ModelPlex: Verified Runtime Validation of Verified CPS Models

From Model Checking to Checking Models

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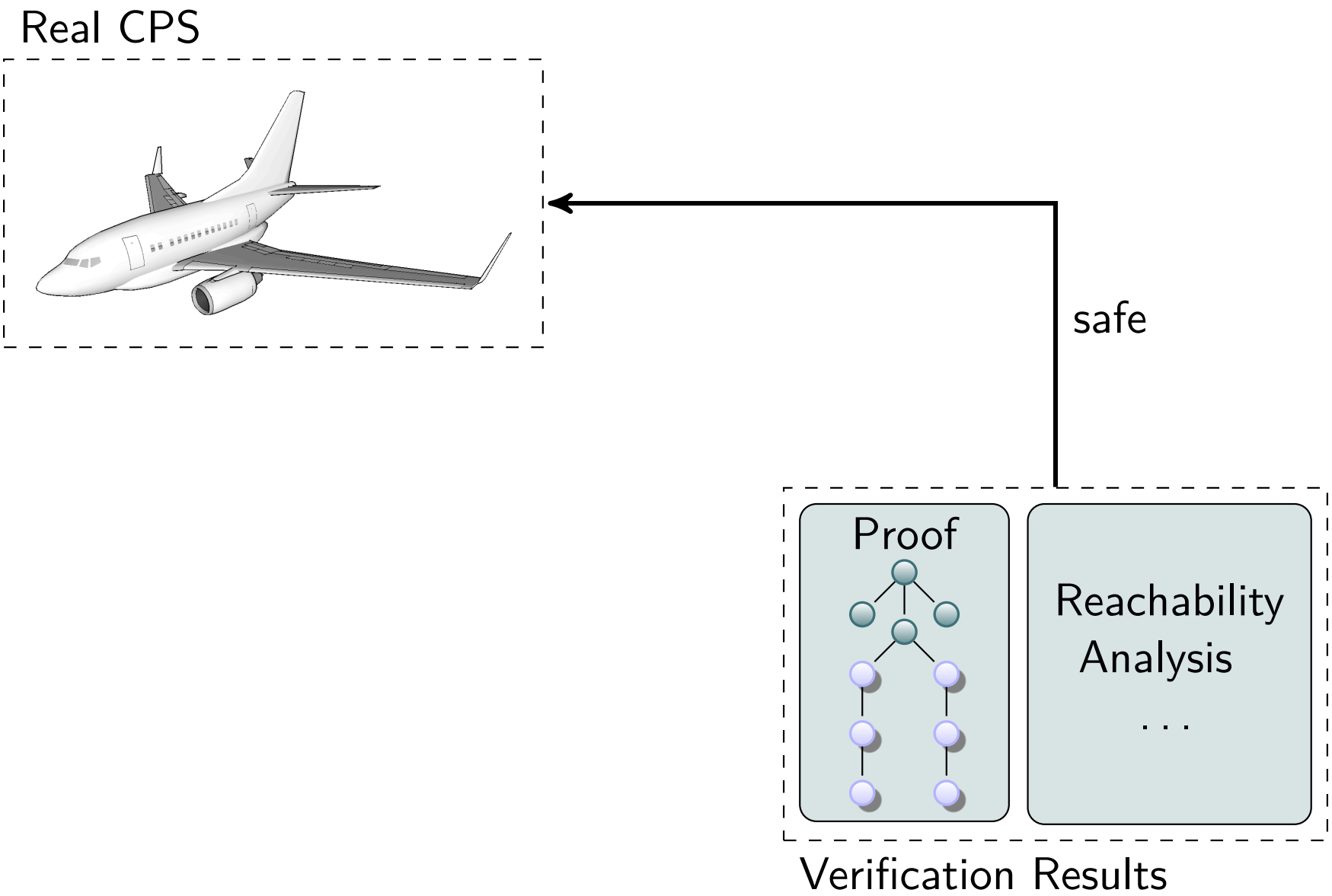
Computer Science Department, Carnegie Mellon University

Clarke Symposium, Sept. 20, 2014

For details, see ModelPlex paper at RV'14

Formal Verification in CPS Development



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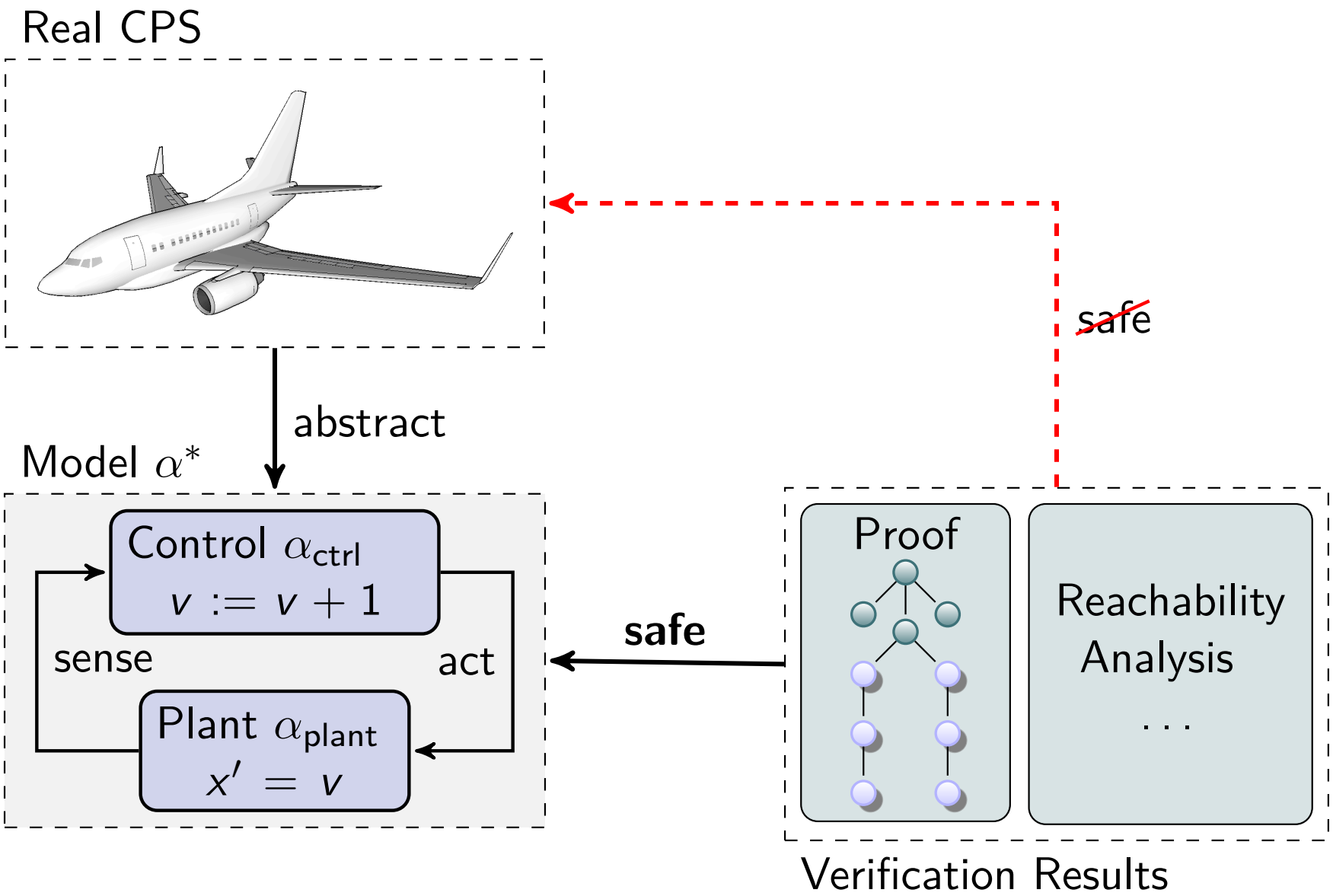

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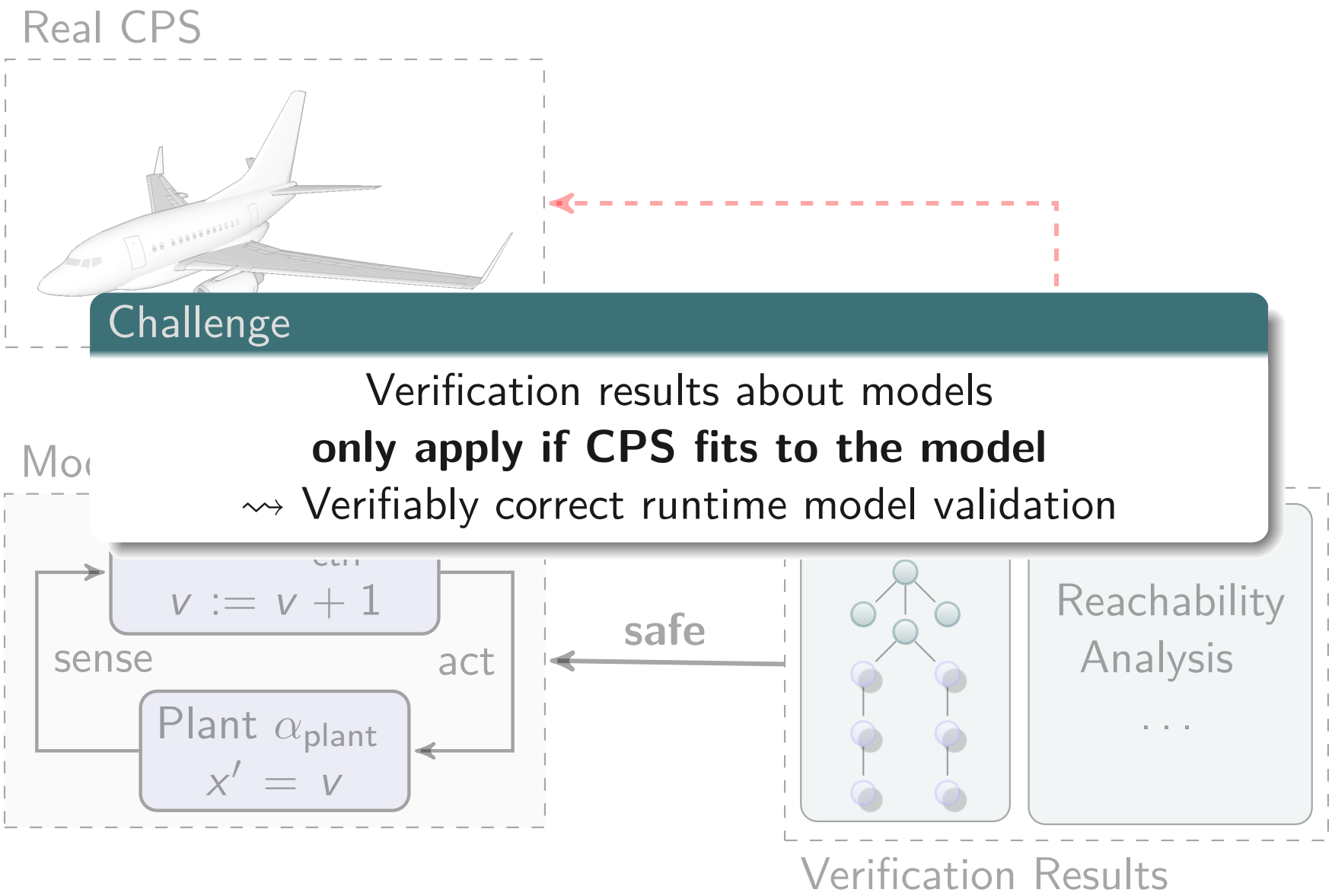
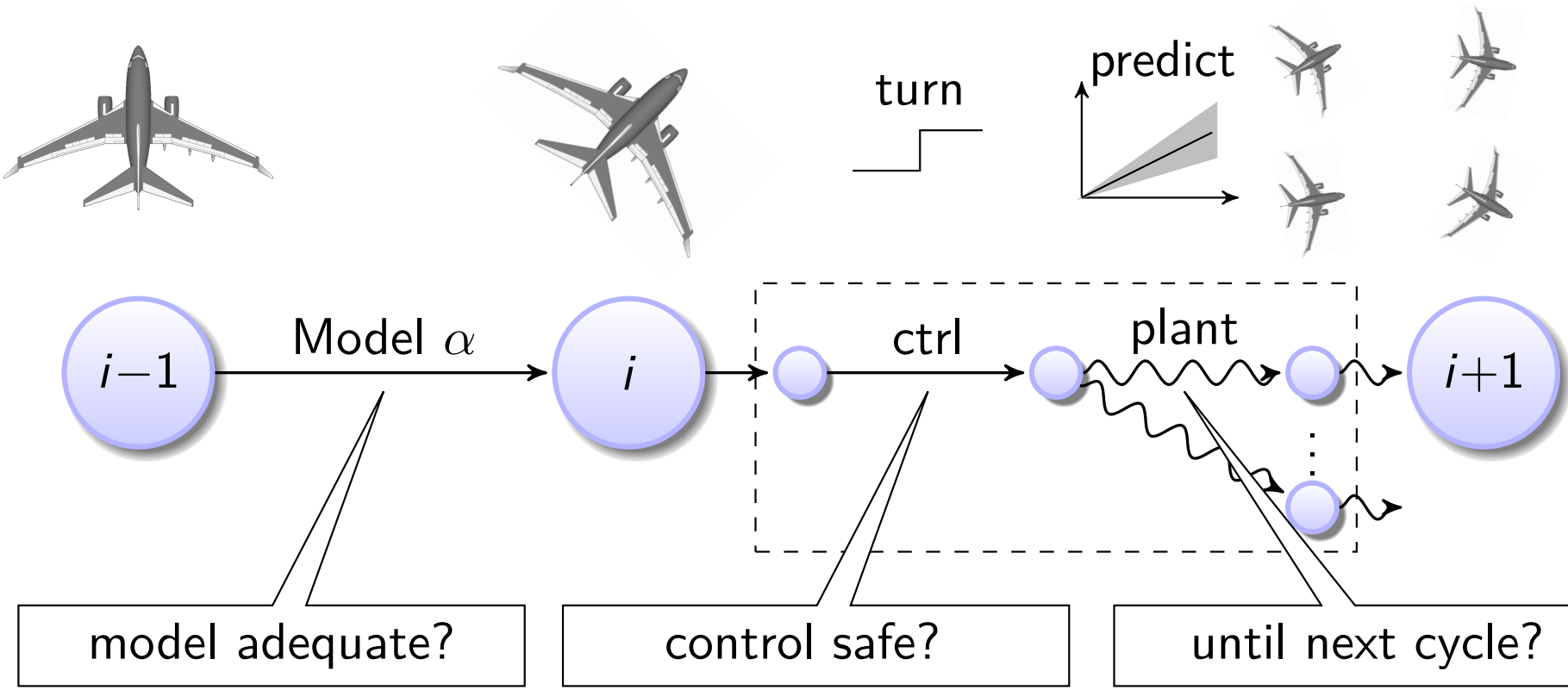


ModelPlex Runtime Model Validation

ModelPlex **ensures that verification results** about models **apply to CPS** implementations



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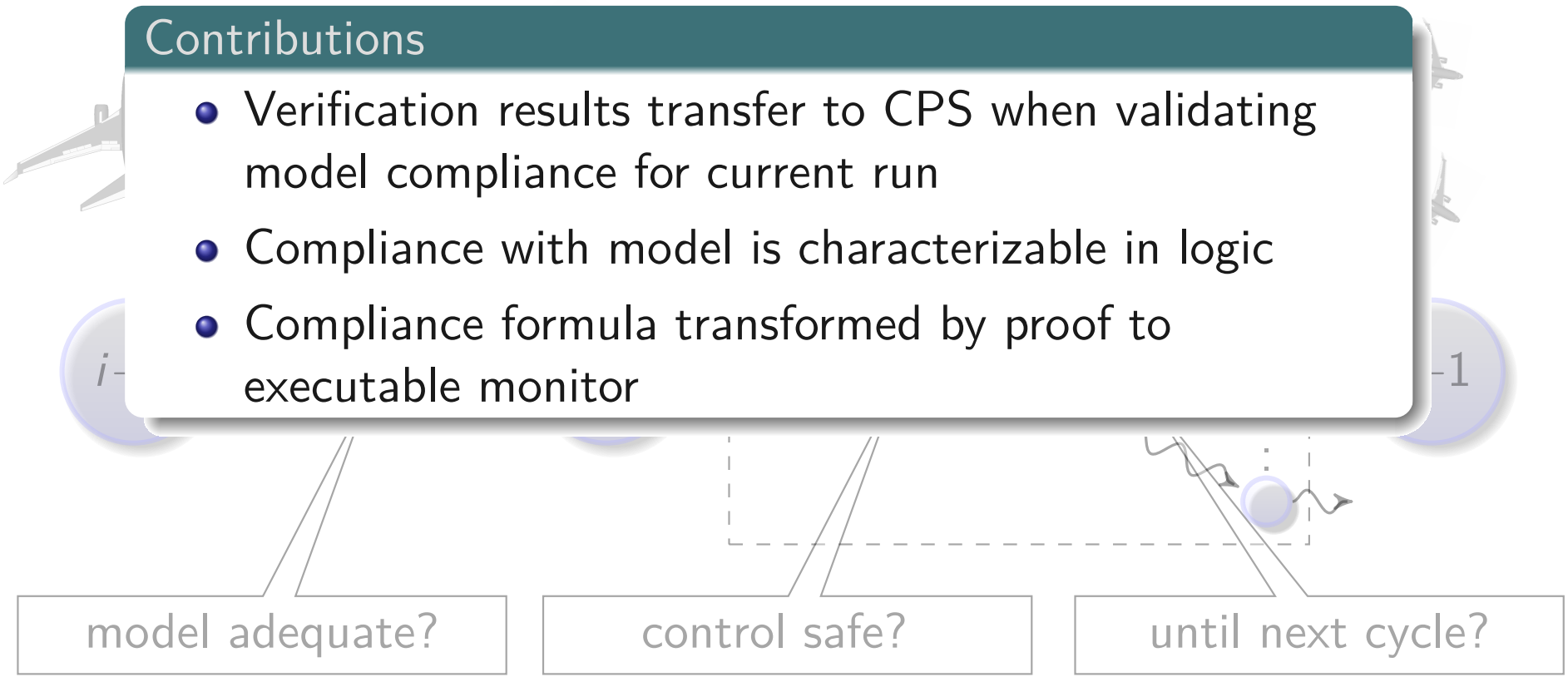
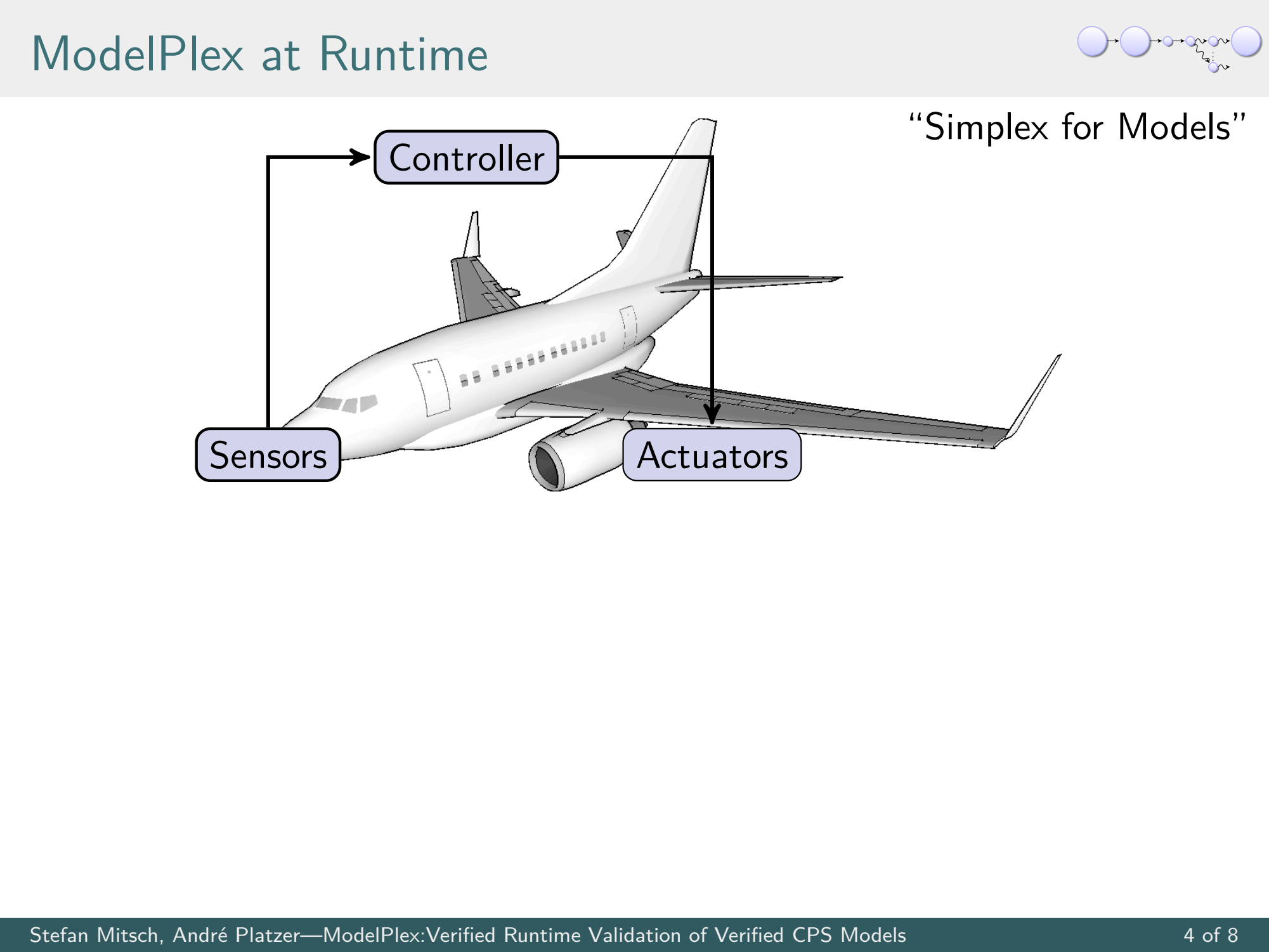


Contributions

- Verification results transfer to CPS when validating model compliance for current run
- Compliance with model is characterizable in logic
- Compliance formula transformed by proof to executable monitor

ModelPlex at Runtime



"Simplex for Models"

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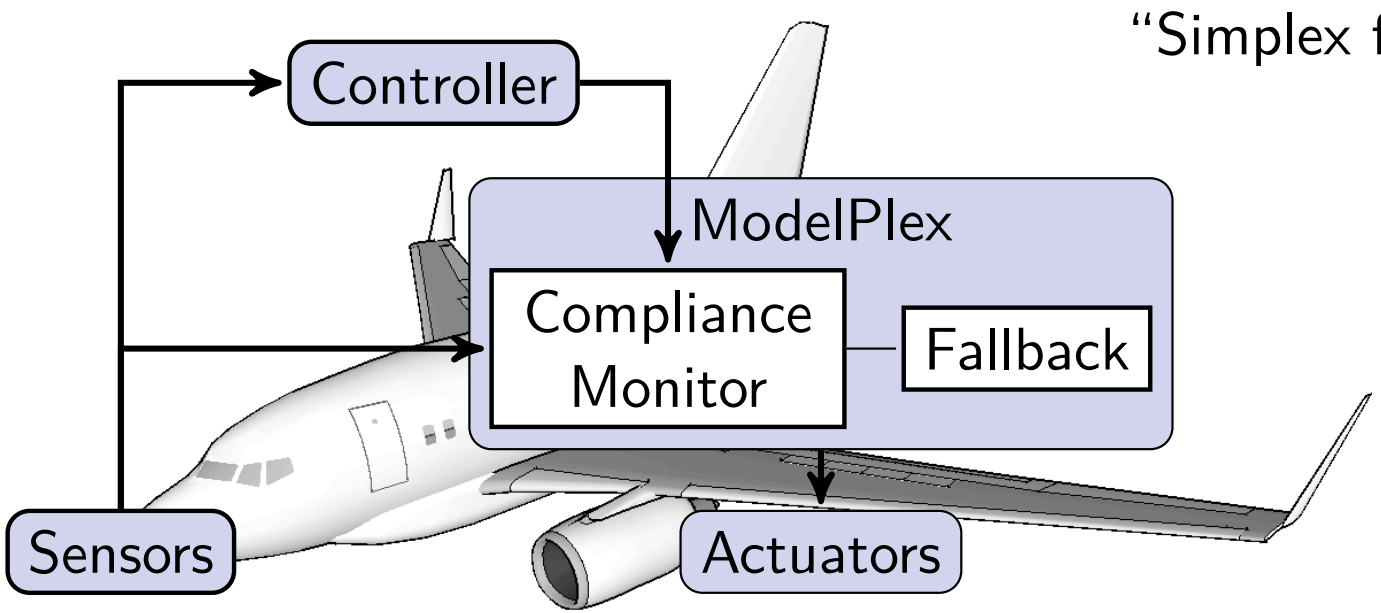


Compliance Monitor Checks CPS for compliance with model at runtime

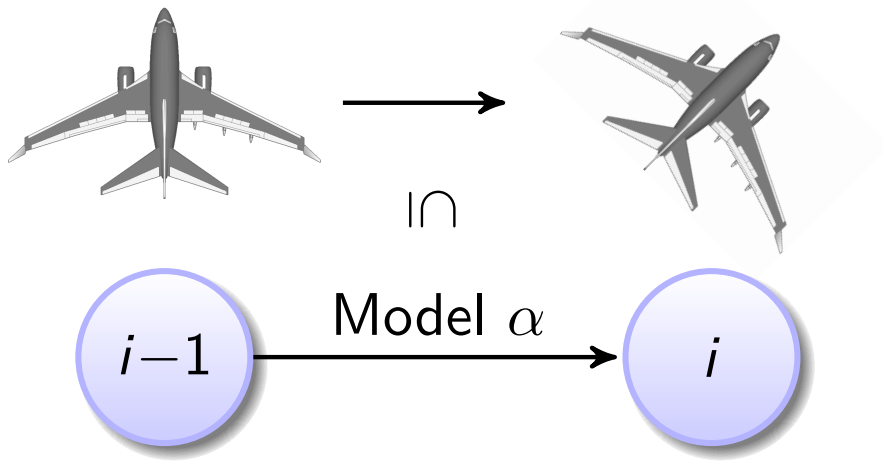
- Model Monitor: model adequate?
- Controller Monitor: control safe?
- Prediction Monitor: until next cycle?

Fallback Safe action, executed when monitor is not satisfied

Challenge What conditions do the monitors need to check to be safe?

Monitor Characterization

When are two states linked through a run of model α?



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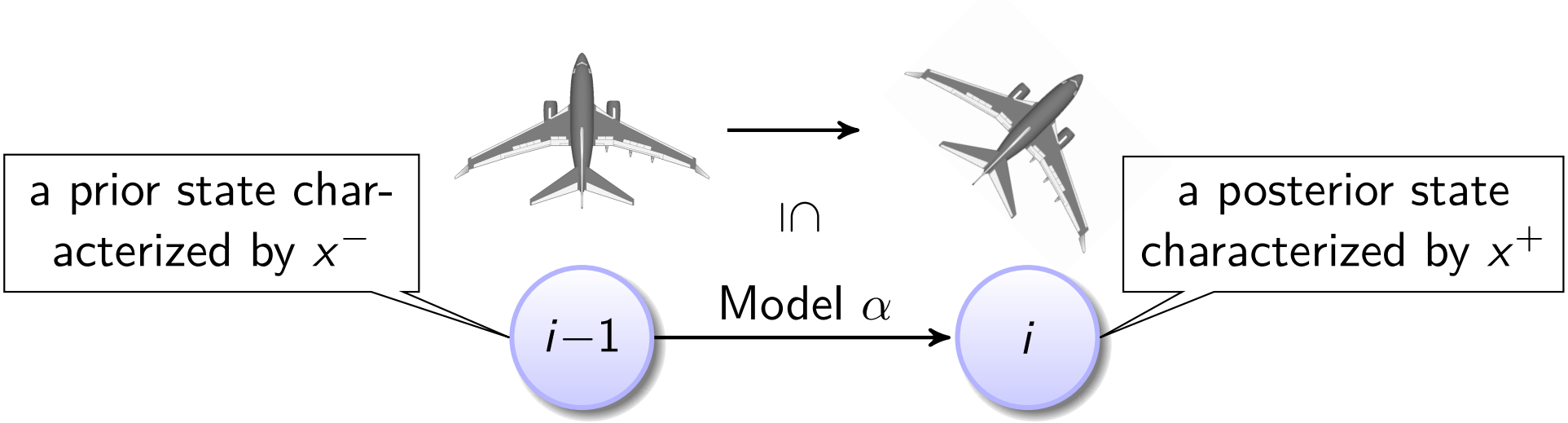

Semantical: $(x^-, x^+) \in \rho(\alpha)$ < reachability relation of α

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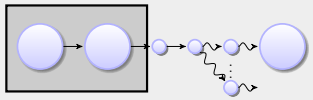

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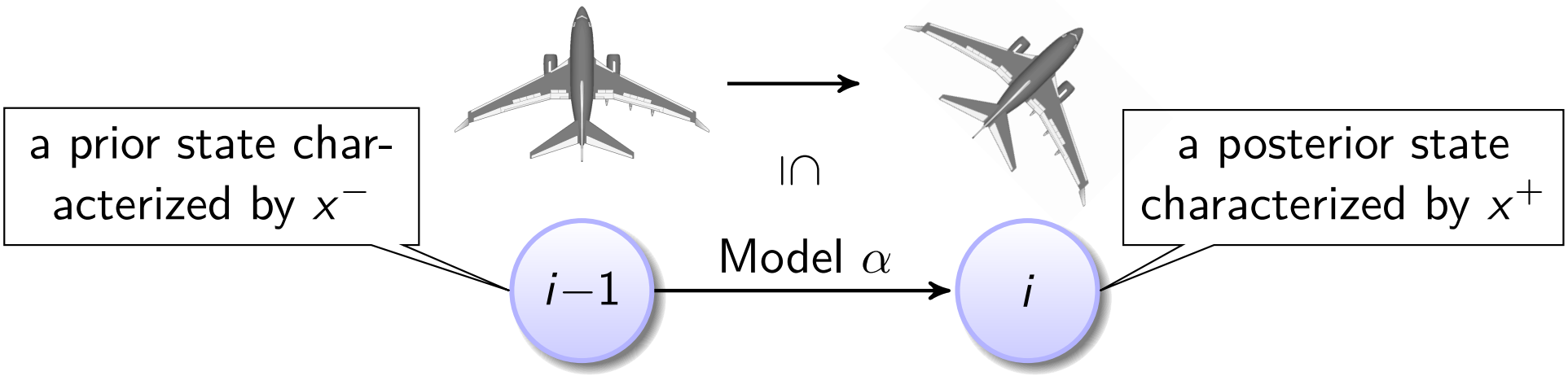

Offline

Semantical: $(x^-, x^+) \in \rho(\alpha)$

$\Updownarrow$ Theorem

Logic (d$\mathcal{L}$): $(x = x^-) \rightarrow \langle \alpha_{(x)} \rangle (x = x^+)$

starting at $x = x^-$ exists a run of α to a state where $x = x^+$

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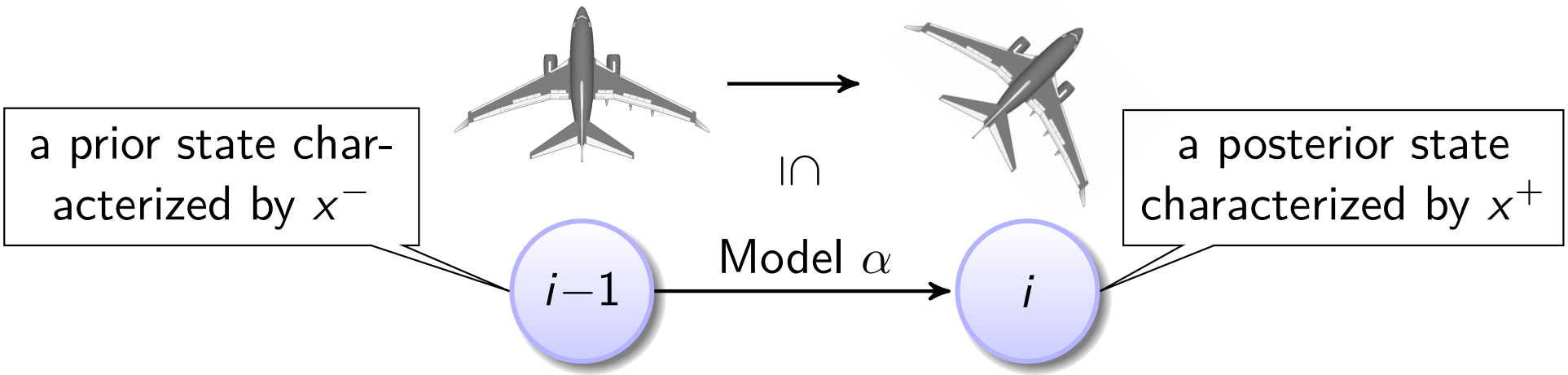

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Real arithmetic: $F(x^-, x^+)$

check at runtime (efficient)

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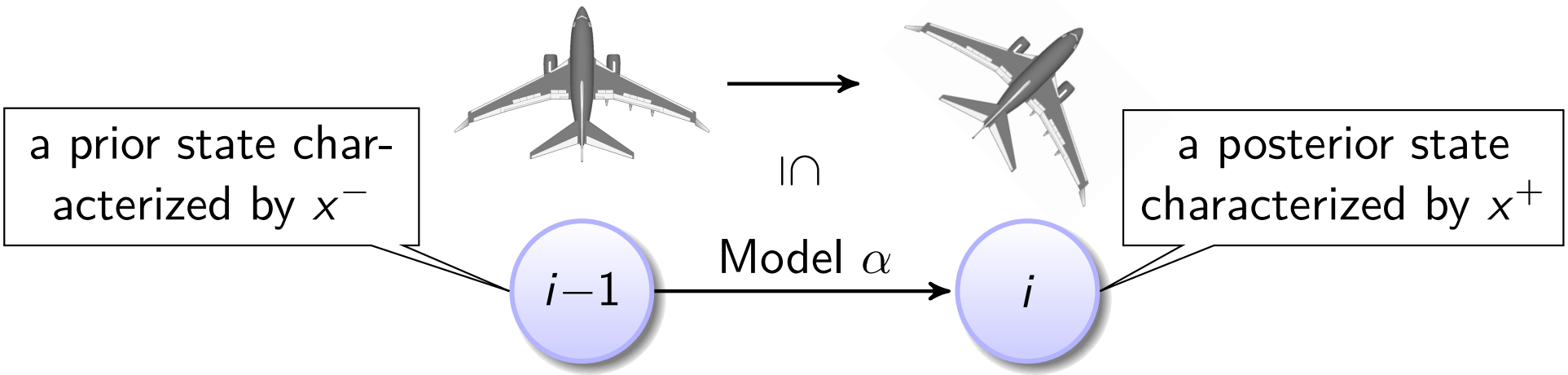

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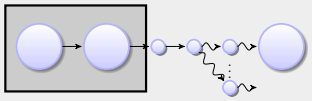
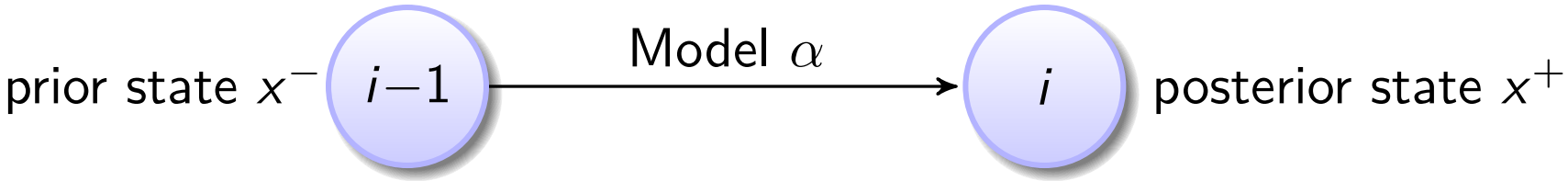
Provably Correct Synthesis of Monitors



- Proof calculus of d$\mathcal{L}$ executes models symbolically



proof attempt

- $(x = x^-) \rightarrow \langle\alpha\rangle (x = x^+)$

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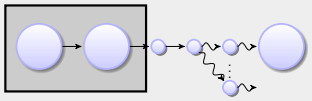

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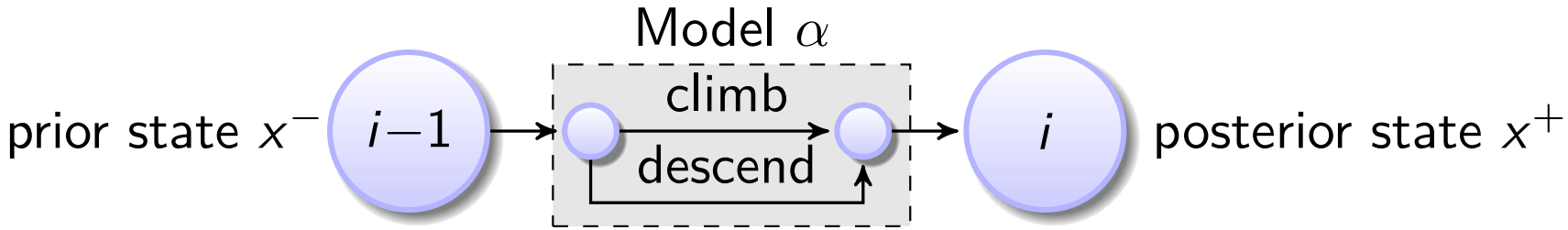
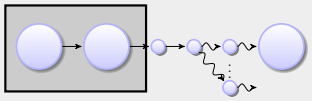


proof attempt

- $(x = x^-) \rightarrow \langle \text{climb} \cup \text{descend} \rangle (x = x^+)$

$$\langle \cup \rangle \frac{\langle \text{climb} \rangle \phi \vee \langle \text{descend} \rangle \phi}{\langle \text{climb} \cup \text{descend} \rangle \phi}$$

Provably Correct Synthesis of Monitors



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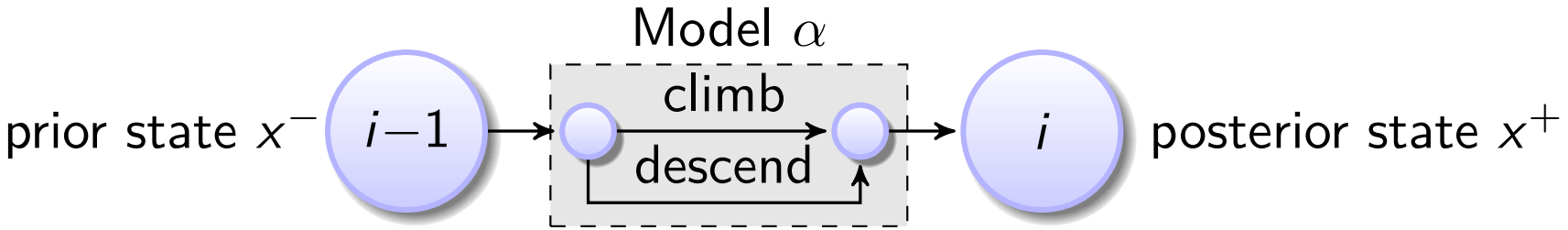

proof attempt

$$(x = x^-) \rightarrow \langle \text{climb} \cup \text{descend} \rangle (x = x^+)$$

$$\langle \text{climb} \rangle (x = x^+) \quad \vee \quad \langle \text{descend} \rangle (x = x^+)$$

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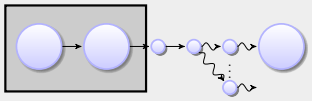

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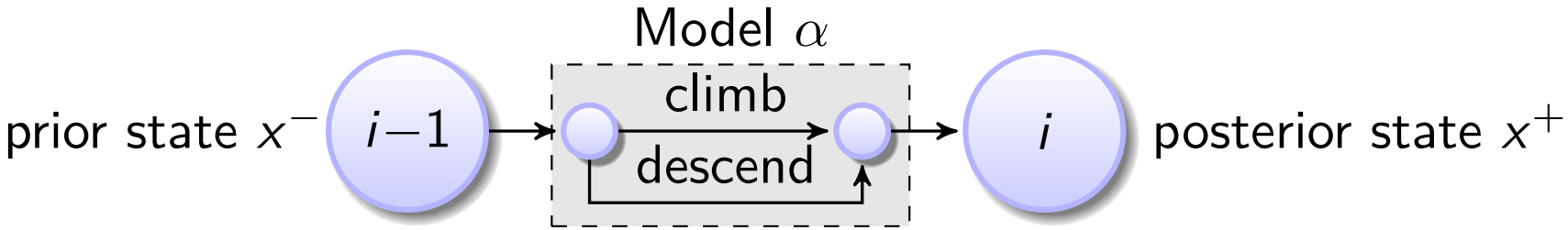

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$$\langle \text{climb} \rangle (x = x^+) \quad \vee \quad \langle \text{descend} \rangle (x = x^+)$$

$$F_1(x^-, x^+) \qquad\qquad F_2(x^-, x^+)$$

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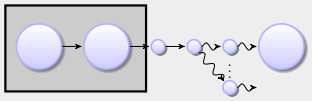

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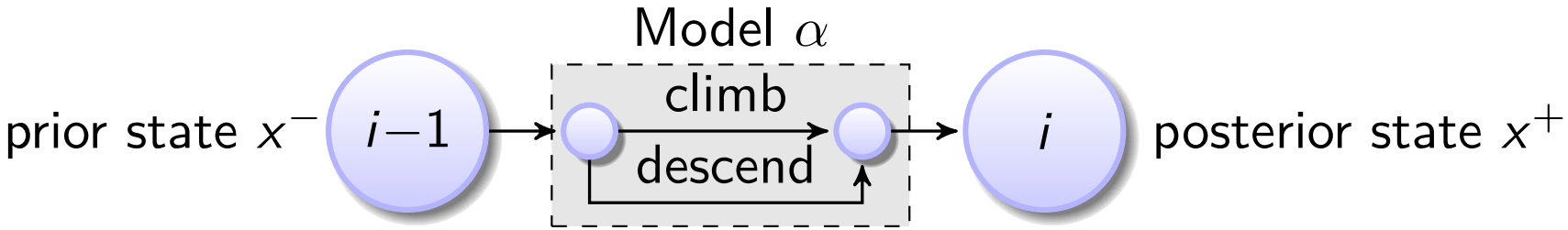

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$$\vee$$

$$\langle \text{climb} \rangle (x = x^+) \qquad \langle \text{descend} \rangle (x = x^+)$$

$$F_1(x^-, x^+) \qquad F_2(x^-, x^+)$$

Monitor: $F_1(x^-, \overbrace{x^+) \vee F_2(}x^-, x^+)$

- The subgoals that cannot be proved express all the conditions on the relations of variables imposed by the model

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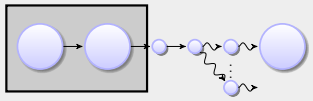

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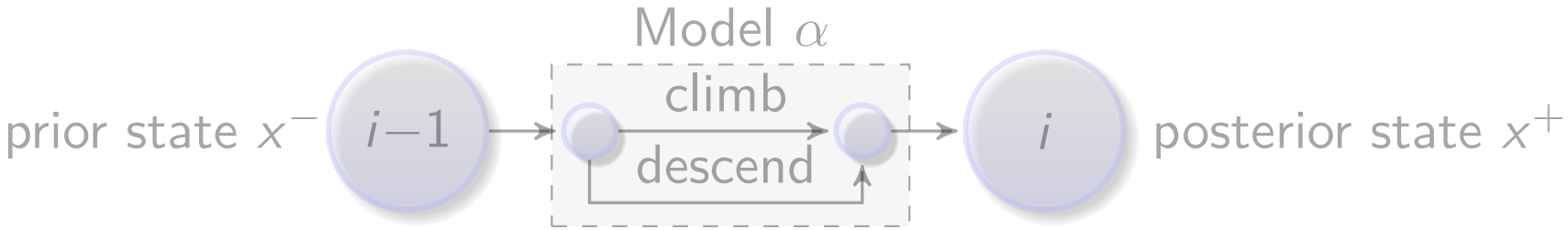


Model Monitor

Immediate detection of model violation

$\rightsquigarrow$ Mitigates safety issues with safe fallback action

$F_1(x^-, x^+)$ $F_2(x^-, x^+)$

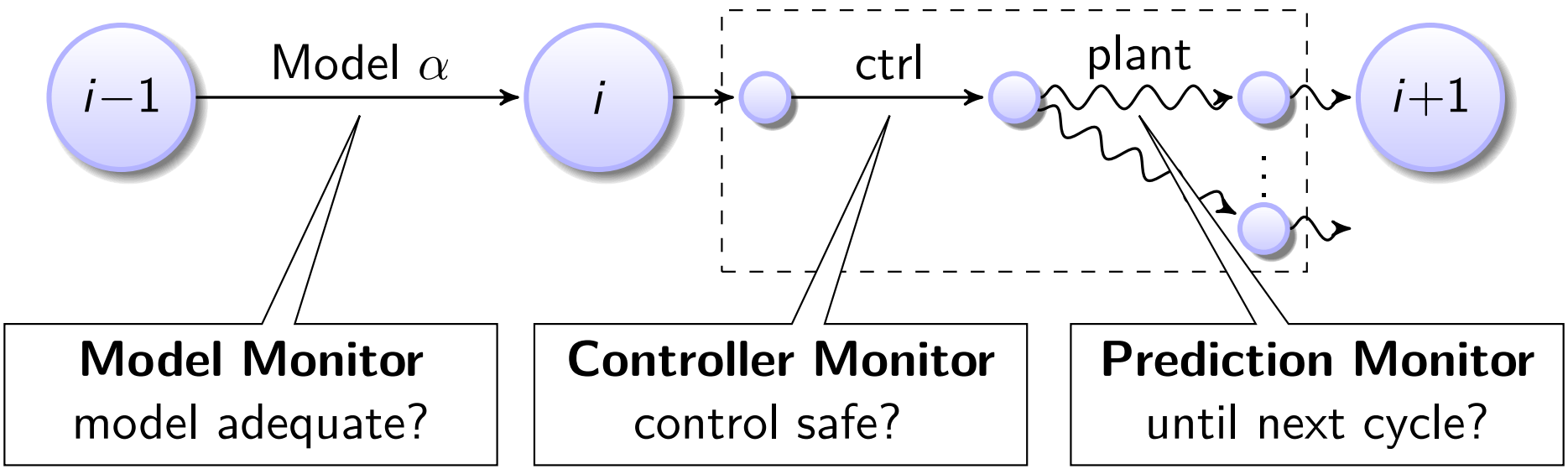
Monitor: $F_1(x^-, x^+) \vee F_2(x^-, x^+)$

- The subgoals that cannot be proved express all the conditions on the relations of variables imposed by the model

Conclusion

ModelPlex ensures that proofs apply to real CPS

- Validate model compliance
- Characterize compliance with model in logic
- Prover transforms compliance formula to executable monitor

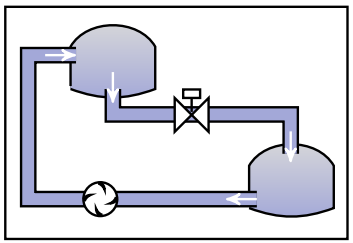


Thank You!

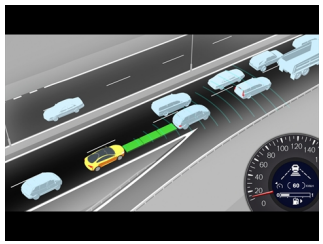
Evaluation

- Evaluated on hybrid system case studies

Water tank



Cruise control



© Volvo

Traffic control

© ASFINAG

Ground robots

© Black-I Robotics

Train control

© Harald Eisenberger

- Model sizes: 5–16 variables
- Monitor sizes: 20–150 operations (larger if automated simplification to remove redundant checks is computationally infeasible)
- Theorem: ModelPlex is decidable and monitor synthesis can be automated in important classes