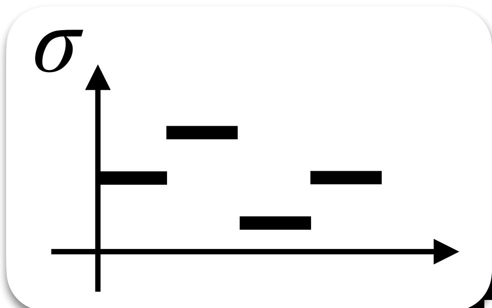
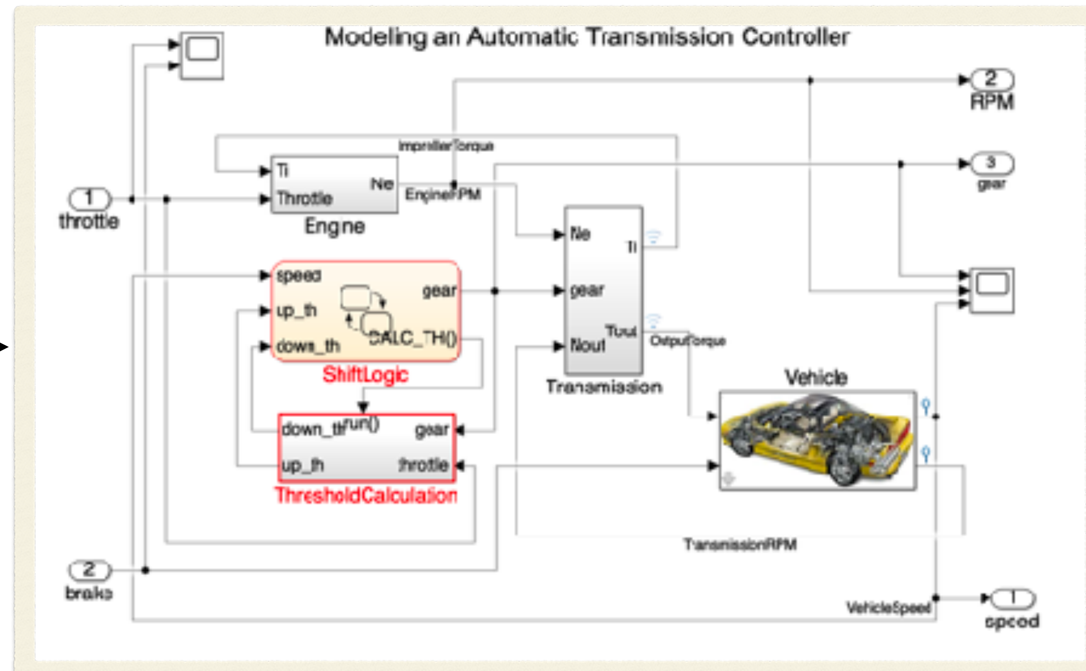
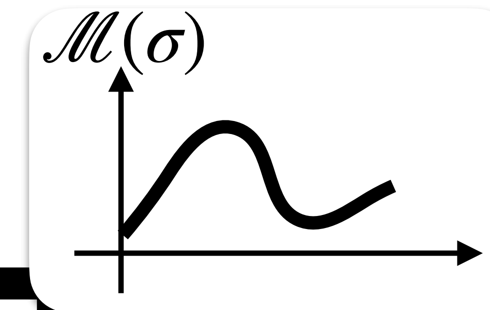






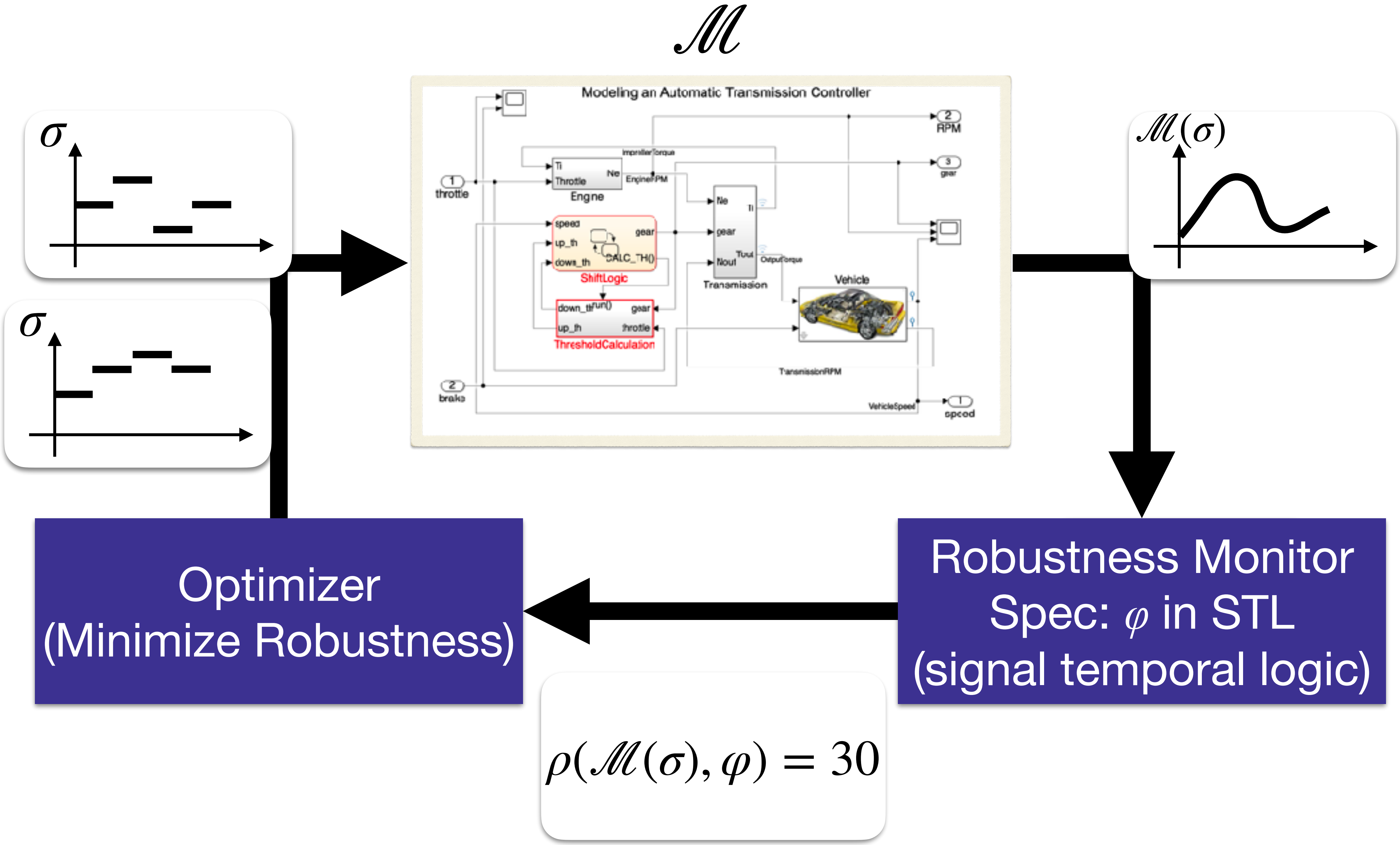
Robustness Monitor
Spec: φ in STL
(signal temporal logic)

$$\rho(\mathscr{M}(\sigma), \varphi) = 30$$

Optimizer
(Minimize Robustness)

M. Waga (NII)

Falsification: Robustness + Optimization



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Falsification: Robustness + Optimization

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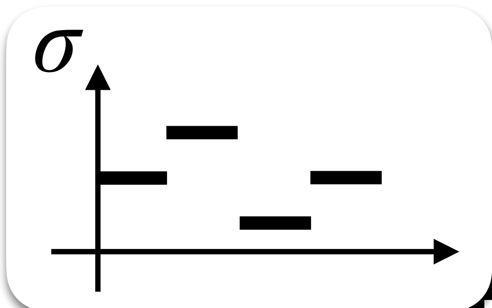

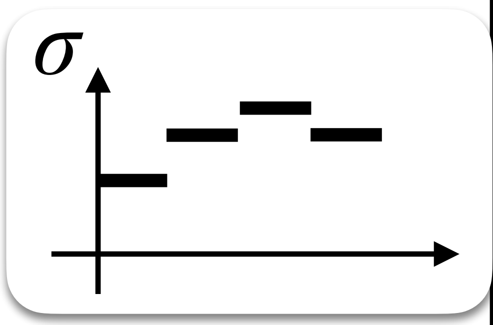

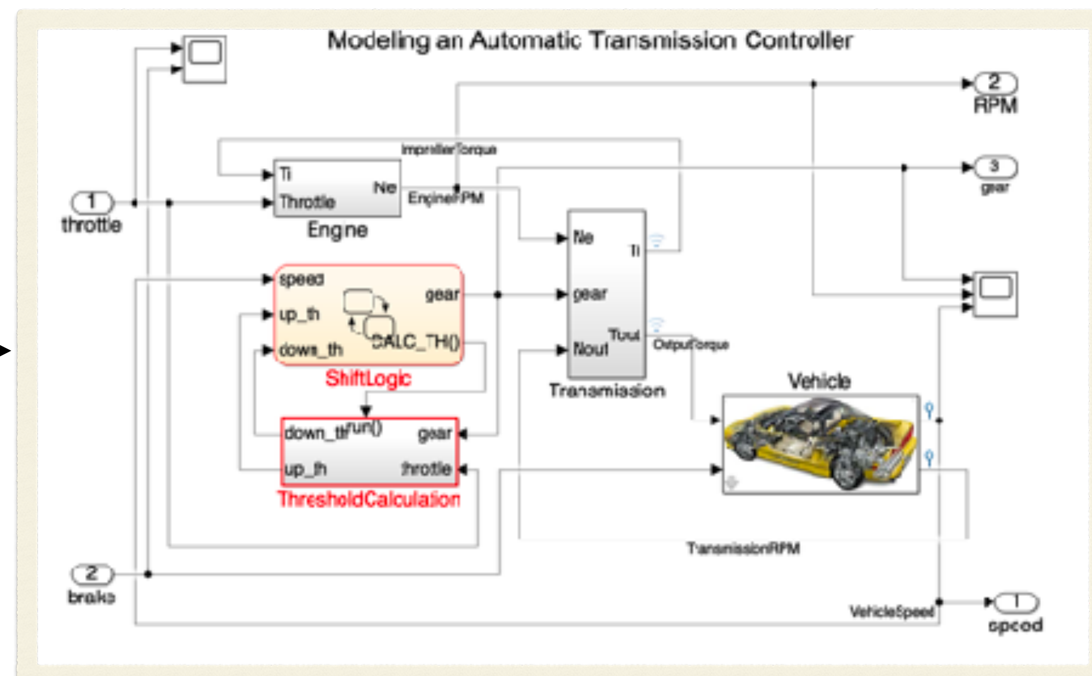

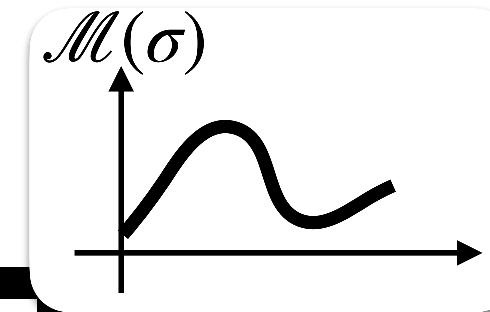

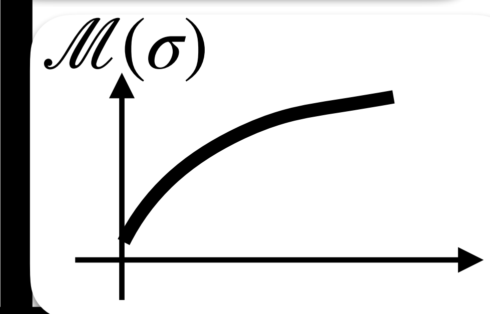

Robustness Monitor
Spec: φ in STL
(signal temporal logic)

$\rho(\mathscr{M}(\sigma), \varphi) = 30$

Optimizer
(Minimize Robustness)

$\rho(\mathscr{M}(\sigma), \varphi) = -10$

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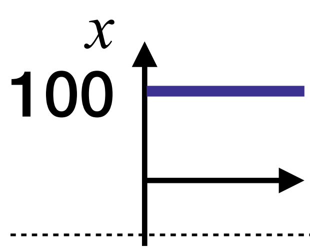
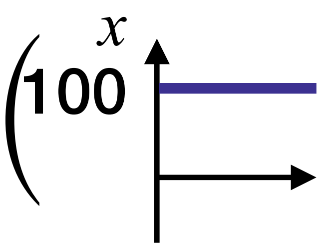
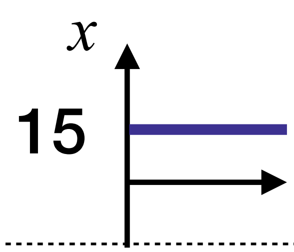
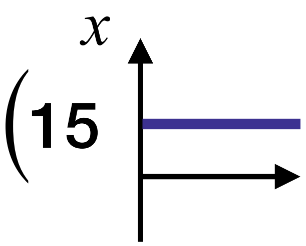
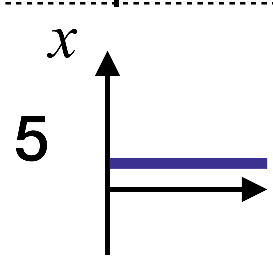
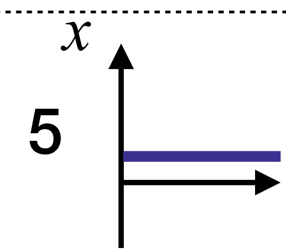
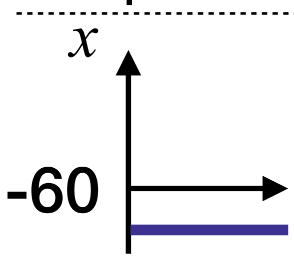
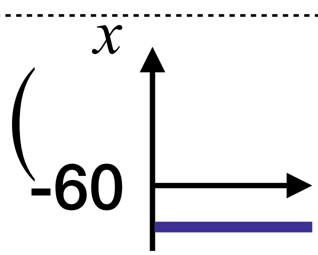
Robustness of STL

Boolean	Robust
 $\models \Box\, x > 10$	$\rho\Big($  $, \Box\, x > 10\Big) =$ **90**
 $\models \Box\, x > 10$	$\rho\Big($  $, \Box\, x > 10\Big) =$ **5**
 $\not\models \Box\, x > 10$	$\rho\Big($  $, \Box\, x > 10\Big) =$ **-5**
 $\not\models \Box\, x > 10$	$\rho\Big($  $, \Box\, x > 10\Big) =$ **-70**

Clearly satisfied

Boarder

Clearly violated

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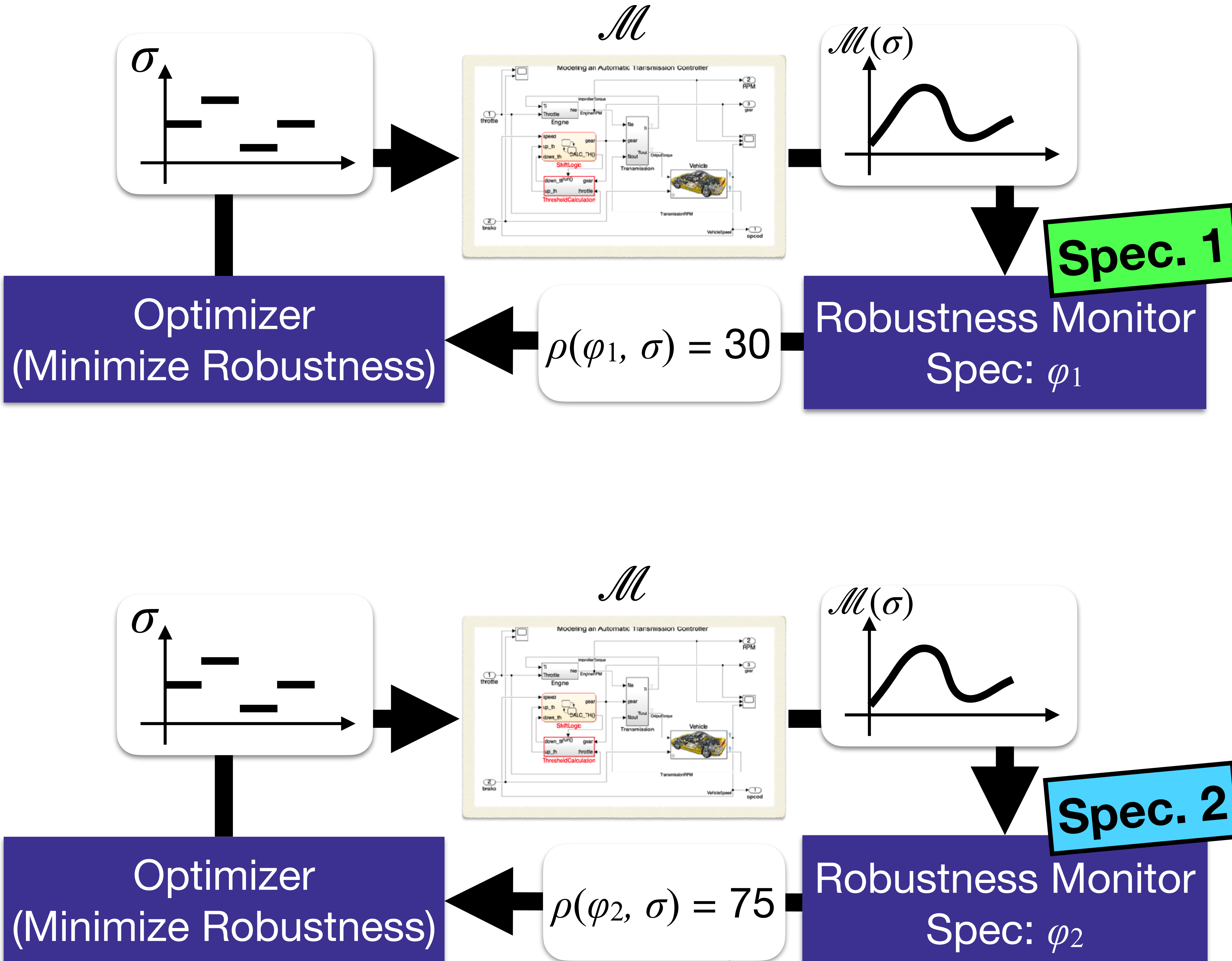
Falsification is Oneshot



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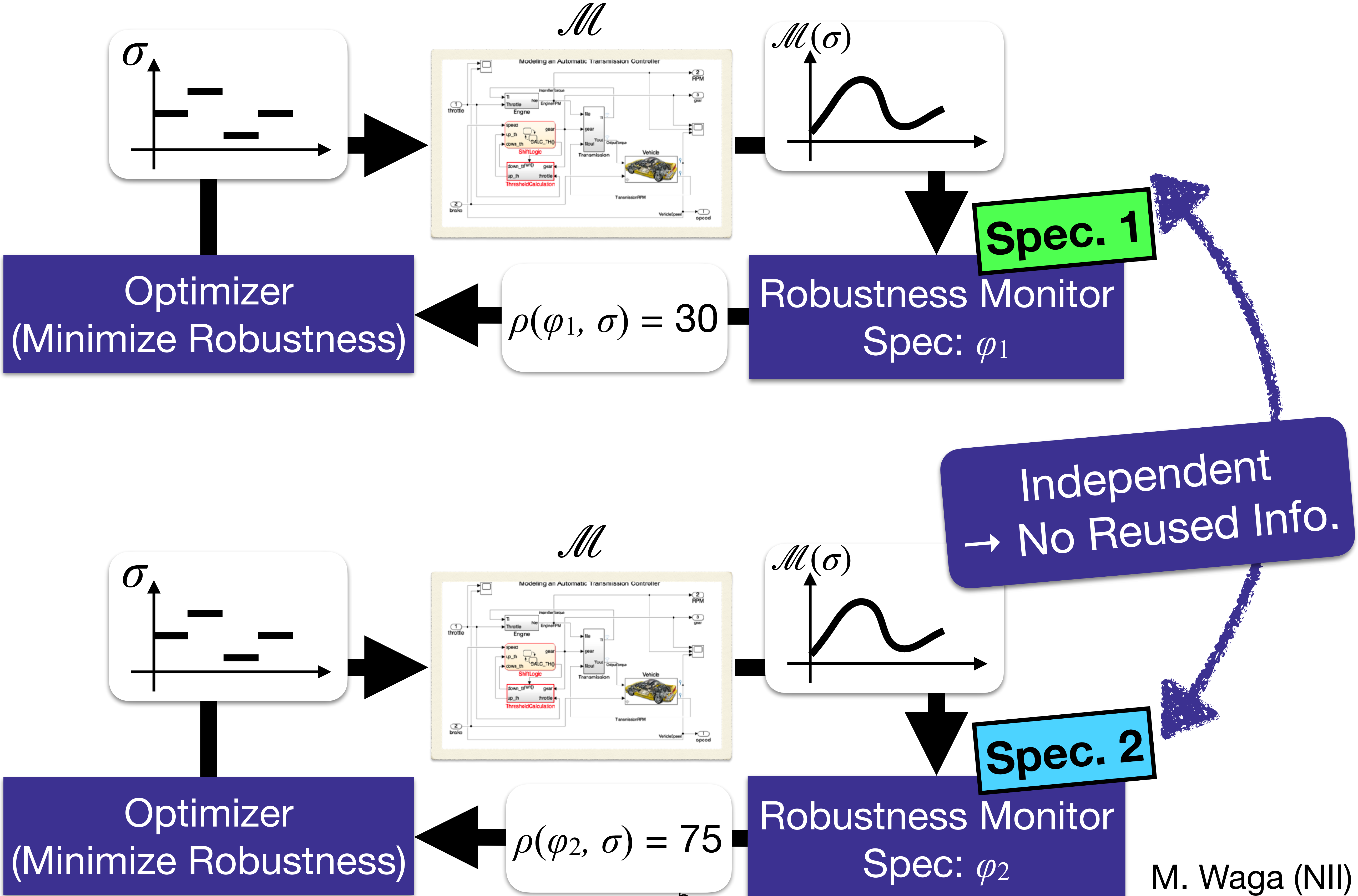

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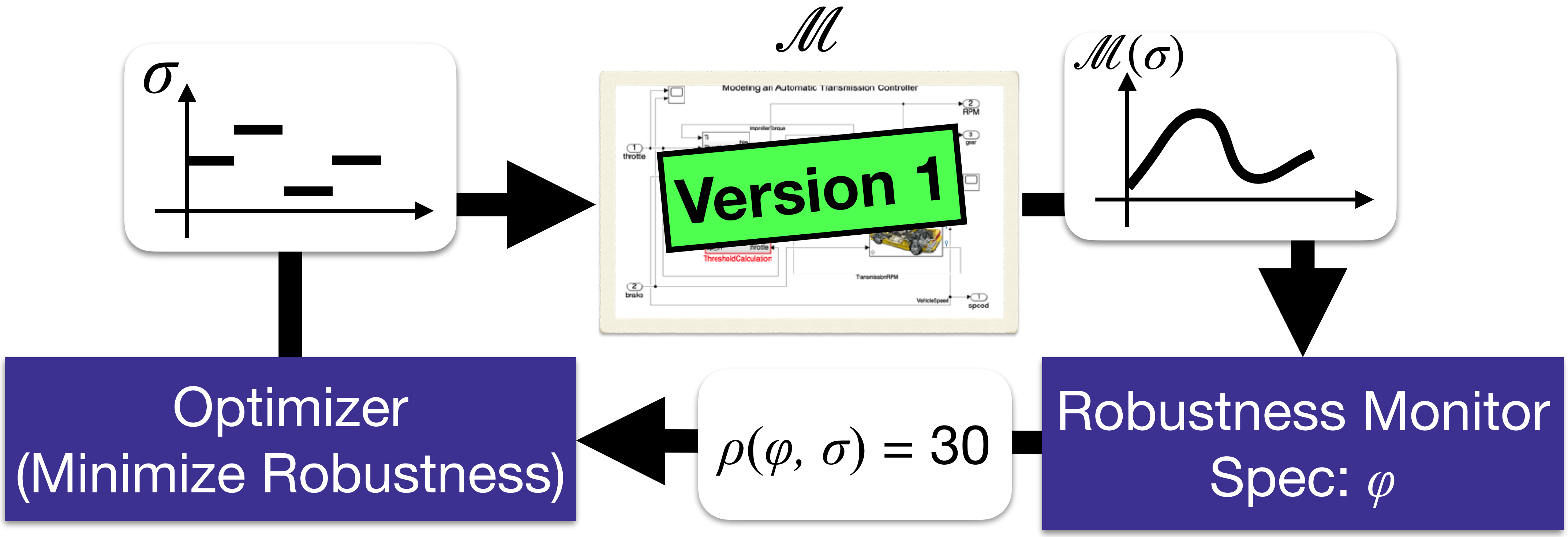

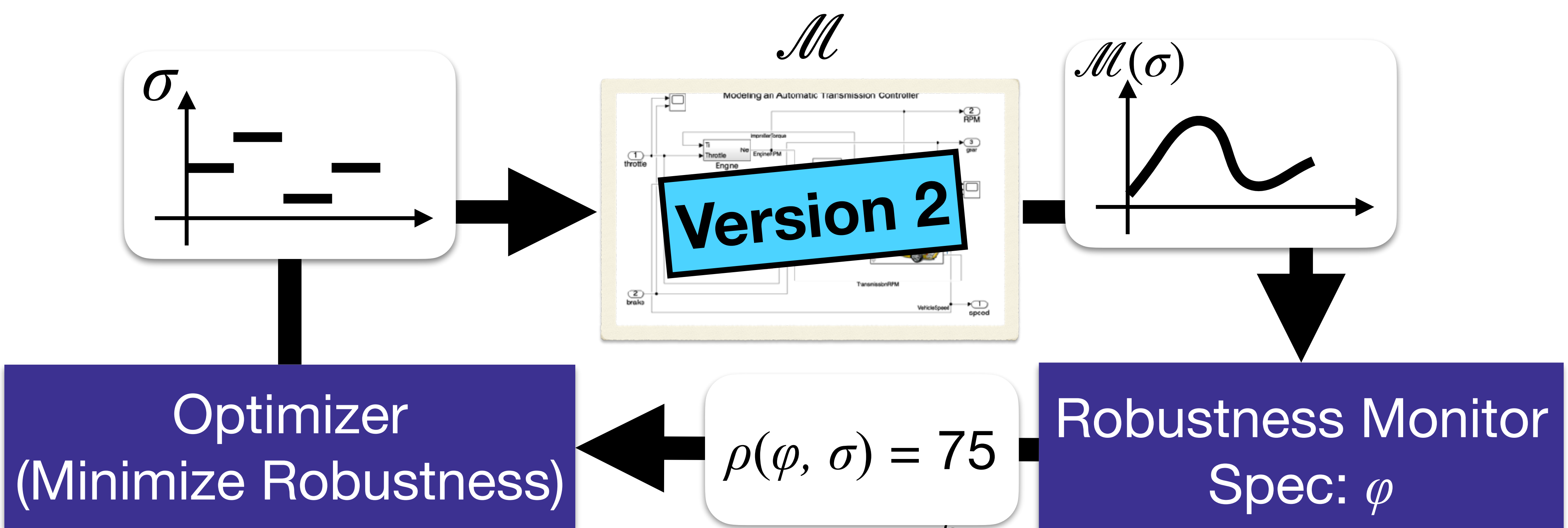

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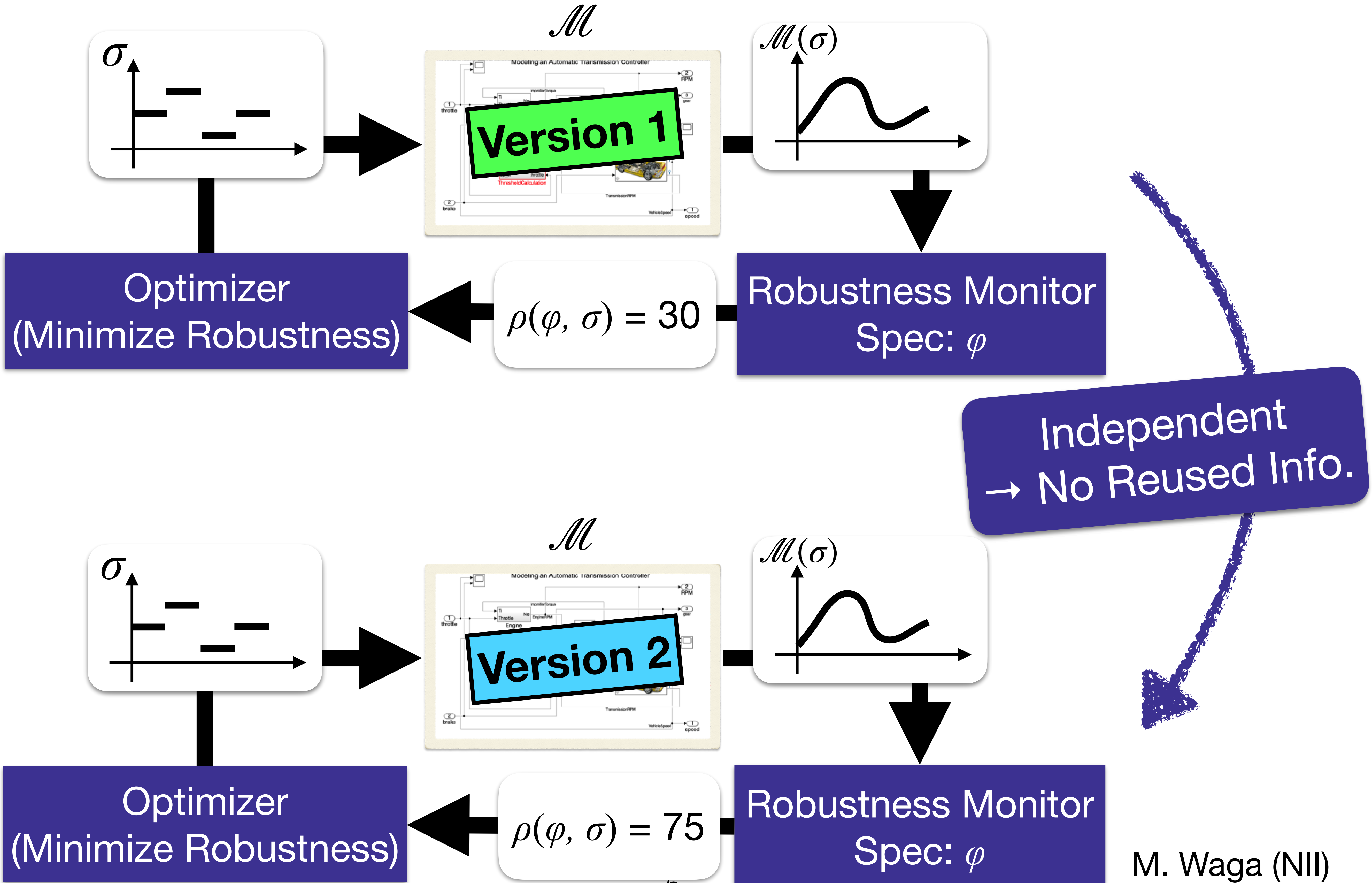

Q. How to reuse the previous exploration information

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Our Approach:
Black-Box Checking (BBC)

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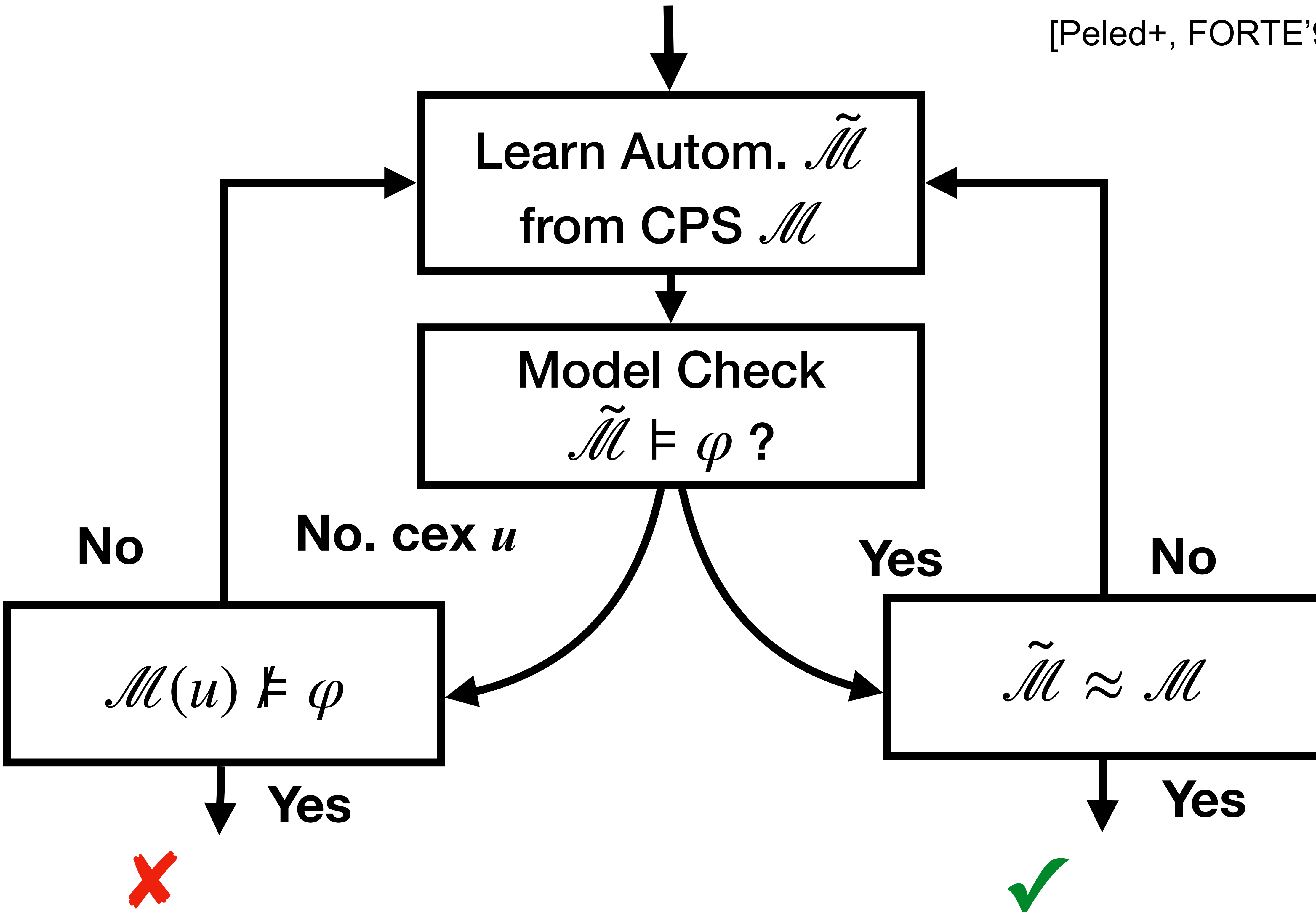
Black-Box Checking (BBC)

[Peled+, FORTE'99]



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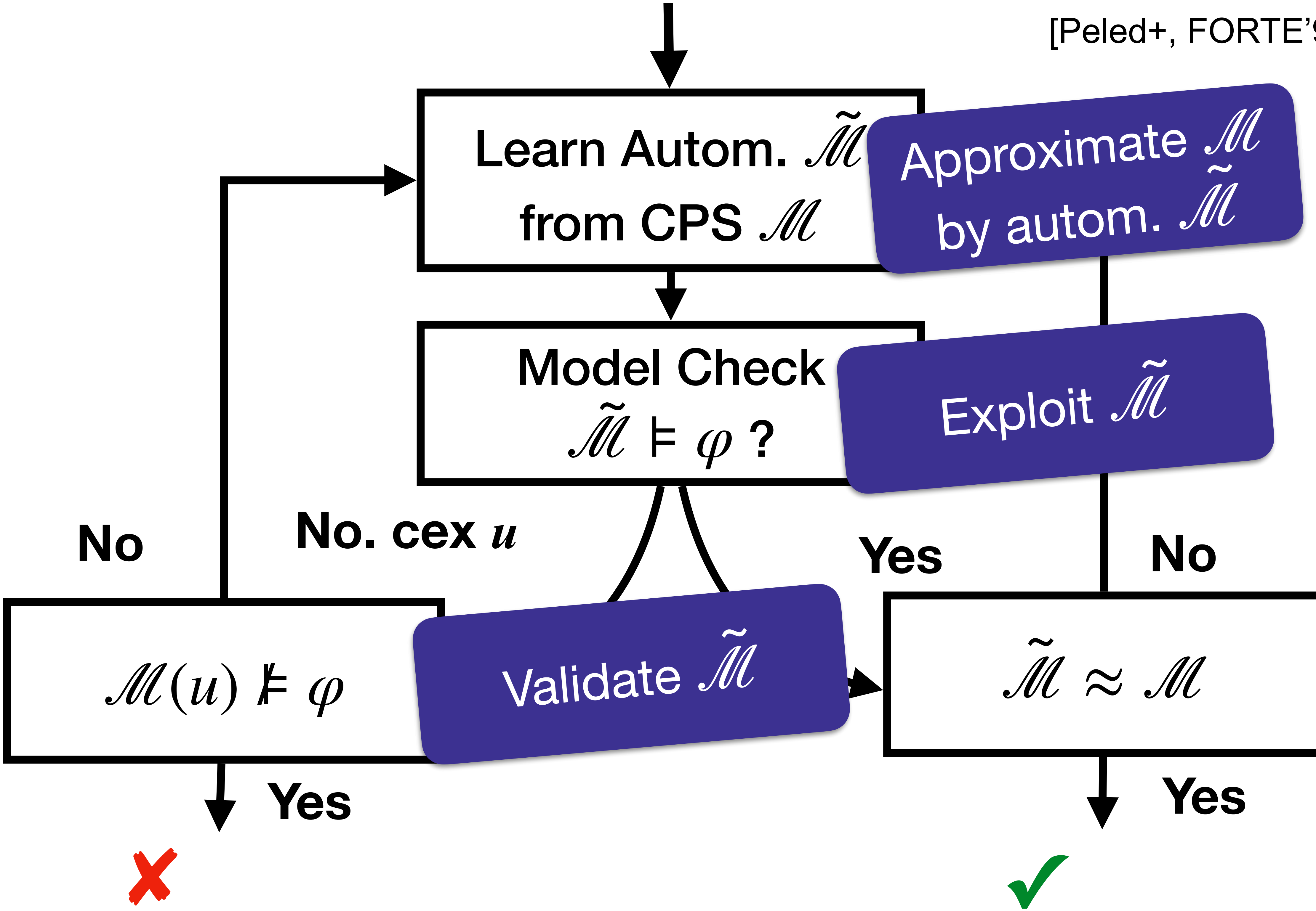

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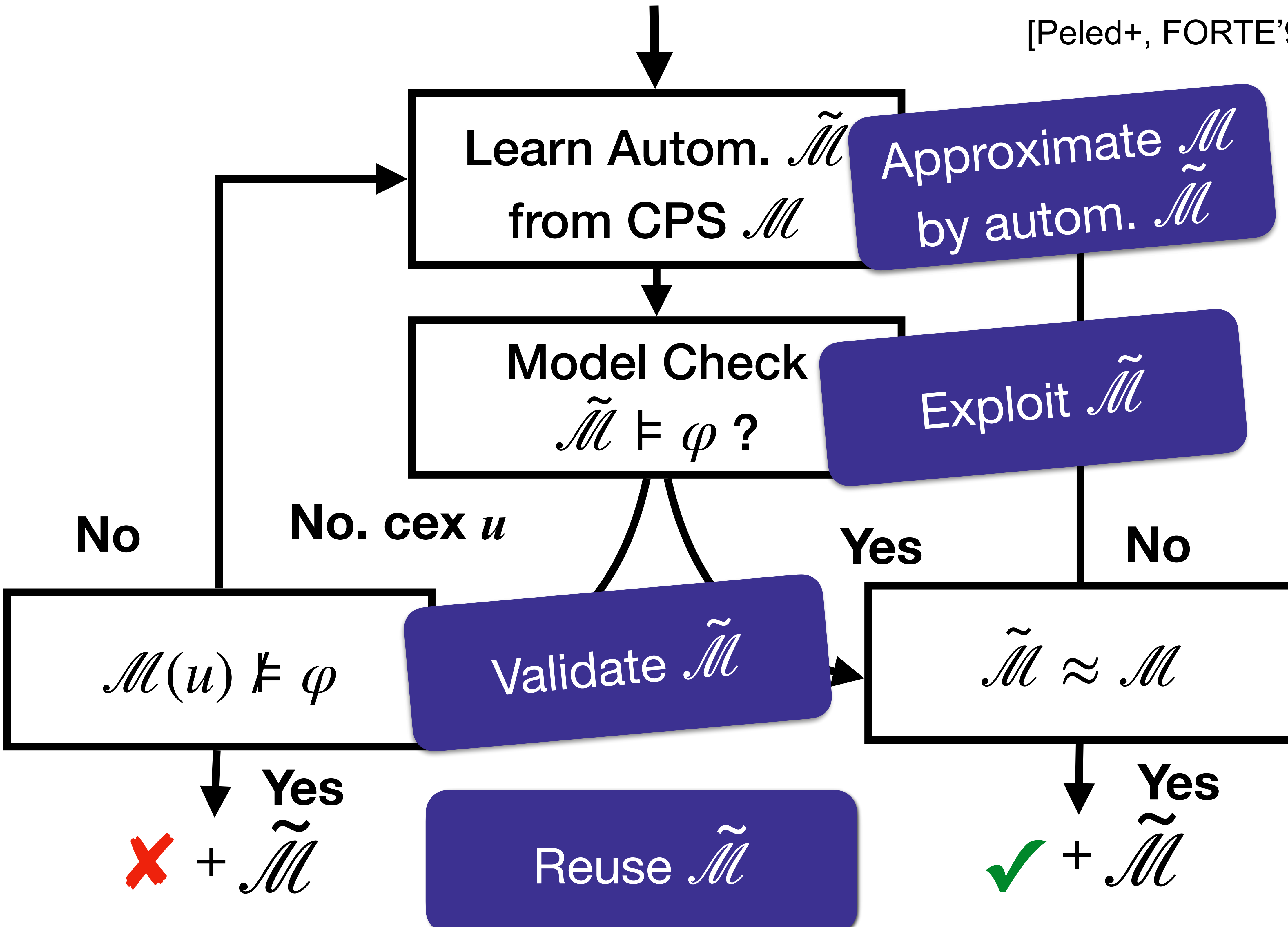

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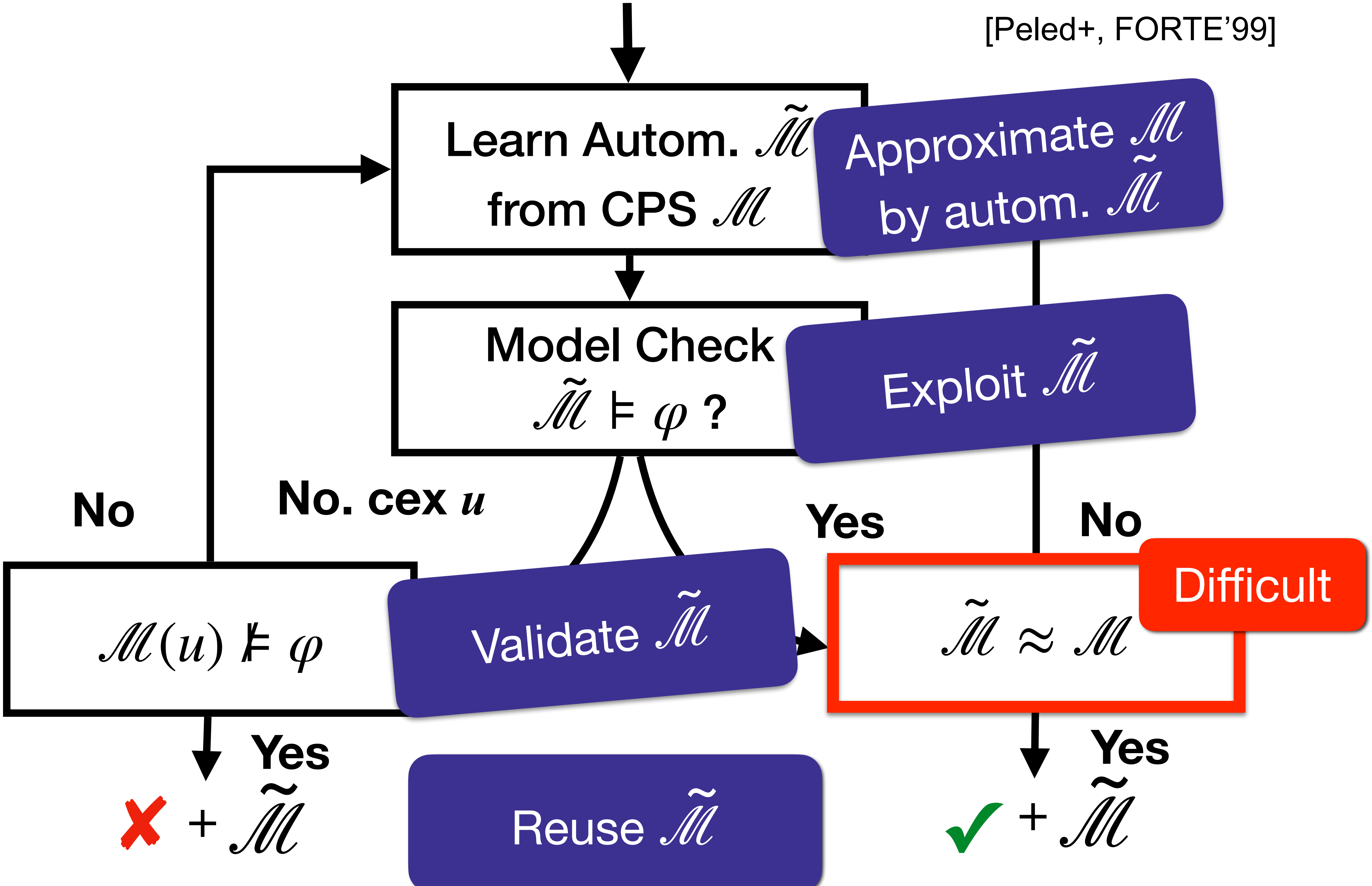

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Equivalence Test: $\tilde{\mathscr{M}} \approx \mathscr{M}$

- **Theoretically**: Automata-based conformance test e.g., W-method [Chow, TSE'78], Wp-method [Fujiwara+, TSE'91]
  - ☹️ # of states is necessary for soundness
- **Practically**:
  - Random test
    - ☹️ Not good at "rare" cex

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- **Practically**:
  - Random test
    - ☹️ Not good at "rare" cex

Q. How about hitting "rare" cex with robustness of STL?

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Robustness-Guided Equivalence Test

[Contribution]

- Equivalence Test with Robustness + Optimization
  - Search for u s.t. $\tilde{\mathscr{M}}(u) \neq \mathscr{M}(u)$
  - Genetic algorithm or hill climbing
  - Fitness function: Robustness of STL
- $\tilde{\mathscr{M}}$ is not directly evaluated
  - Discrete behavior of $\tilde{\mathscr{M}}$ is not a problem

Detail is later

Contributions

- Presented robustness-guided equivalence test
  - Also introduced a new robustness suitable to model checking
- Used it for black-box checking of CPS
- Experimental evaluation: outperforms the baseline

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Outline

- Introduction
- Preliminary: Black-box checking
    - Automata learning, model checking, & equiv. test
- Main Contribution:
  Robustness-guided equivalence test
    - **idea:** Optimization + robustness
- Experiments

Black-Box Checking (BBC)

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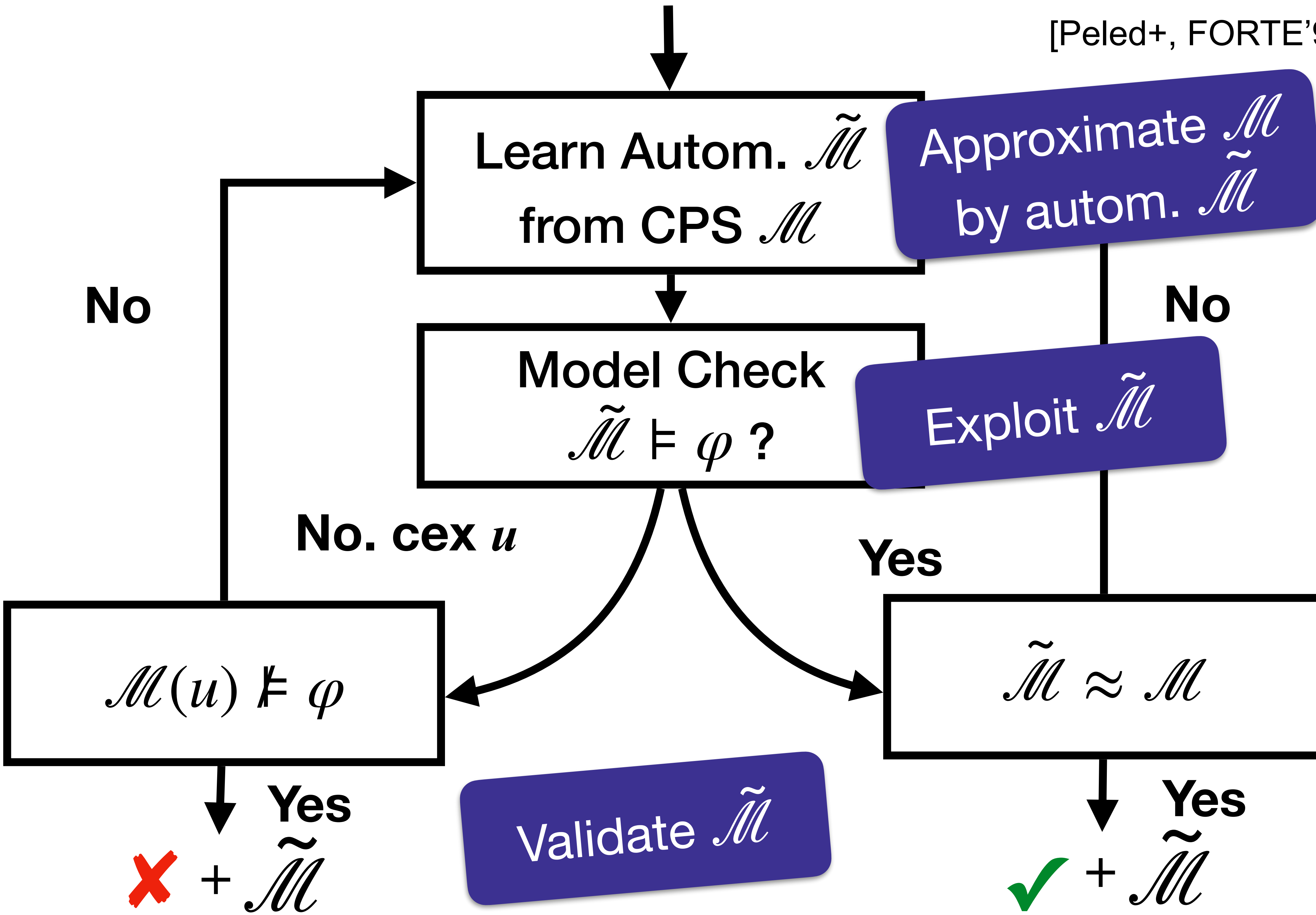

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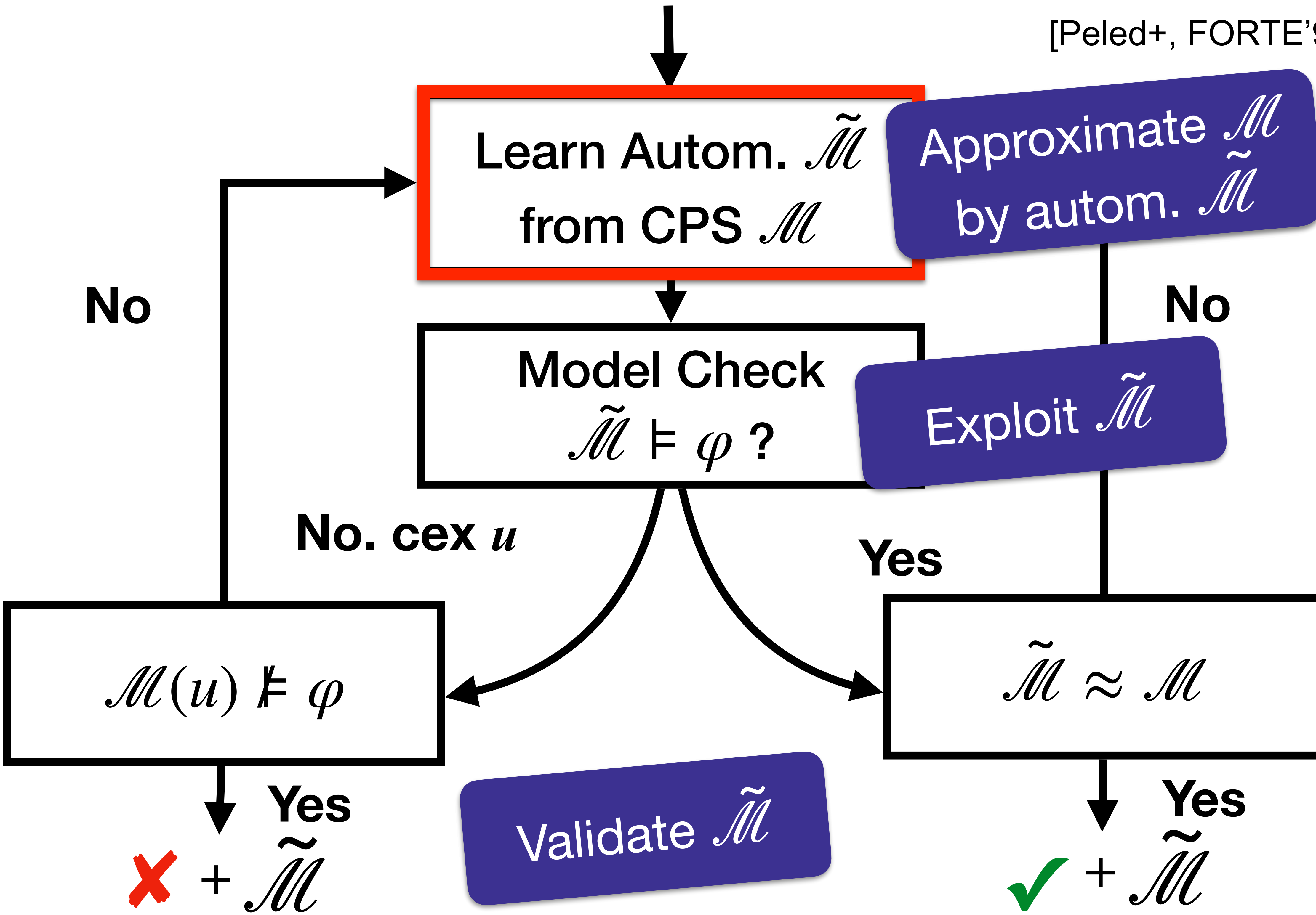
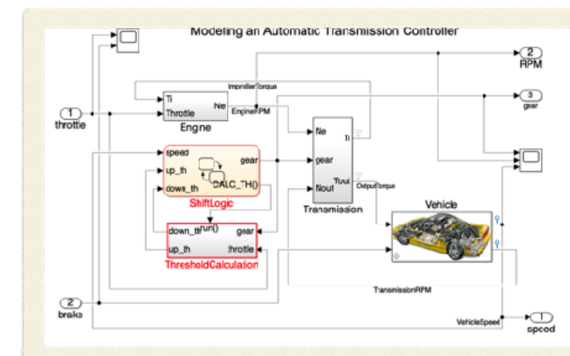
Black-Box Checking (BBC)



Automata Learning

1. Obtain suitable input/output pairs $\big(u, \mathscr{M}(u)\big)$ of $\mathscr{M}$
    - Input/output: finitely discretized



2. Generate a candidate Myhill-Nerode equiv. rel.

3. Construct the corresponding Mealy machine $\tilde{\mathscr{M}}$

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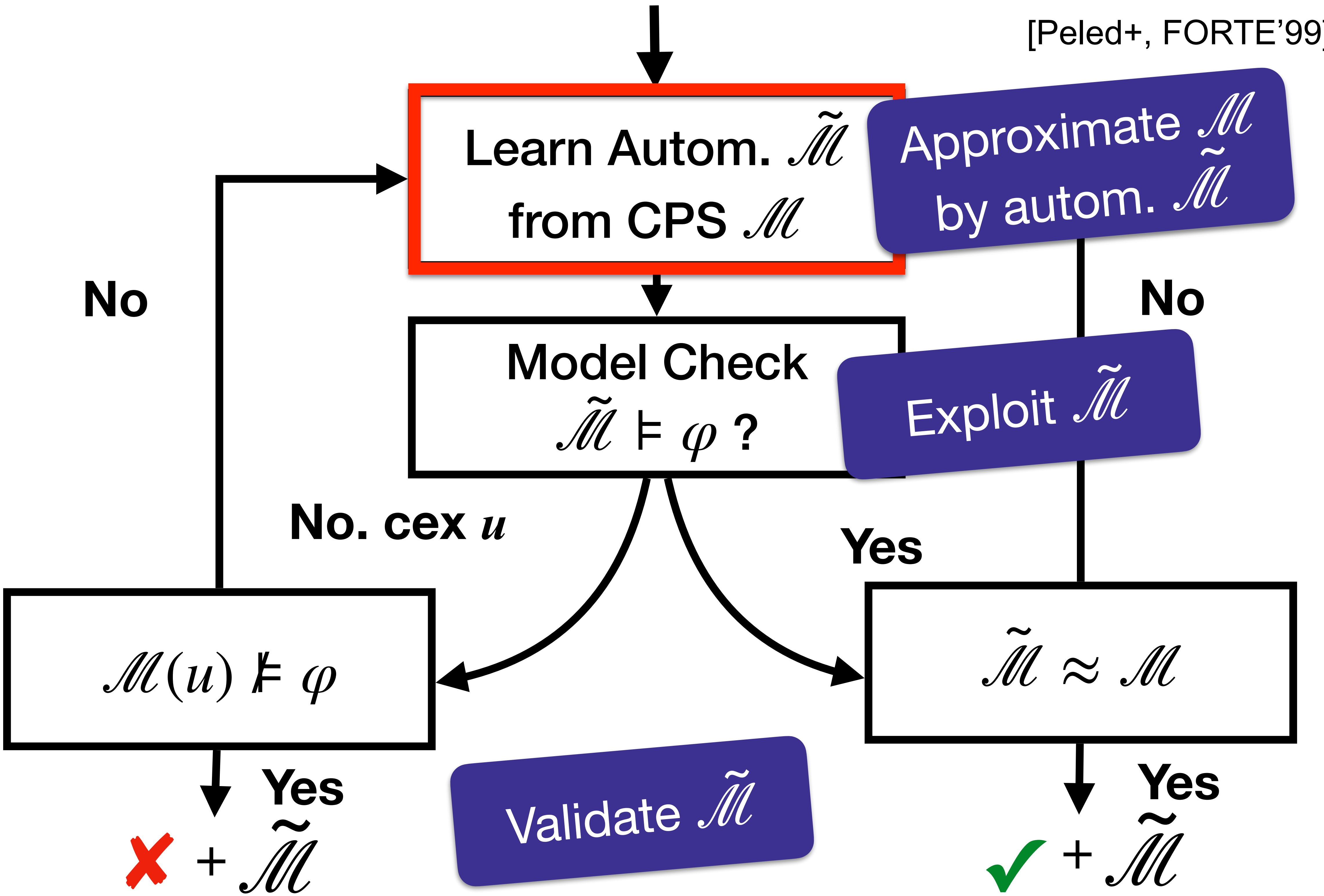
Black-Box Checking (BBC)



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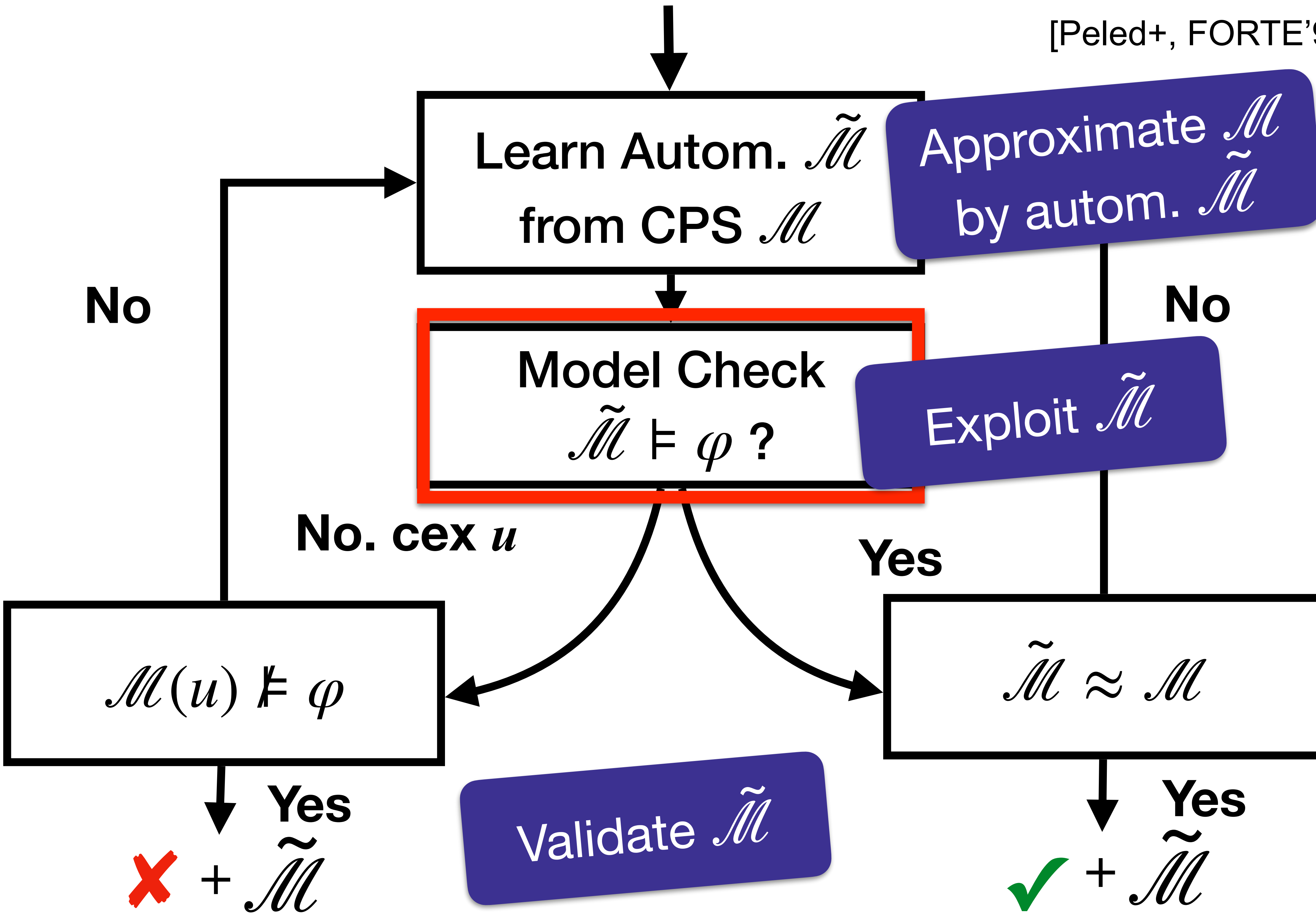

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Model Check: $\tilde{\mathscr{M}} \models \varphi$?

Issue: φ is not in LTL but in STL

Our Solution: Encode to LTL model checking

STL

$\varphi ::= \underline{x \bowtie c} \mid \varphi \land \varphi \mid \cdots \mid \varphi \mathcal{U}_I \varphi$

Inequality

LTL

$\varphi ::= \underline{P} \mid \varphi \land \varphi \mid \cdots \mid \varphi \mathcal{U} \varphi$

Proposition

Assumption:
signal is discrete-time with constant interval

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Black-Box Checking (BBC)

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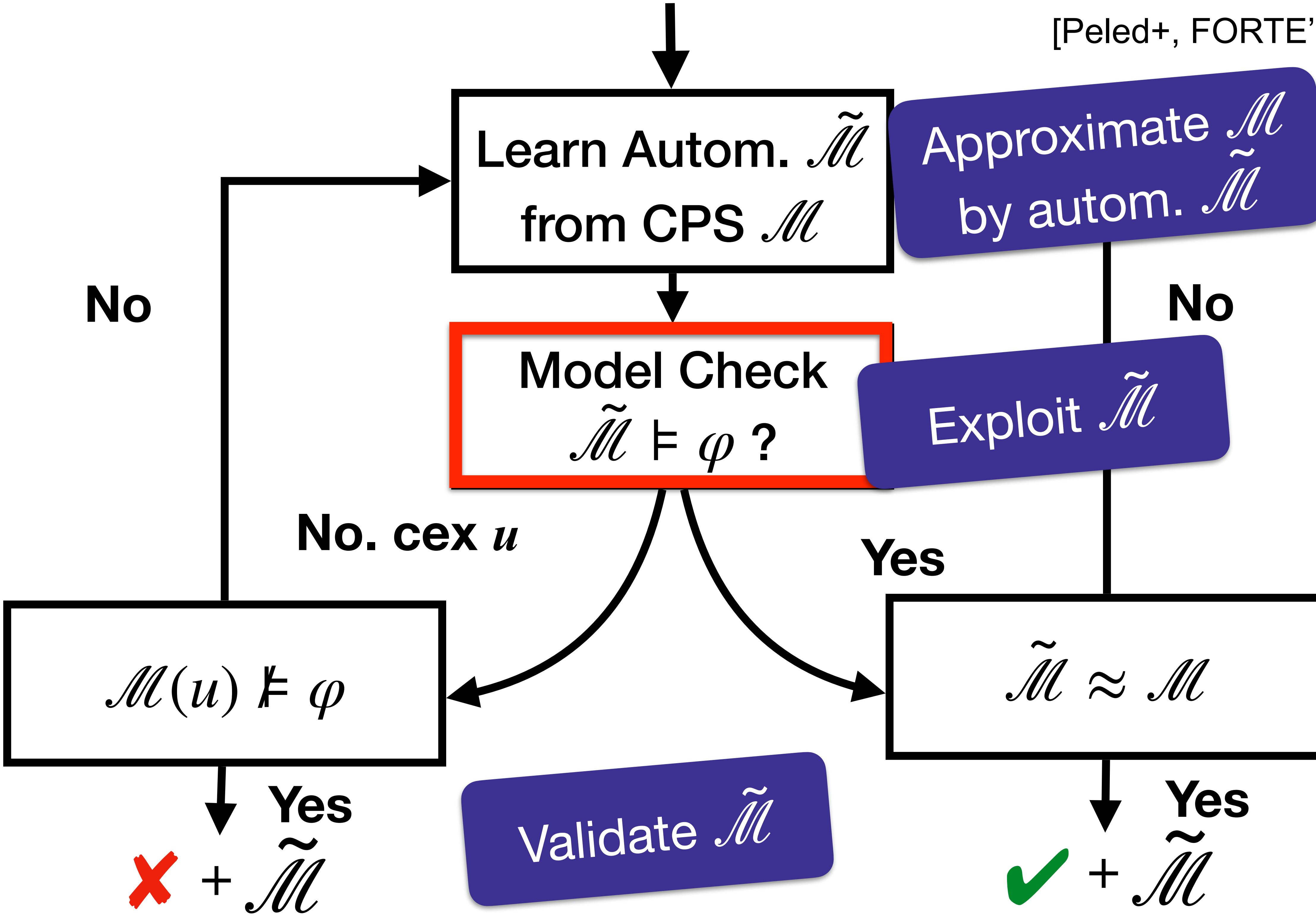

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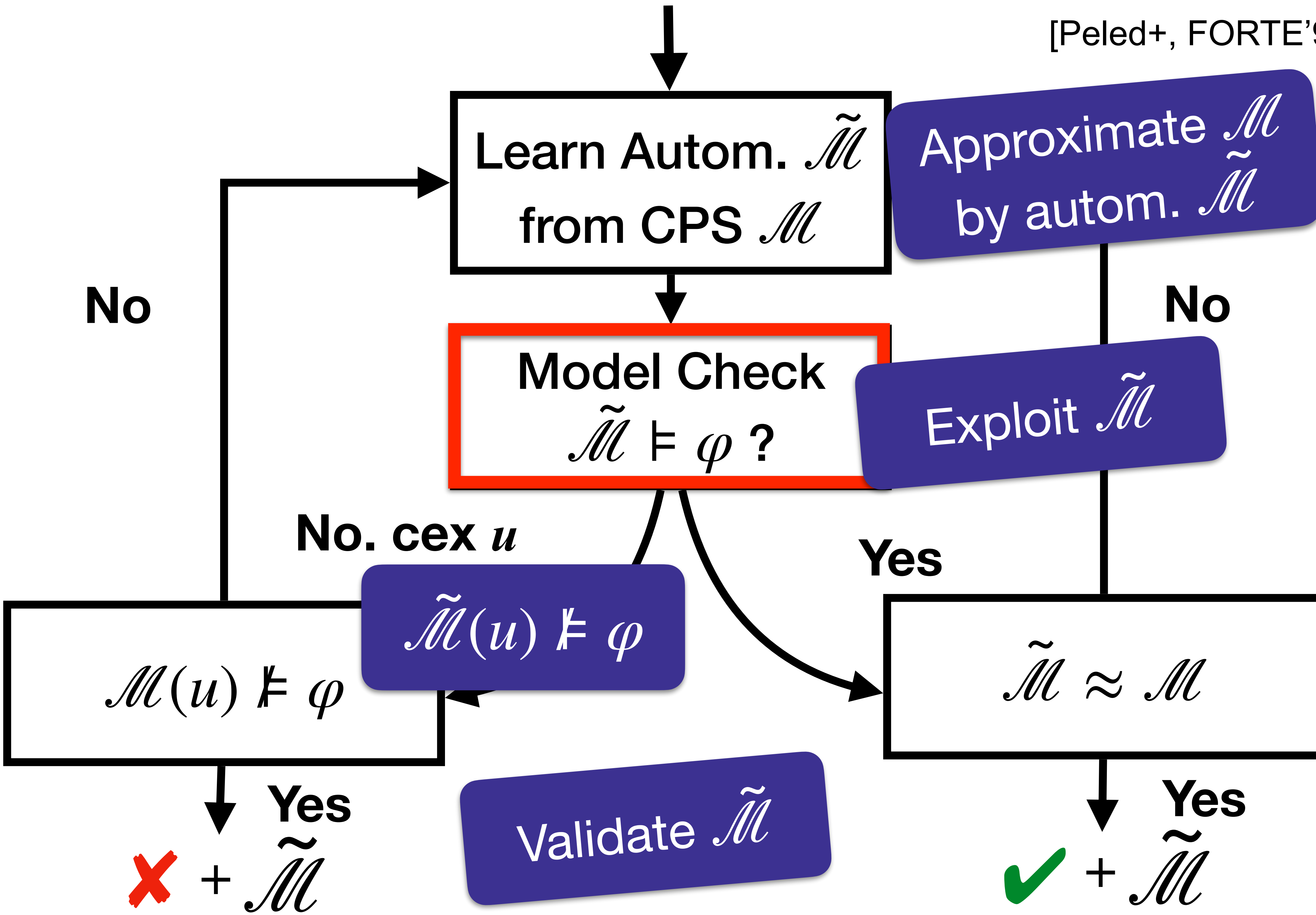

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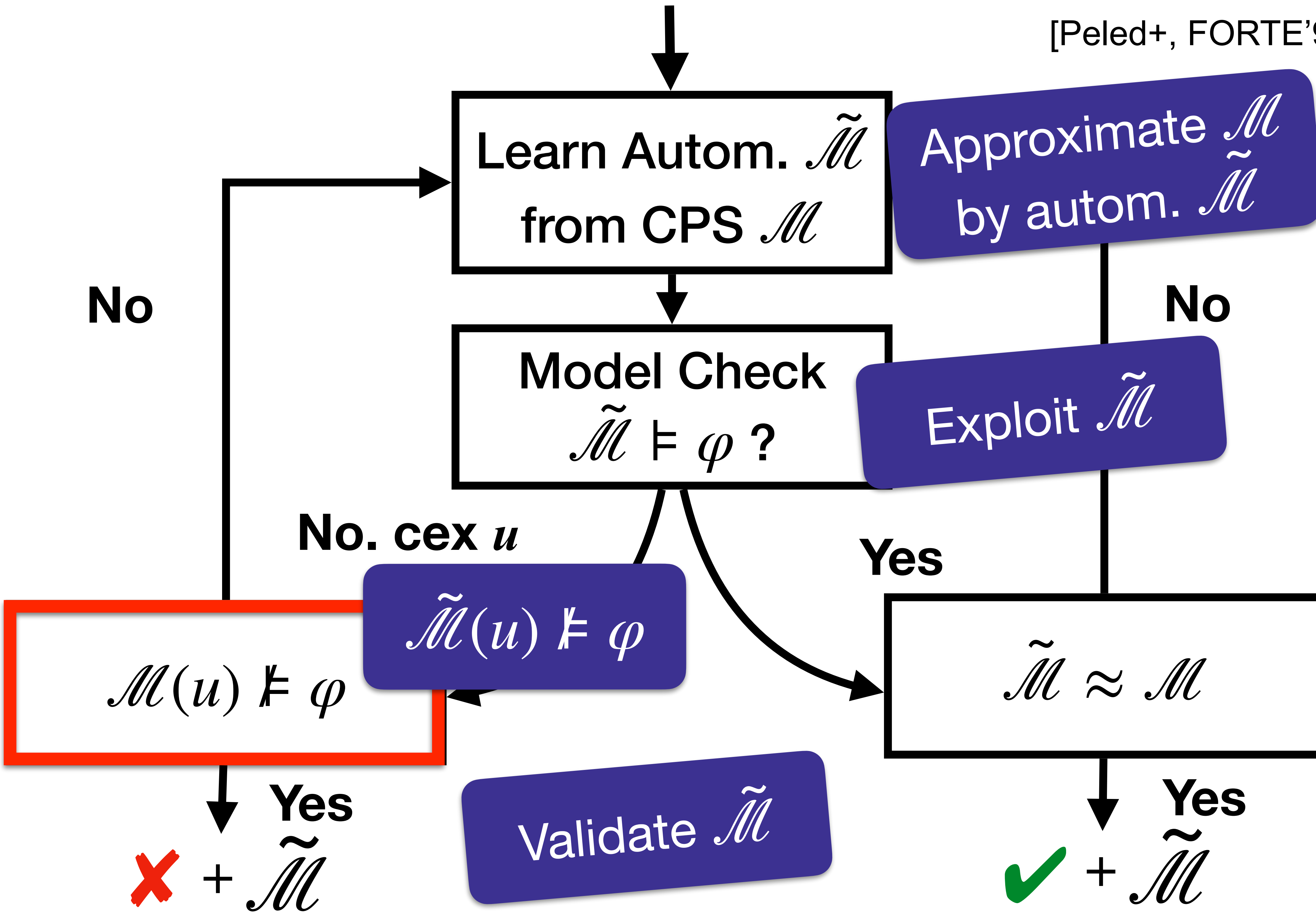

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Black-Box Checking (BBC)

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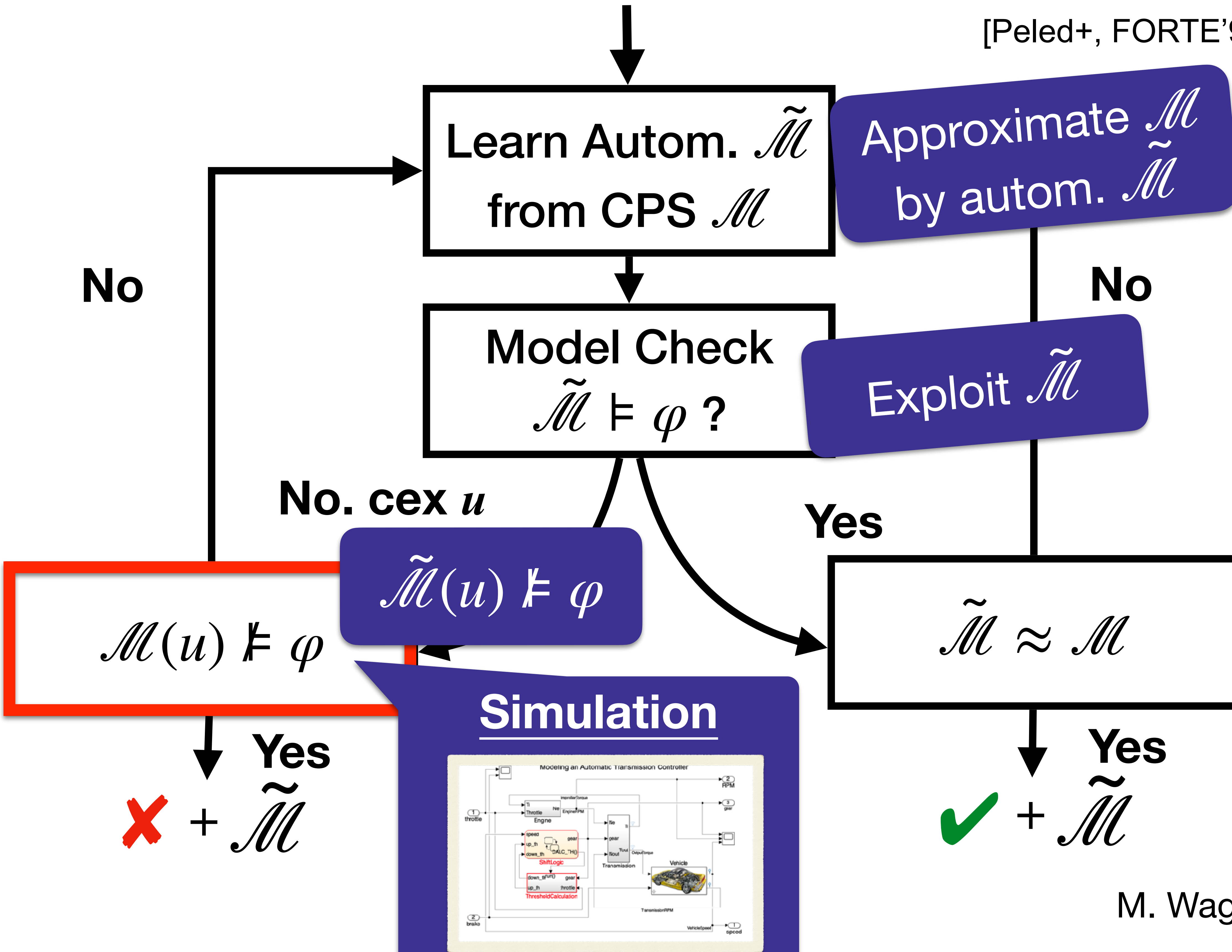

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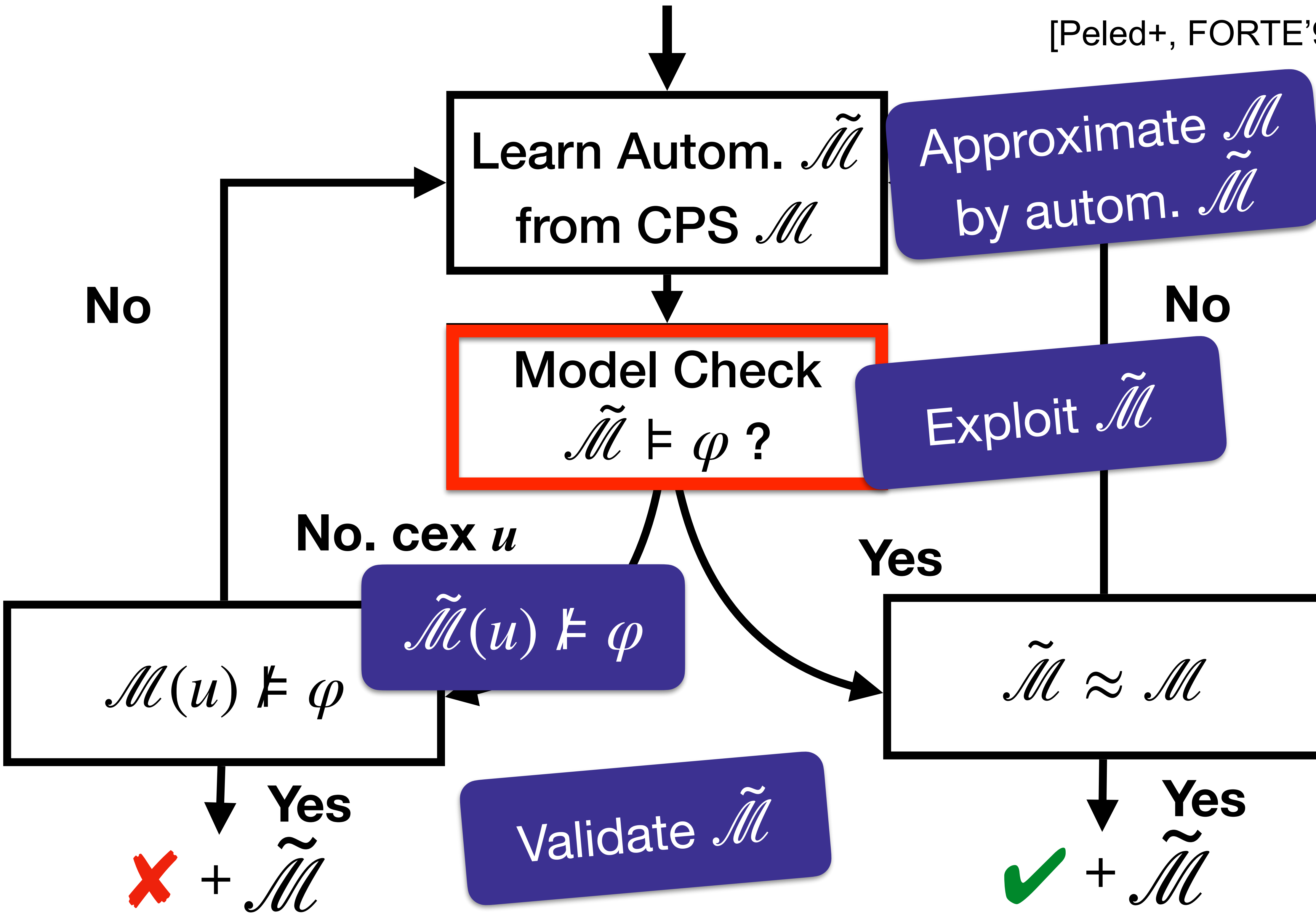

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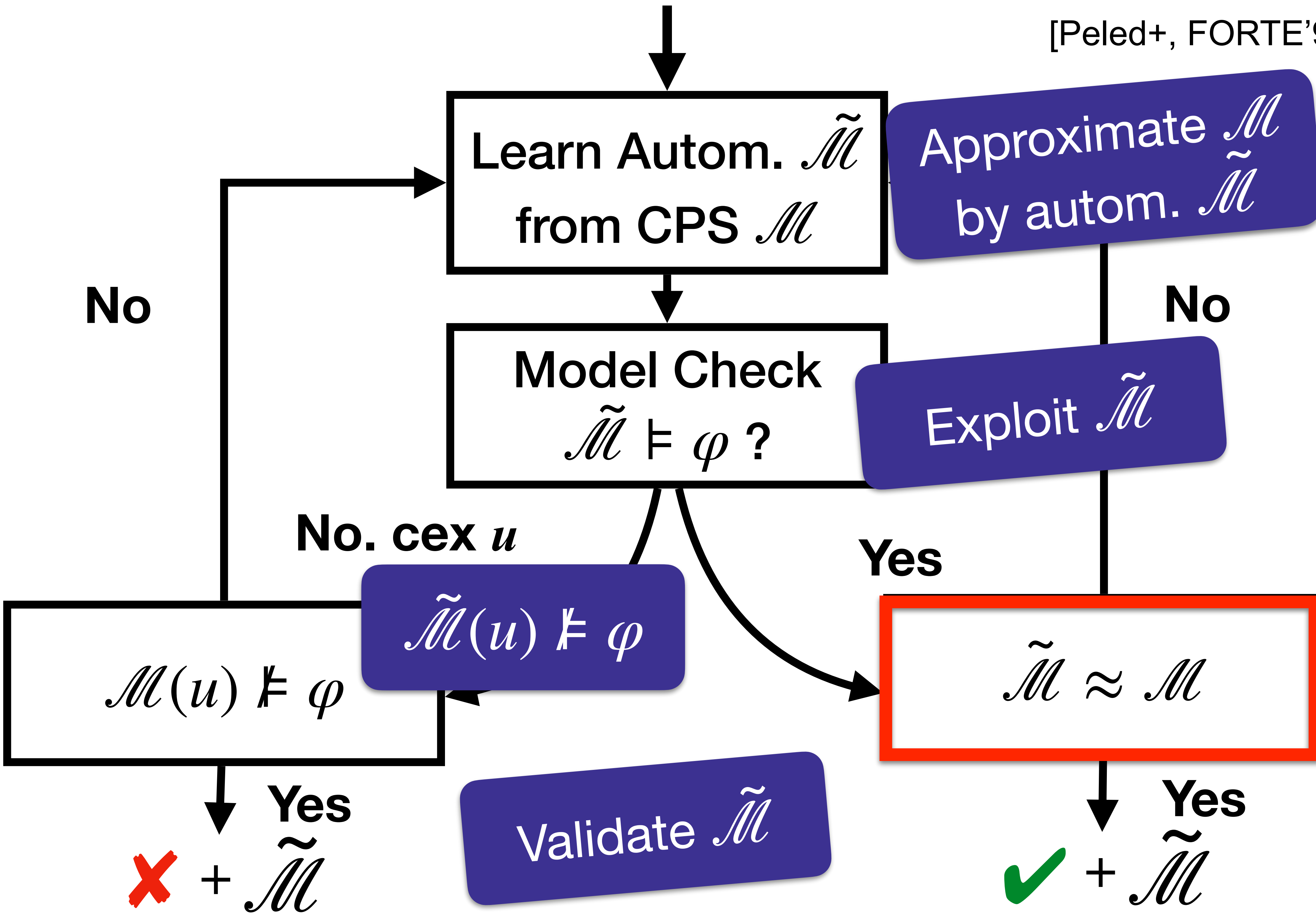

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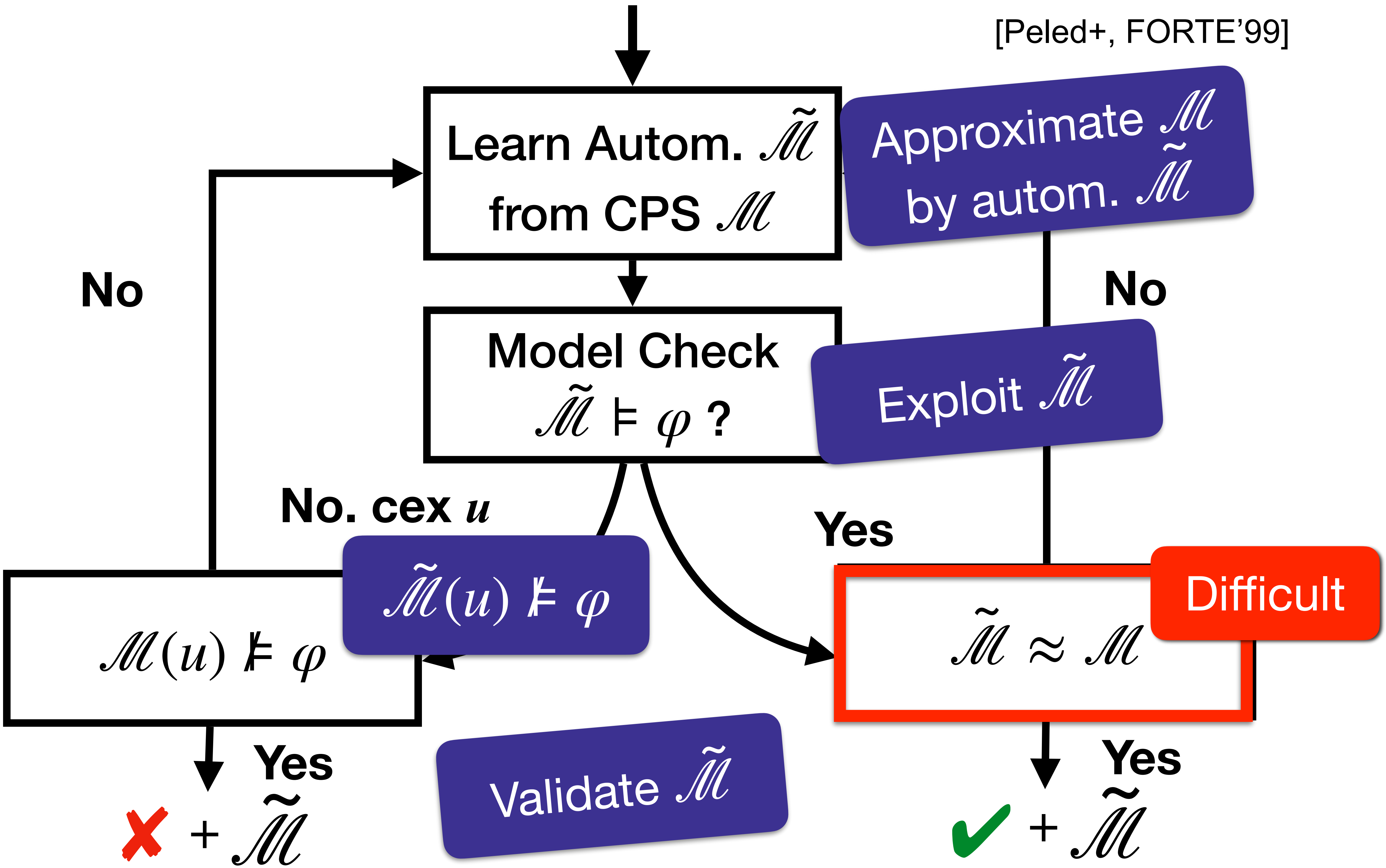

M. Waga (NII)

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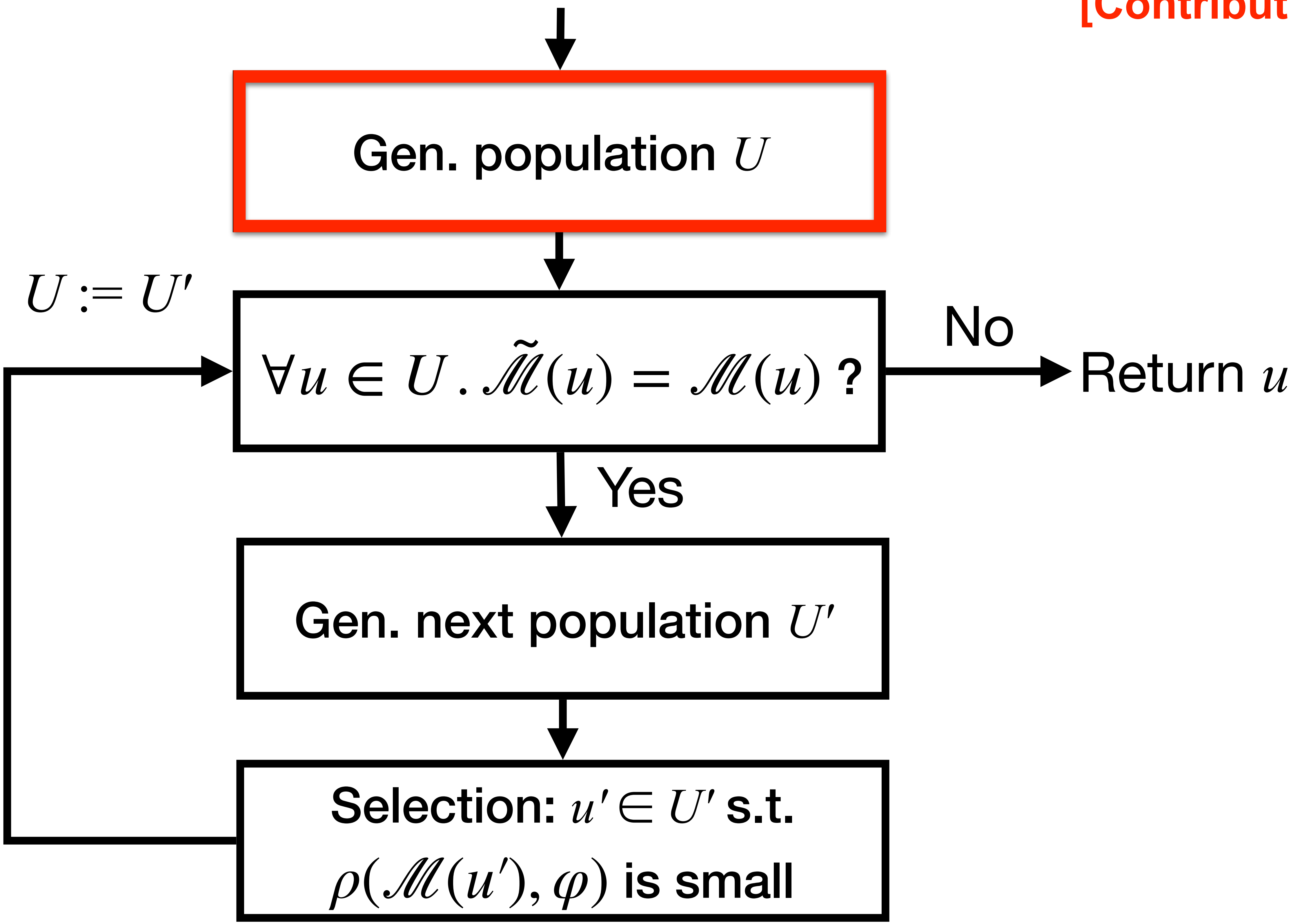
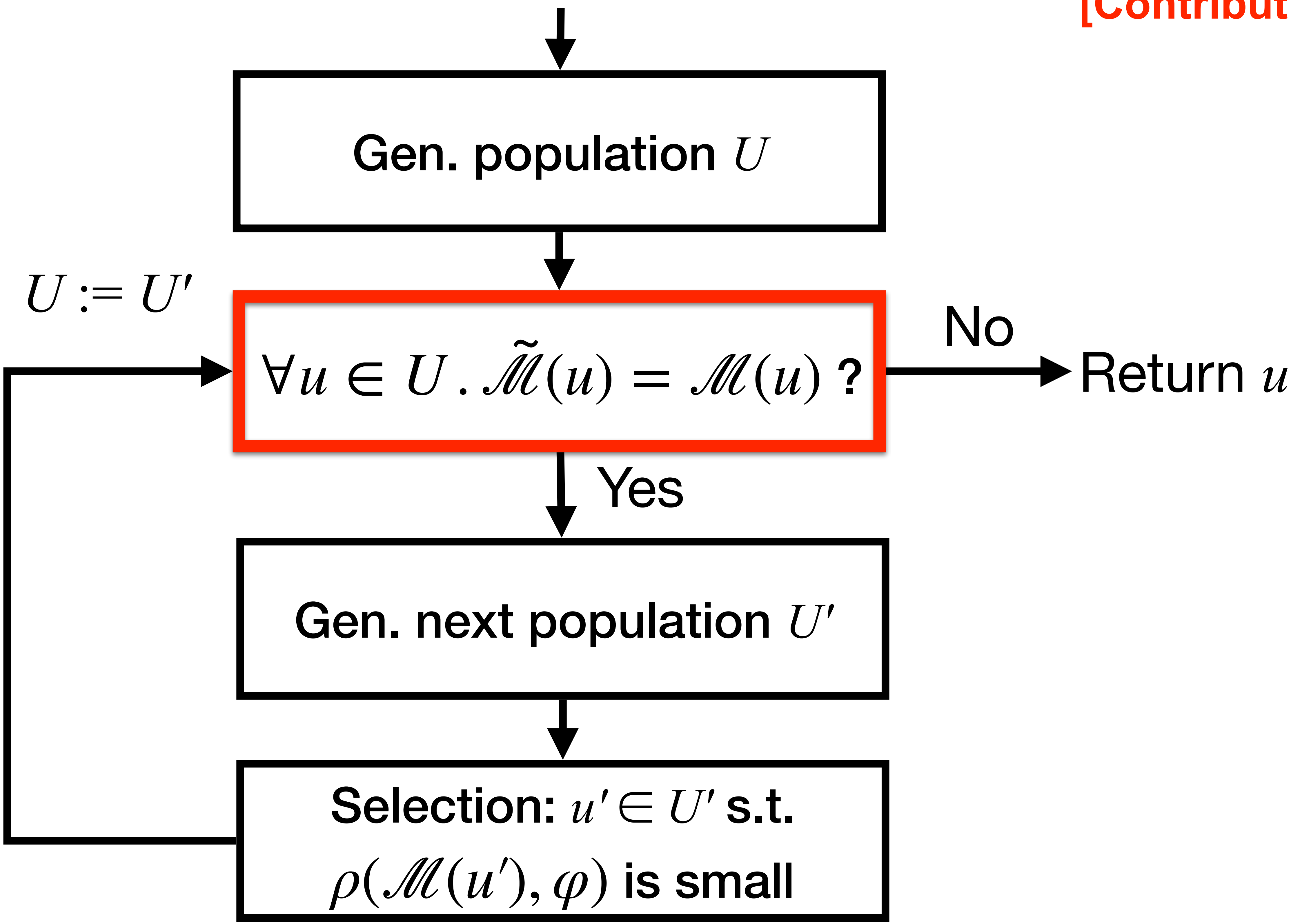
Robustness-Guided Equivalence Test

[Contribution]



Robustness-Guided Equivalence Test

[Contribution]



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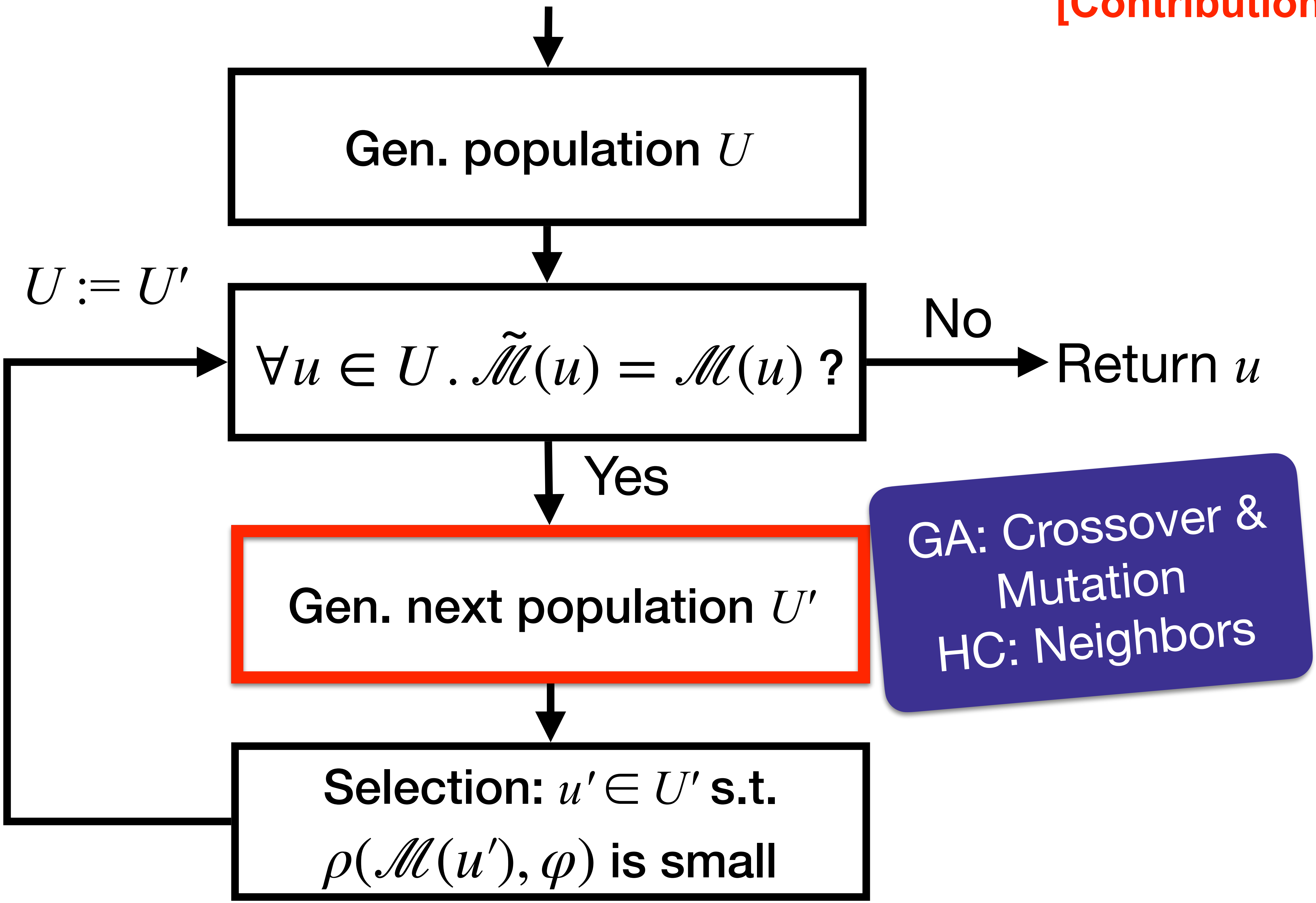
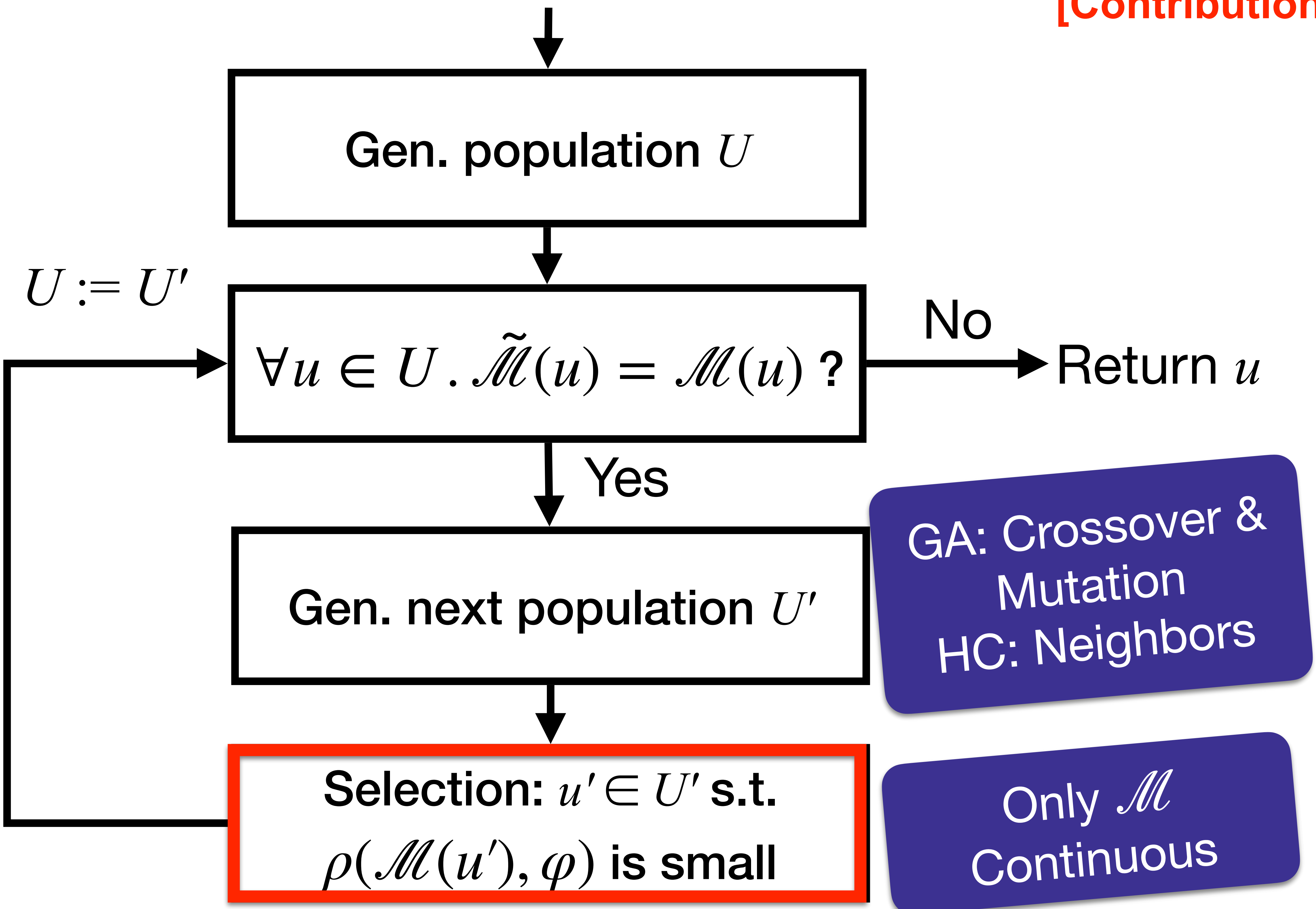
Robustness-Guided Equivalence Test

[Contribution]



Robustness-Guided Equivalence Test

[Contribution]



Why $\rho(\mathscr{M}(u'), \varphi)$ as Fitness?

Assumption: $\mathscr{M} \not\models \varphi$

i.e. $\exists u. \rho(\mathscr{M}(u), \varphi) \leq 0$

Fact: $\tilde{\mathscr{M}} \models \varphi$ i.e.

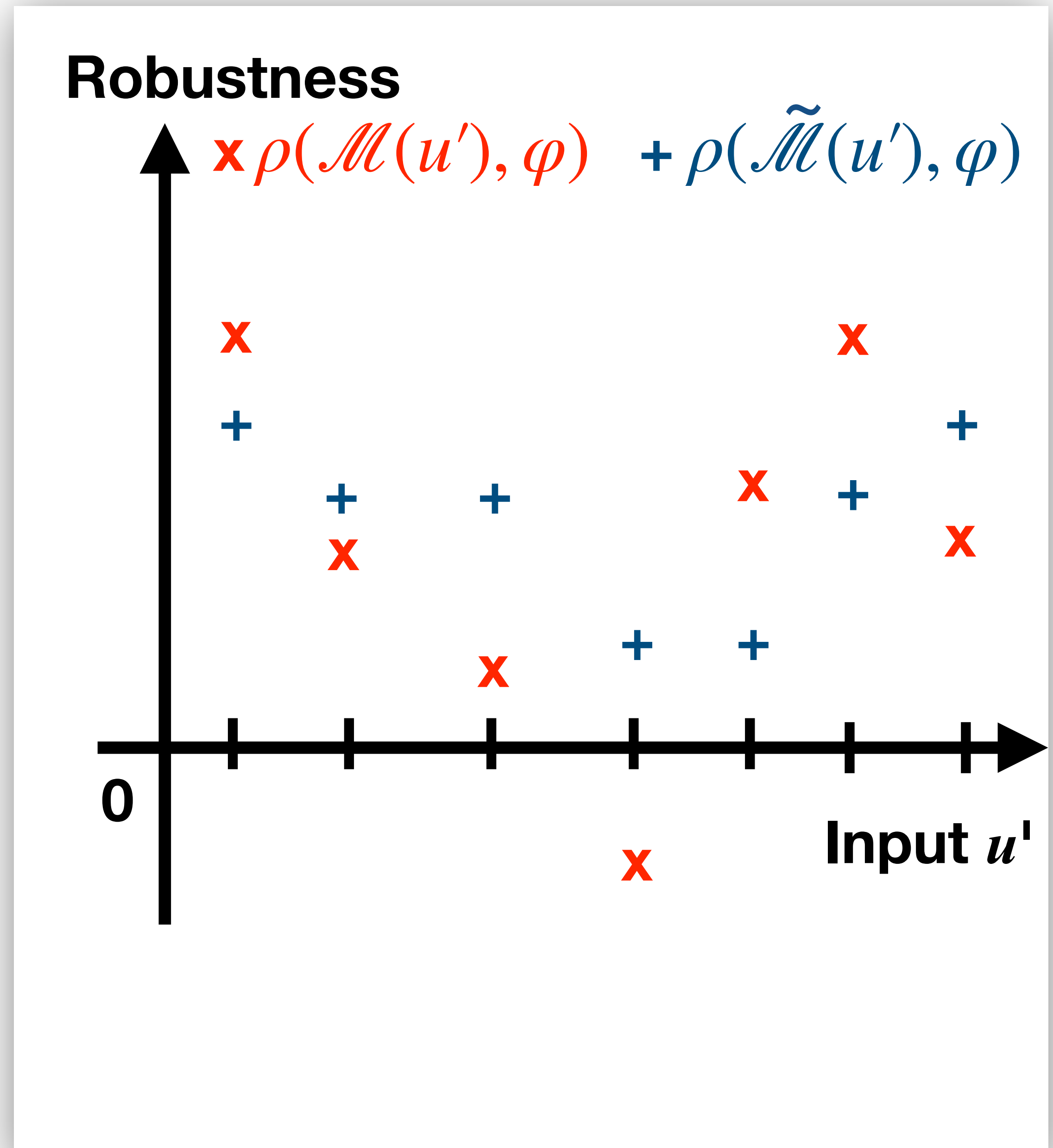
$\forall u \,.\, \rho(\tilde{\mathscr{M}}(u), \varphi) \geq 0$

by model checking

Heuristic: Find u' s.t.

$\tilde{\mathscr{M}}(u') \neq \mathscr{M}(u')$ in

$\rho(\mathscr{M}(u'), \varphi)$ is small



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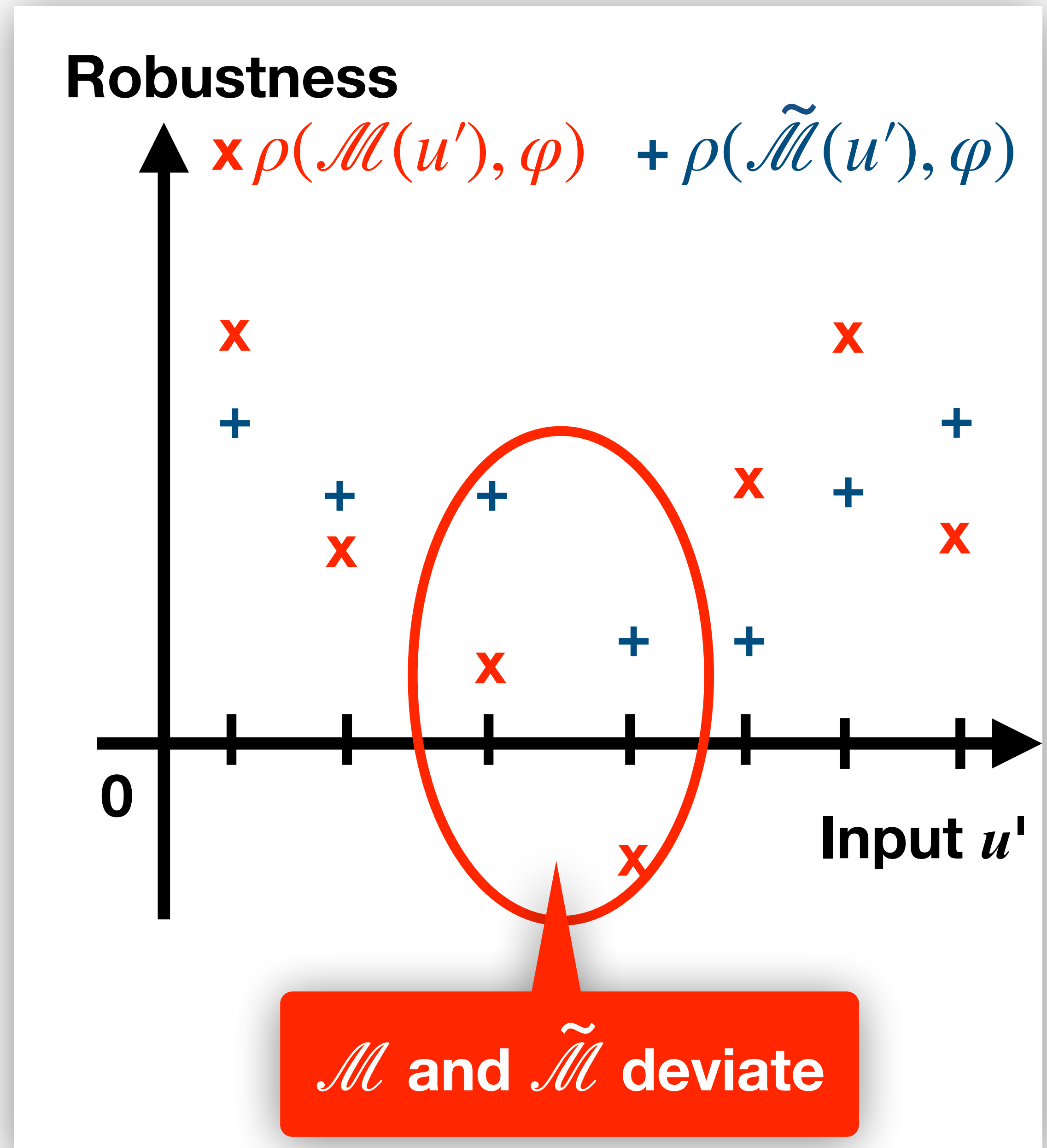

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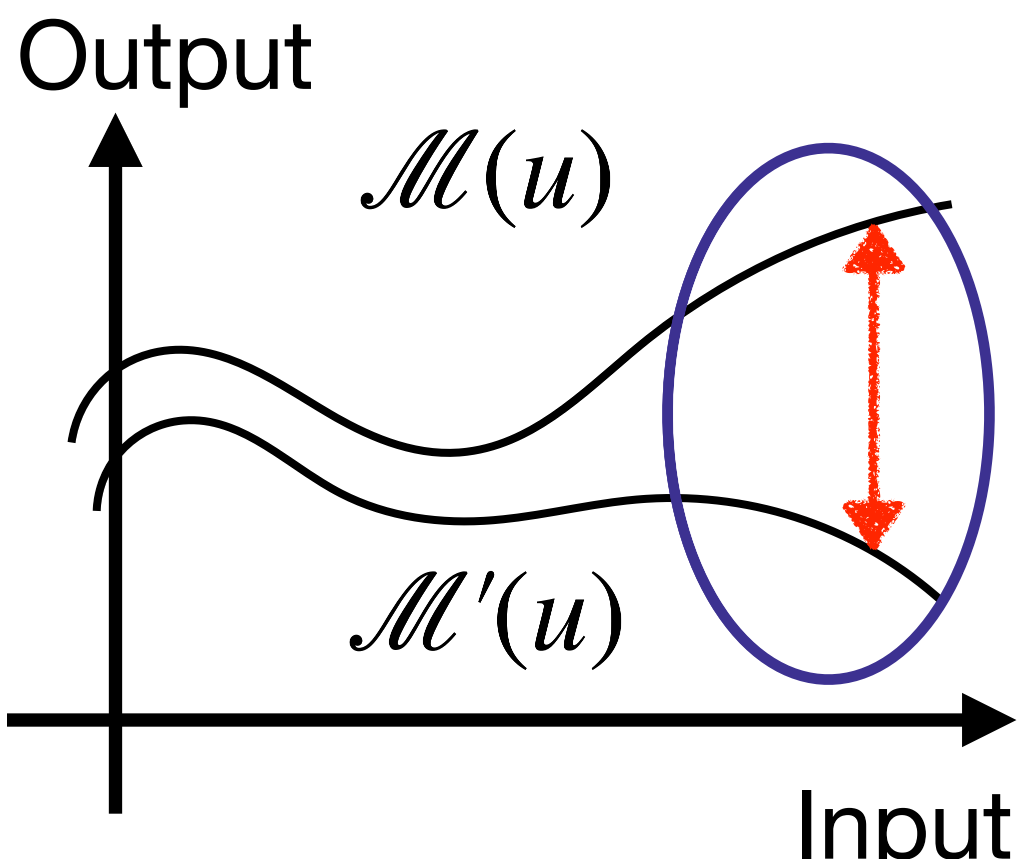
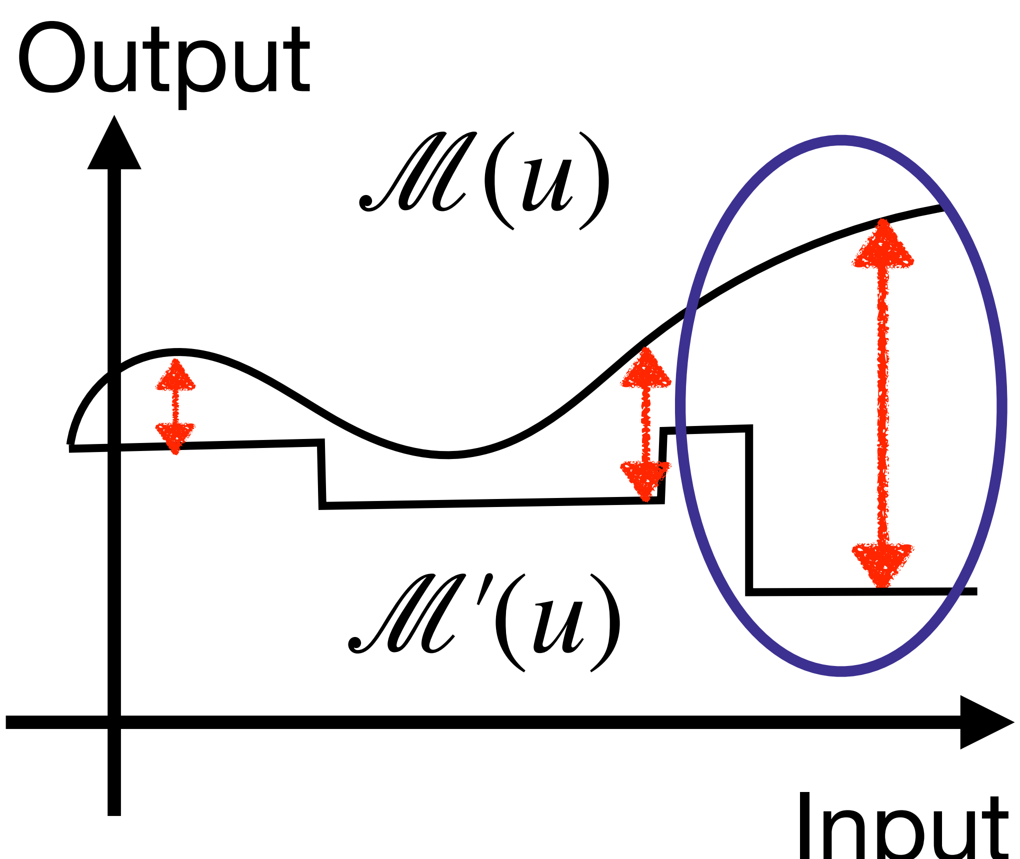
How About Direct Comparison?

- Direct comparison is also available e.g. [Abbas+, MEMOCODE'14]
- **Potential Issue**: more local maxima

Cont. vs Cont.



Cont. vs Disc.



Outline

- Introduction
- Preliminary: Black-box checking
    - Automata learning, model checking, & equiv. test
- Main Contribution:
  Robustness-guided equivalence test
    - **idea:** Optimization + robustness
- Experiments

Research Questions

RQ1: Does RobBBC falsify as many spec. as baseline?

RQ2: Which BBC is the best: Random, GA, and HC?

RQ3: Scalable wrt # of spec?

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Experiment Setting: Algorithms

- Robustness-guided BBC with
  - Genetic Algorithm (RobBBC(GA))
  - Hill Climbing (RobBBC(HC))

Ours

- BBC (equivalence test by random search)
- Breach: one of the SoTA falsification tools
- Pure random search
  - show the difficulty of the specifications

Baseline

Experiment Setting: Benchmark

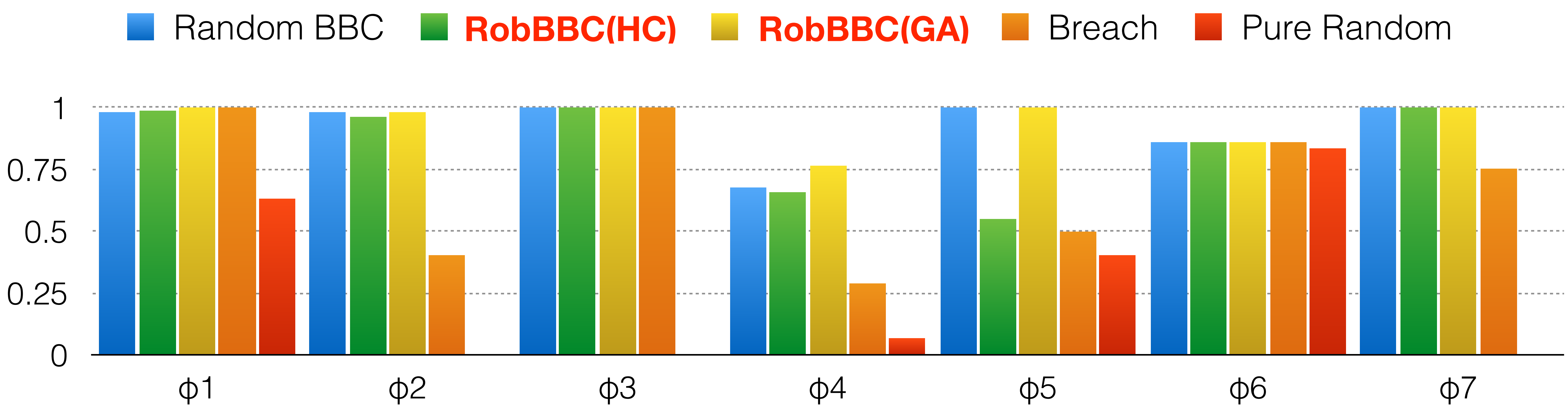
Model: Automatic Transmission [Hoxha+,ARCH'14-15]

Spec: Set of STL formulas

- Similar specifications with different thresholds
- Motivation: hard to decide the threshold

	STL template	parameter valuations	size
φ_1	$\Box(v < p)$	$p \in \{100, 102.5, 105, 107.5, 110, 112.5, 115, 117.5, 120\}$	9
φ_2	$\Box(g = 3 \Rightarrow v > p)$	$p \in \{20, 22.5, 25, 27.5, 30\}$	5
φ_3	$\Diamond_{[p_1,p_2]}(v < p_3 \lor v > p_4)$	$(p_1, p_2) \in \{(5, 20), (5, 25), (15, 30), (10, 30)\}, (p_3, p_4) \in \{(50, 60), (53, 57)\}$	8
φ_4	$\Box_{[0,26]}(v < p_1) \lor \Box_{[28,28]}(v > p_2)$	$p_1 \in \{90, 100, 110\}, p_2 \in \{55, 65, 75\}$	9
φ_5	$\Box(\omega < p_1 \lor \mathcal{X}(\omega > p_2))$	$p_1 \in \{4000, 4700\}, p_2 \in \{600, 1000, 1500\}$	6
φ_6	$\Box(v < p_1 \Rightarrow \Box_{[0,p_2]}(v < p_3))$	$p_1 \in \{30, 40, 50\}, p_2 \in \{6, 8, 10\}, p_3 \in \{60, 70, 80, 90\}$	36
φ_7	$\Box(((g \neq p_1) \land \mathcal{X}(g = p_1)) \Rightarrow \Box_{[0,p_2]}(g = p_1))$	$p_1 \in \{1, 2, 3, 4\}, p_2 \in \{1, 2, 3\}$	12

$\frac{\text{\# of Falsified Properties}}{\text{\# of Properties}}$



- RobBBC(HC) and Breach: Often fails
- Random BBC: sometimes fails
- RobBBC(GA): the largest for all specifications

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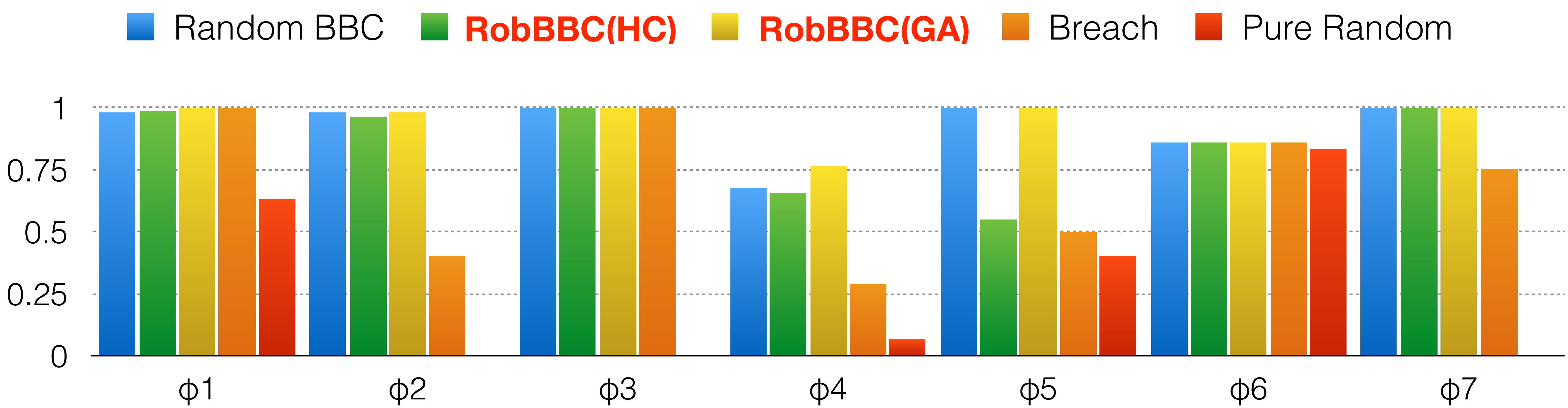
of Falsified Properties / # of Properties

$$\frac{\text{\# of Falsified Properties}}{\text{\# of Properties}}$$



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RQ1: Yes, RobBBC can falsify as many as Breach

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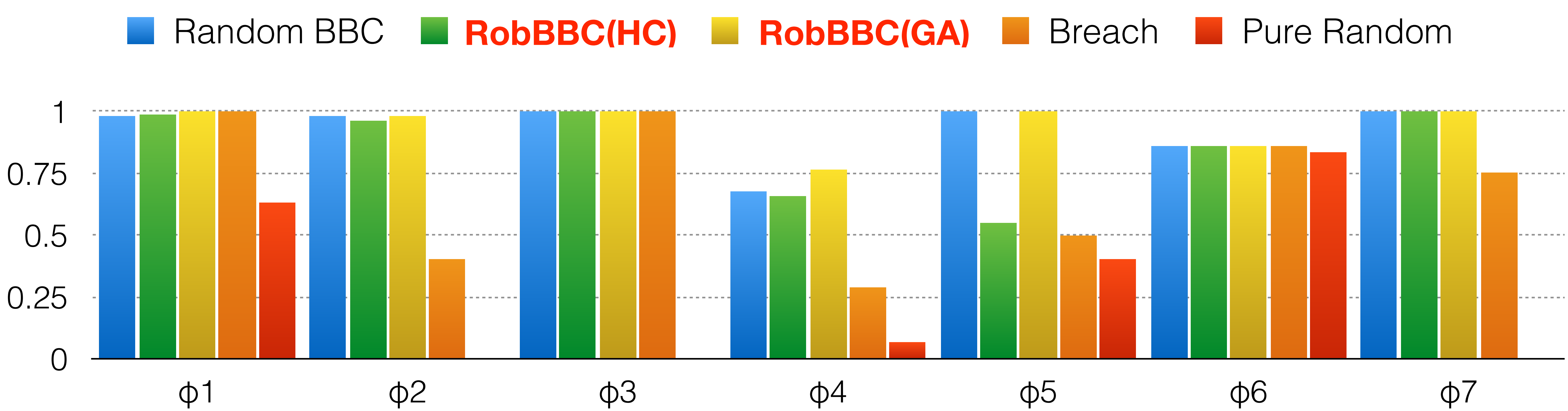
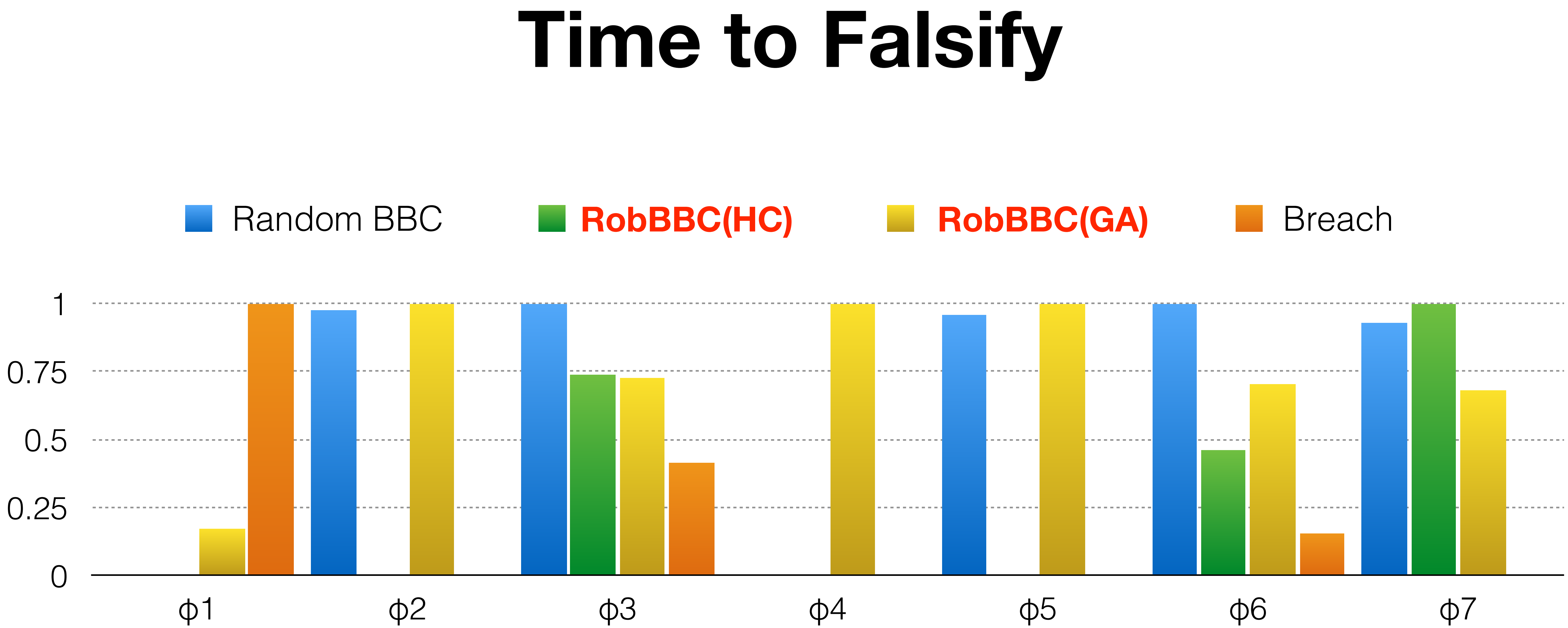


- RobBBC(HC) and Breach: Often fails
- Random BBC: sometimes fails
- RobBBC(GA): the largest for all specifications

RQ1: Yes, RobBBC can falsify as many as Breach

RQ2: GA falsified more than Random and HC…

Time to Falsify by the Fastest Method



- RobBBC(GA) tends not be the fastest when others are available → not the best for easy spec.

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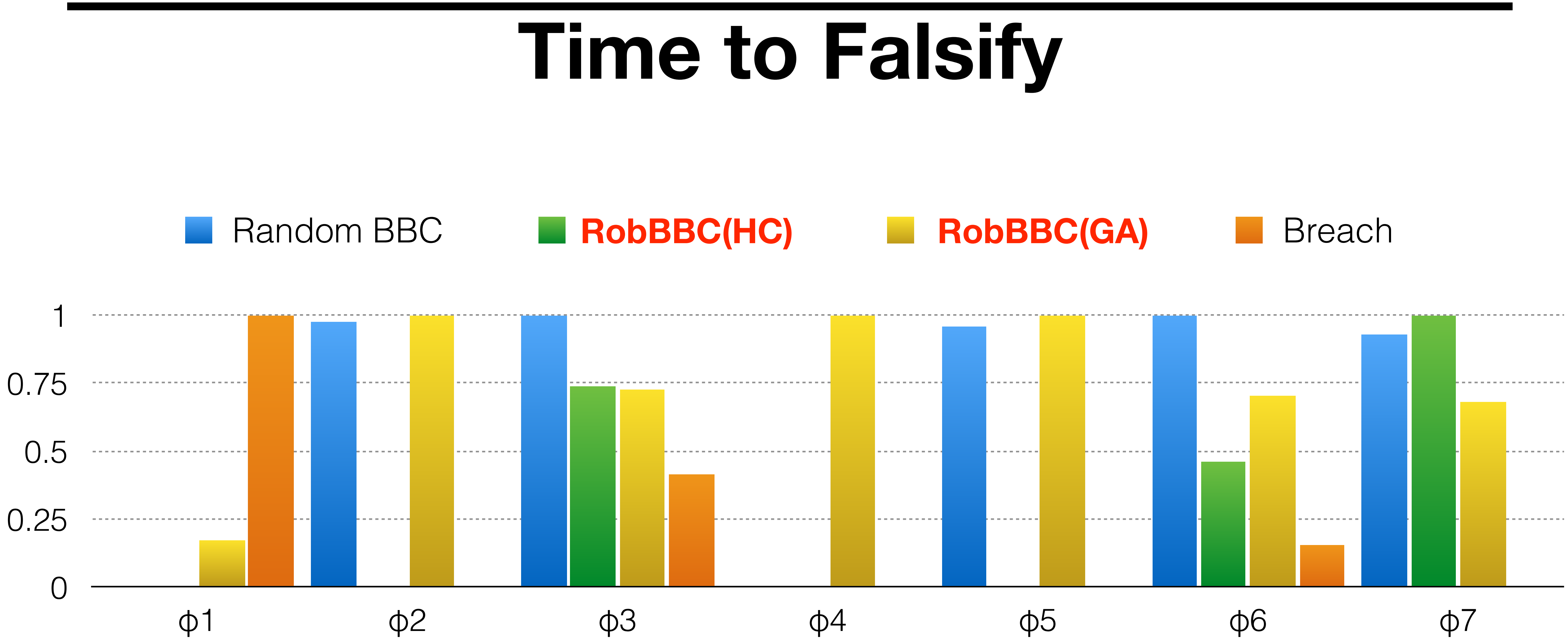
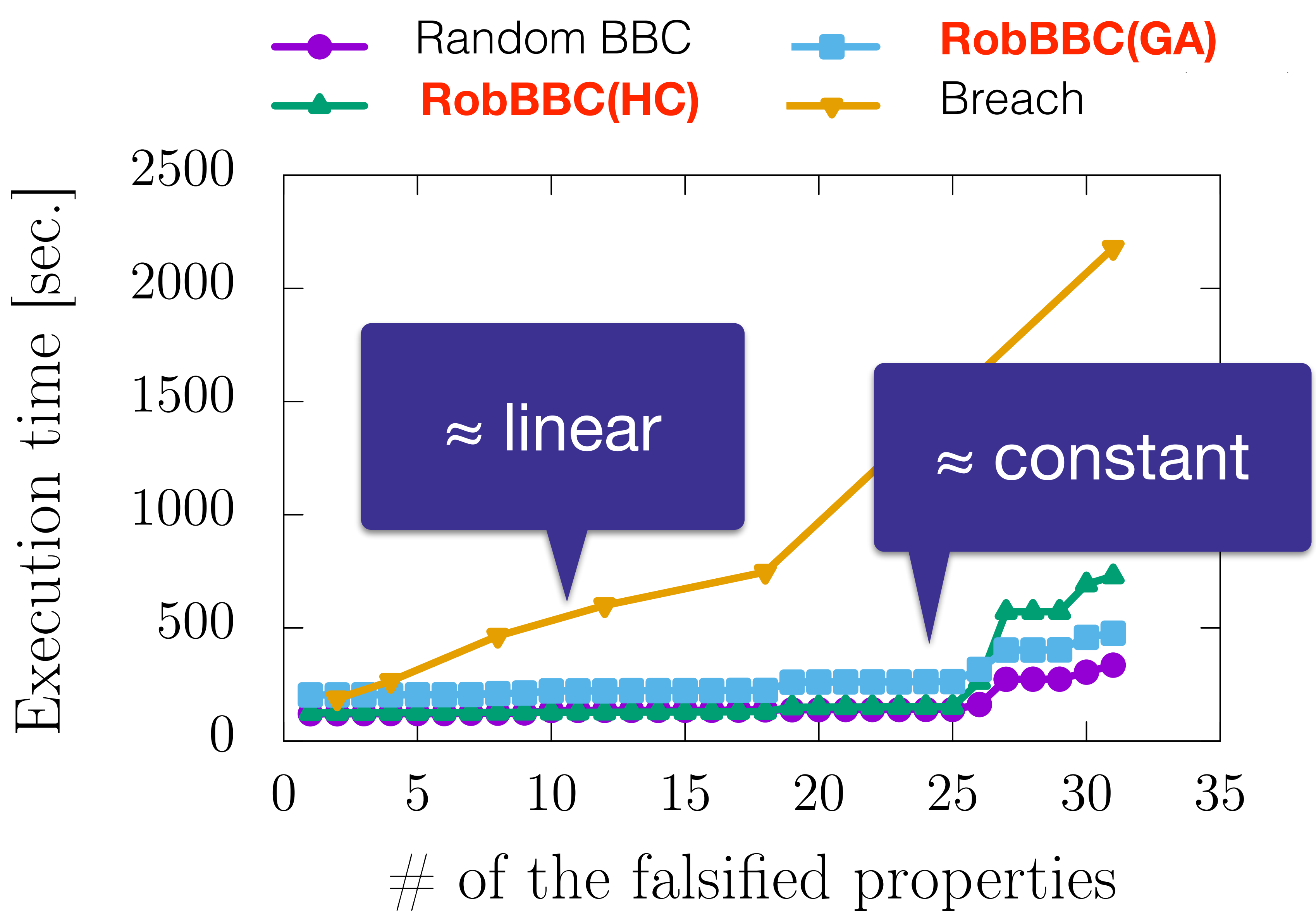


- RobBBC(GA) tends not be the fastest when others are available → not the best for easy spec.

RQ2: GA falsified more than Random HC
For easy spec. Random BBC can be an option

Scalability wrt # of Spec. in φ_6



RQ3: BBC is more scalable than Breach wrt # of Spec.

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Conclusion

- Introduced robustness-guided BBC
  - Equivalence test using robustness
- Experimental evaluation
  - It outperforms Breach

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  - Equivalence test using robustness
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But this is the beginning of the story…

Direct Reuse of $\tilde{\mathscr{M}}$ Does Not Work

Model checking generates ***false*** counter examples

STL formula φ	# of $\varphi \not\models \tilde{\mathcal{M}}$	# of $\varphi \not\models \mathcal{M}$	Average of $[\![\varphi]\!]$	std. dev. of $[\![\varphi]\!]$
$\Box(v < 90)$	10	5	1.10	1.94
$\Box_{[0,26]}(v < 90) \lor \Box_{[28,28]}(v > 40)$	4	0	4.19	0.00
$\Box_{[0,26]}(v < 90) \lor \Box_{[28,28]}(v > 50)$	10	0	3.80	0.60
$\Box_{[0,26]}(v < 90) \lor \Box_{[28,28]}(v > 60)$	10	0	3.24	0.76

But robustness is low

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Future Work

- How to (re-)use the generated Mealy machine?
- Black-box checking for multiple systems
    - Adaptive model checking?
- Try more benchmarks to figure out further issues

Appendix

Experiment Setting (Detail)

- Executed each same experiment setting 10 times
  - We used the average
- Amazon EC2 c4.large (2 vCPUs and 3.75 GiB RAM)