Trusting Outsourced Components in Flight-Critical Systems

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Joint work with ...

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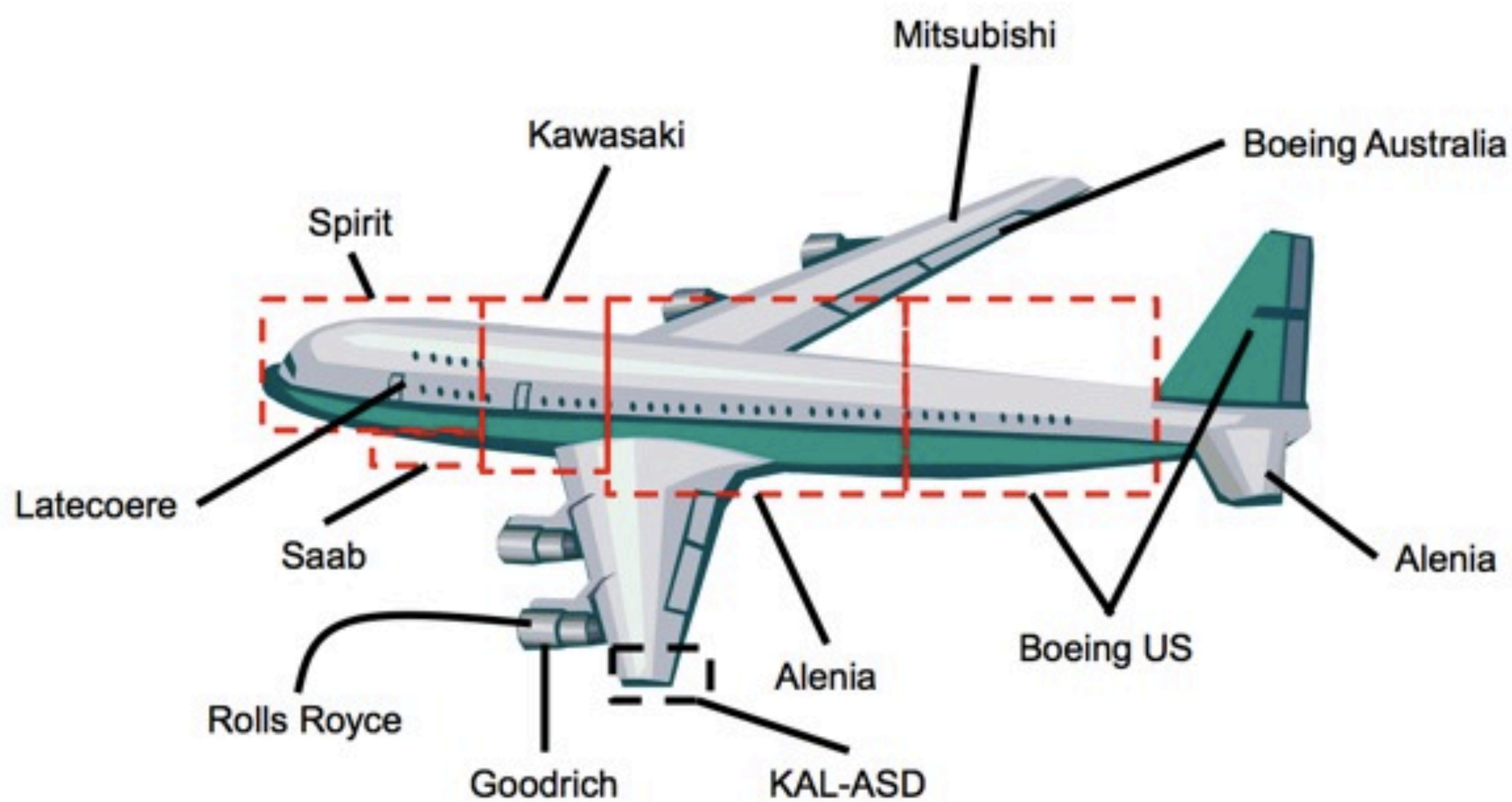
(The University of Iowa)

Dr. Adrien Champion
(The University of Iowa)

Outsourcing in the aerospace industry

Outsourcing in the aerospace industry

The Boeing 787 Dreamliner's flight critical, embedded software is build on the WRS ARINC 653 system and is assembled from software components by multiple subcontractors

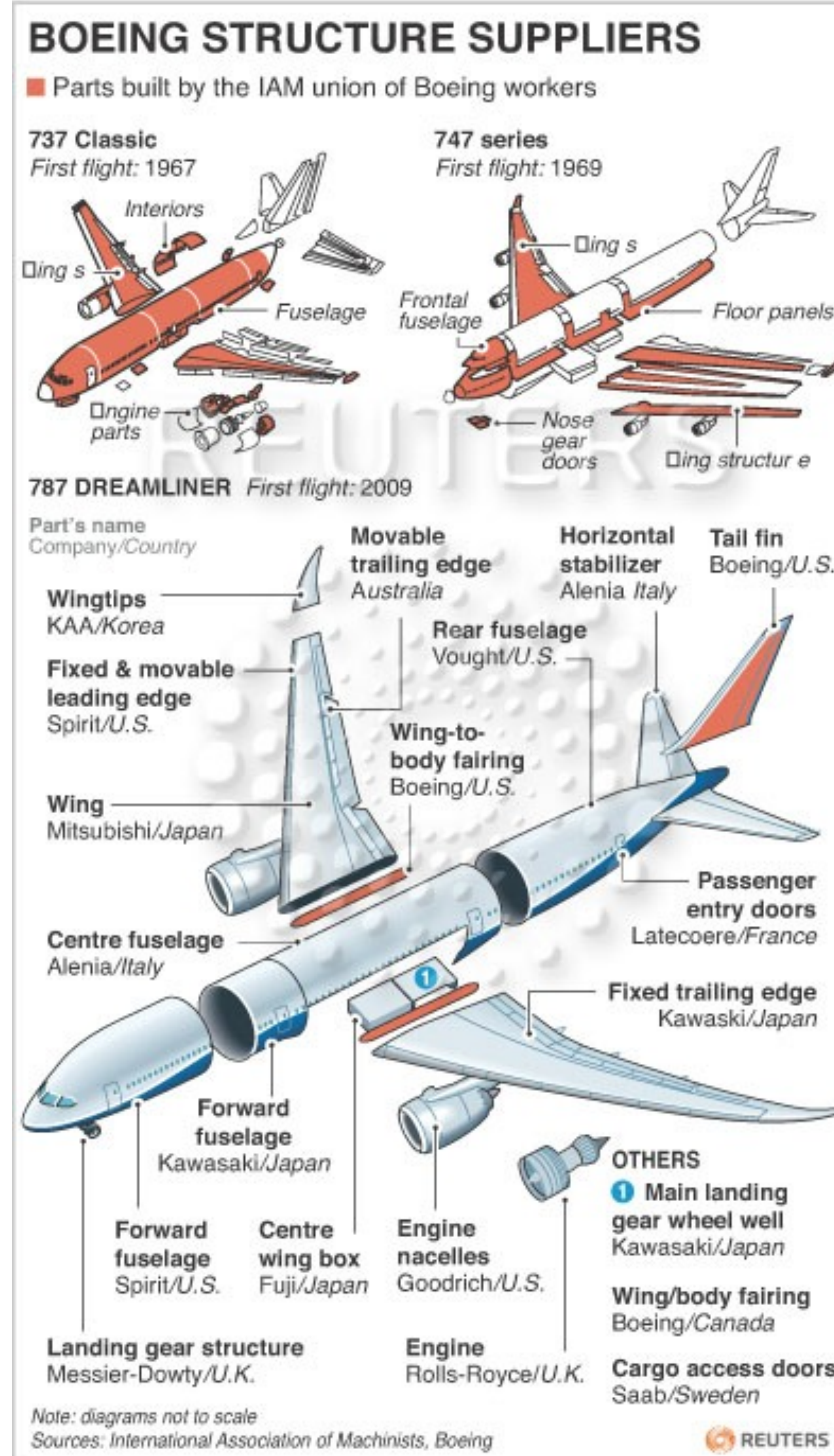


Source: Boeing / Reuters

Outsourcing in the aerospace industry

Boeing 737 and 747 = 35-50%

Boeing 787 = 70%



Outsourcing in the aerospace industry

- The delivery date was pushed back 4 times and was late more than 4 years
- The aft fuselage consisted of 6,000 components, and many of those components failed to conform to Boeing's specified tolerances, resulting in significant cost and schedule delays
- The first Dreamliner to arrive at the company's assembly place was missing tens of thousands of parts

Outsourcing in the aerospace industry

Outsourcing in the aerospace industry

- January 2013: 50 Dreamliner was grounded due to issues with the lithium-ion batteries.
- On balance with just under 60 aircraft in service, the 787 has had 6 reported mechanical incidents in 2013.
- All the individual parts worked in isolation. But, together, under certain circumstances, the parts failed.

Outsourcing in the aerospace industry

"*While we can't completely eliminate failures, the answer lies in system engineering. This involves a process of careful design and architecture ... as well as a staged integration of the entire system, and extensive qualification, verification and validation testing.*" Prof. S. Eppinger (MIT)

* http://executive.mit.edu/blog/will-risk-result-in-reward-for-boeings-dreamliner

This talk ....

.... outsourcing in flight critical software

.... virtual integration of outsourced components

Assurance of Flight Critical Systems (FCS)

Aim:

- Develop multidisciplinary V&V tools and techniques that advance safety assurance and certification

- Flight-critical systems: any systems that directly controls the safe conduct of an aircraft's flight, i.e. air and ground systems

Technical Challenges:

1. Argument-based safety assurance
2. Integrated distributed systems
3. Authority and Autonomy
4. Software intensive systems
5. Assessment environments

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Assurance of Flight Critical Systems (FCS)

Topic: "Support for verification of black-box FCS"

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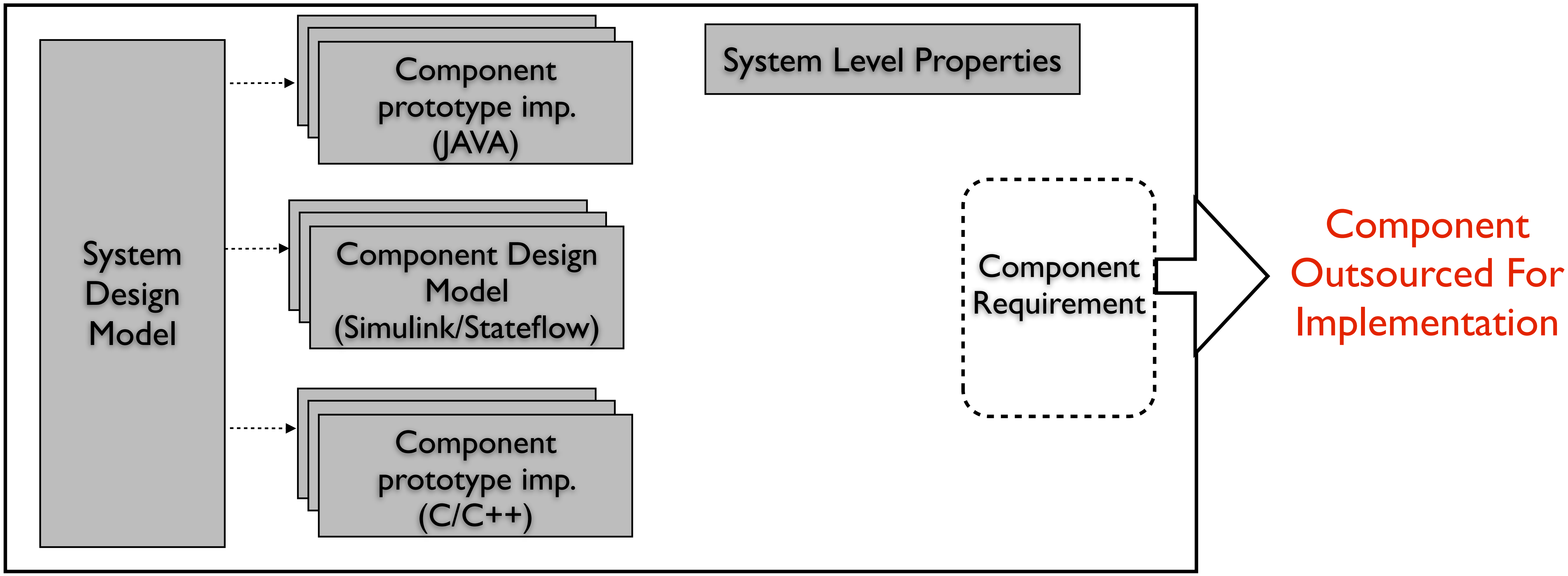
Context:

- More and more design and implementation of FCS is contracted out to external companies
- Example: FAA contracts out the implementation of most of the air traffic systems
- Integration of FCS from Commercial Off-The-Shelf (COTS) components
- Current technique is based on black-box testing
- Many of those systems have been first prototyped in-house
- Example: Many FAA systems has been prototyped by MIT Lincoln Lab, NASA etc. (e.g. TCAS, ACAS-X, TSAFE, etc.)

Assurance of Flight Critical Systems (FCS)

Topic: "Support for verification of black-box FCS"

In house prototyping



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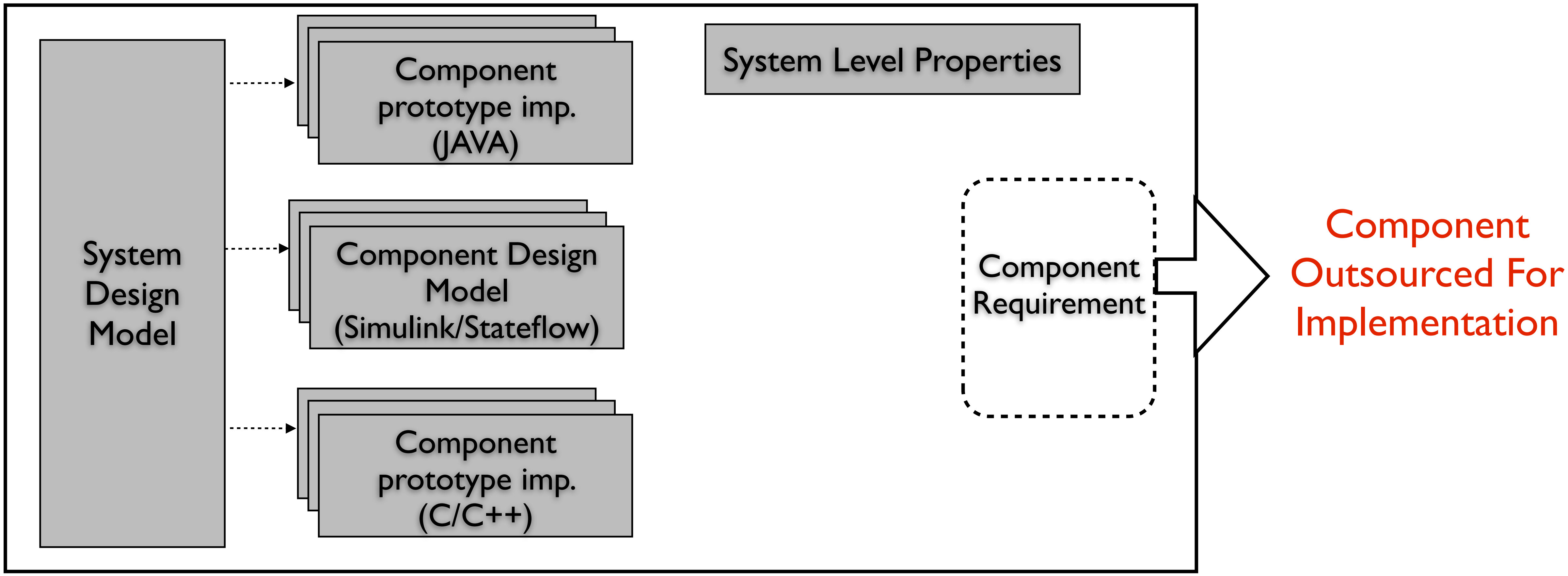
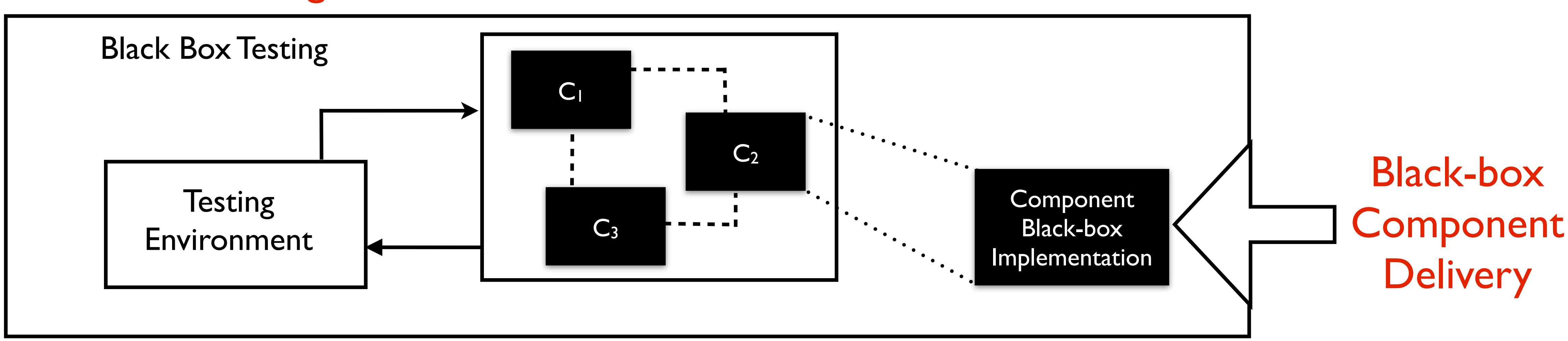


In house assembling



Contract-based Compositional verification for outsourced FCS (CoCo)

Outline

- Two stage solution for virtual integration
- 1st stage: contract generation
- 2nd stage: contract compliance
- Flight critical system case studies

Two Stage solution for virtual integration

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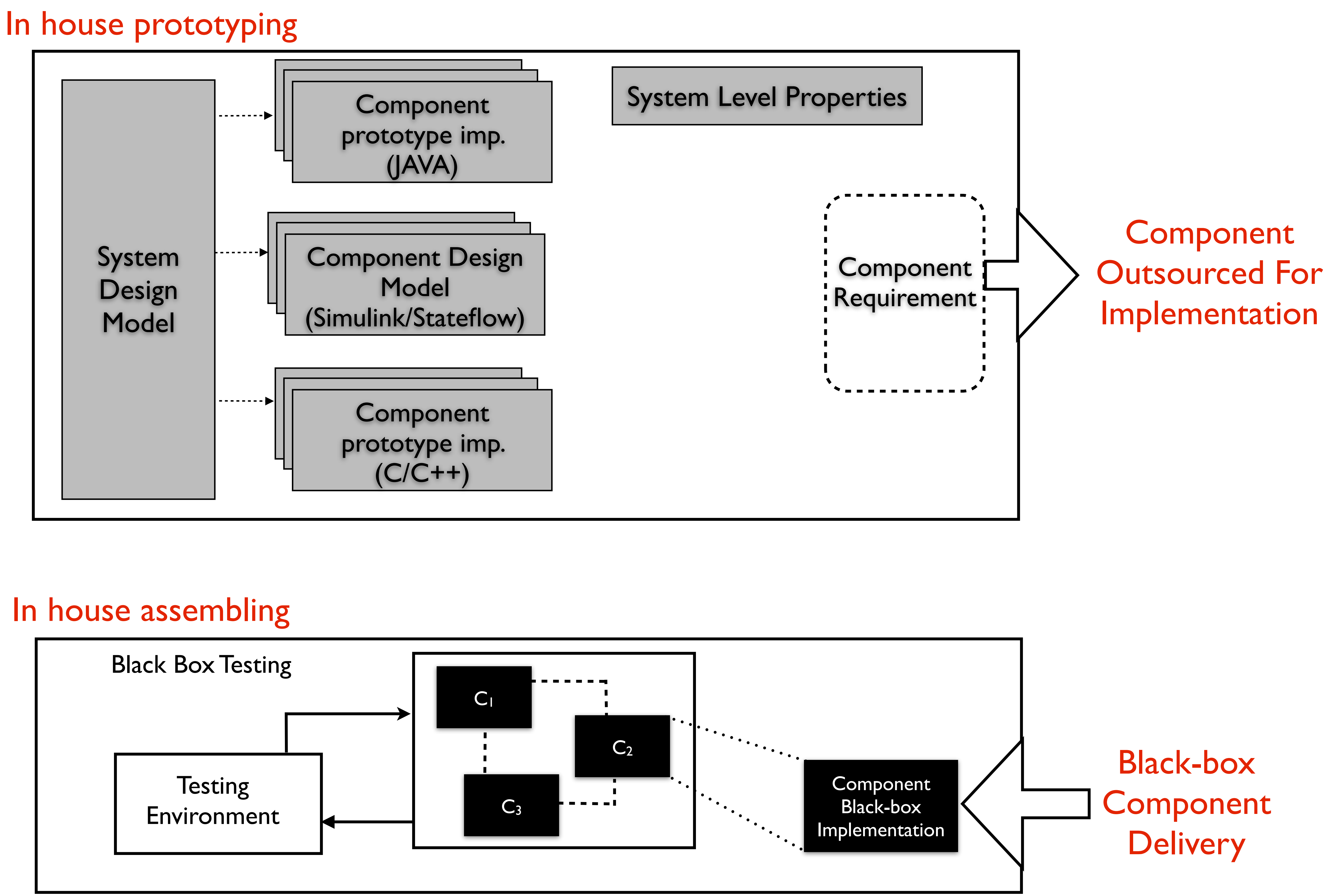

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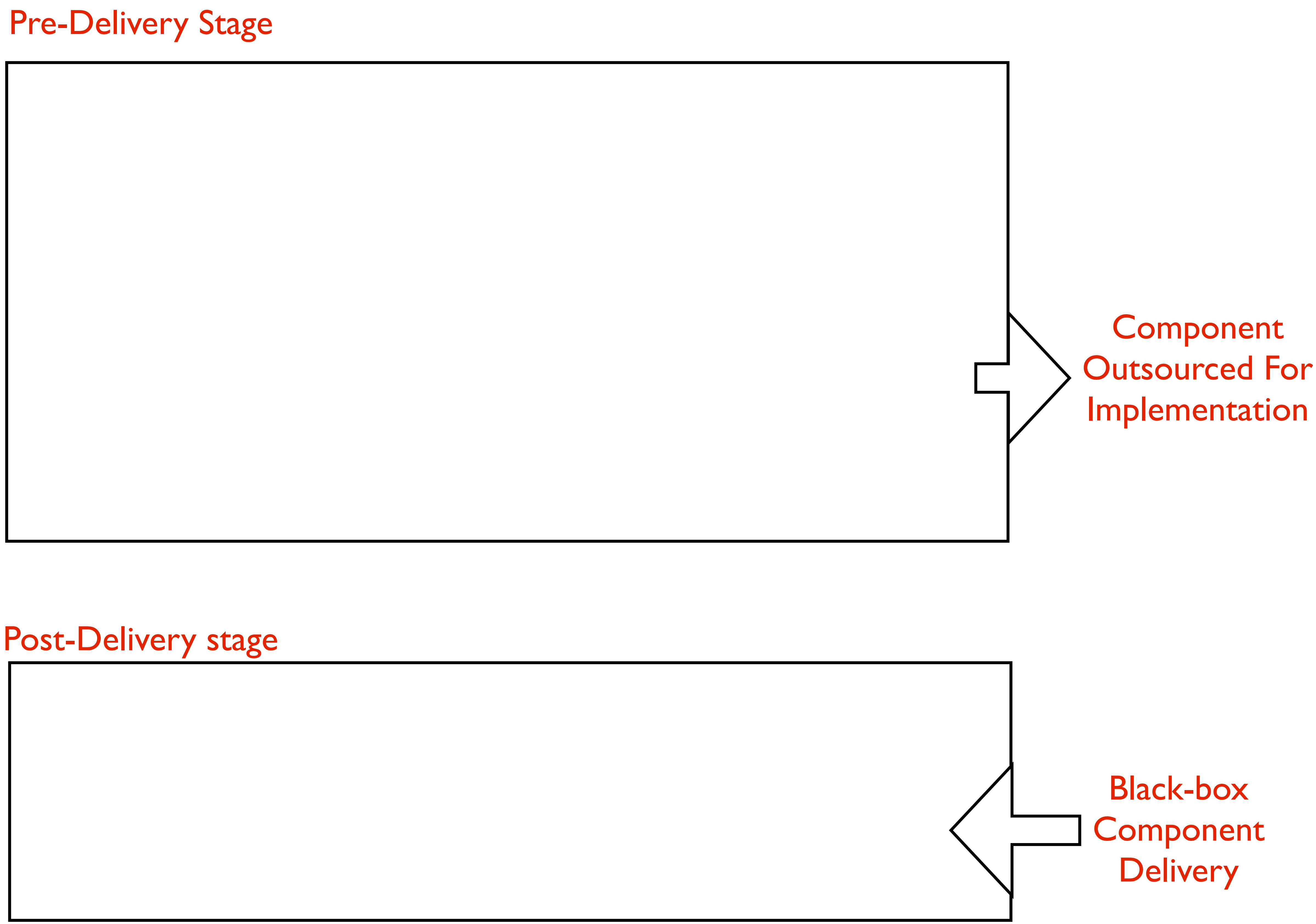

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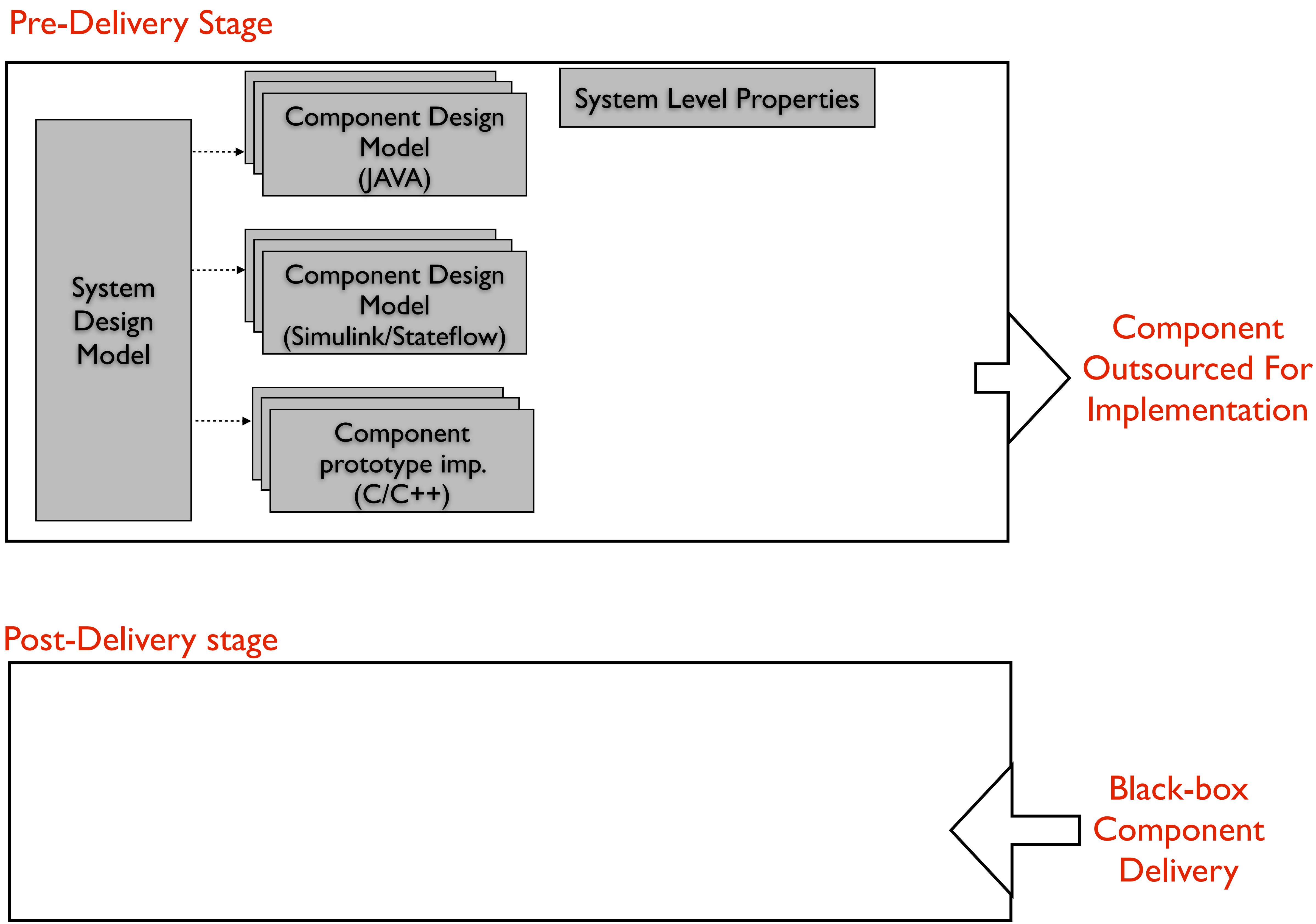

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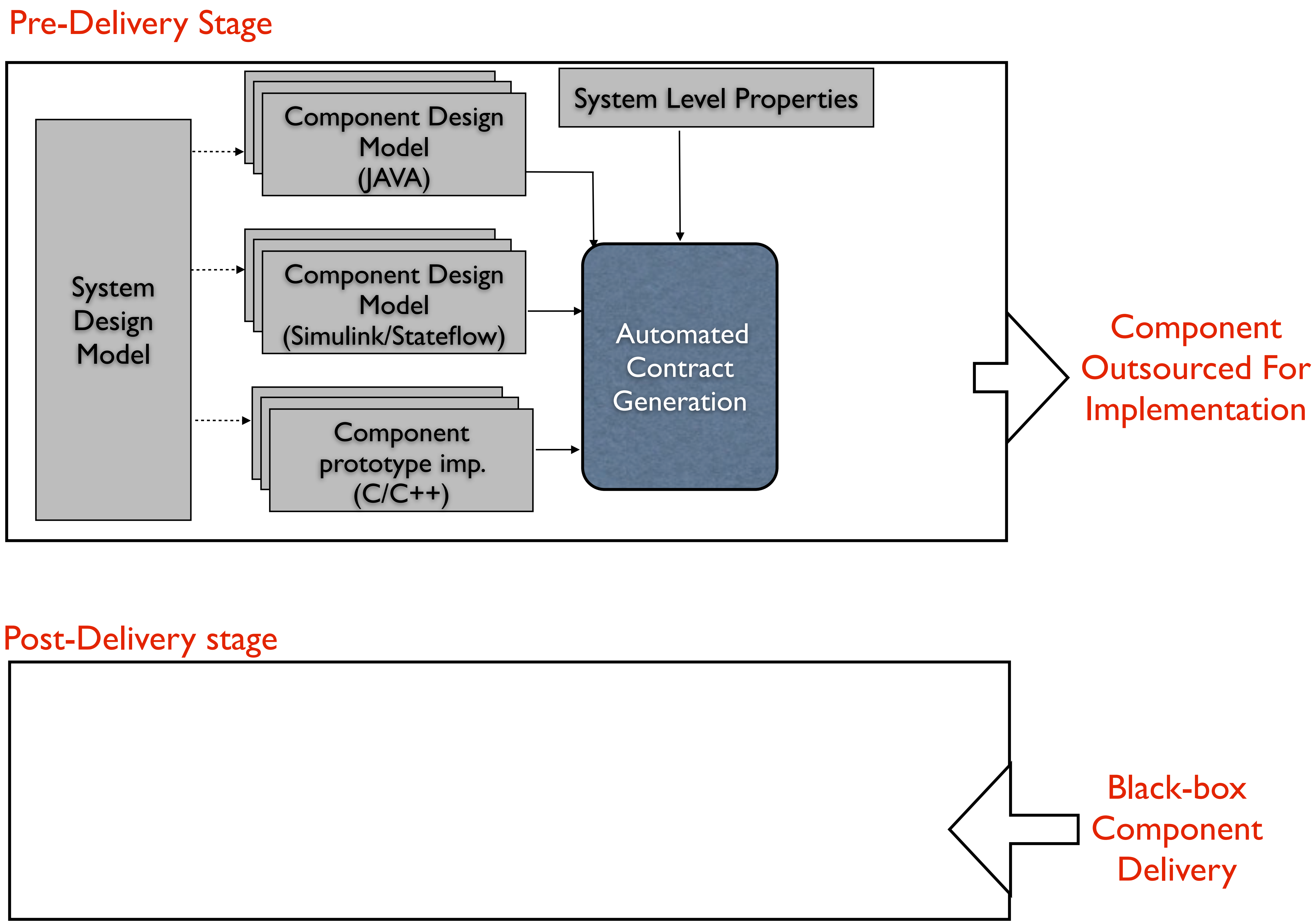

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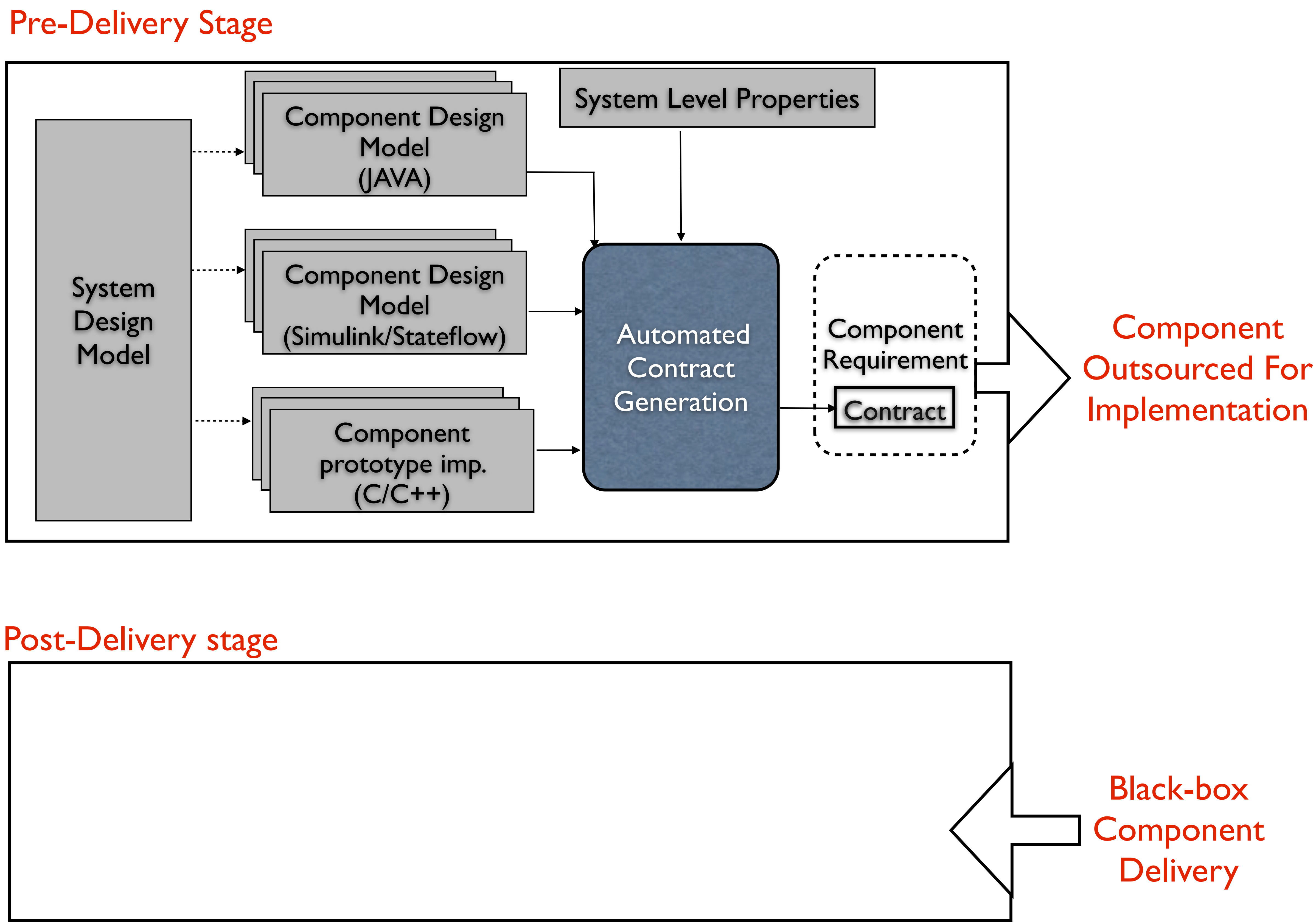

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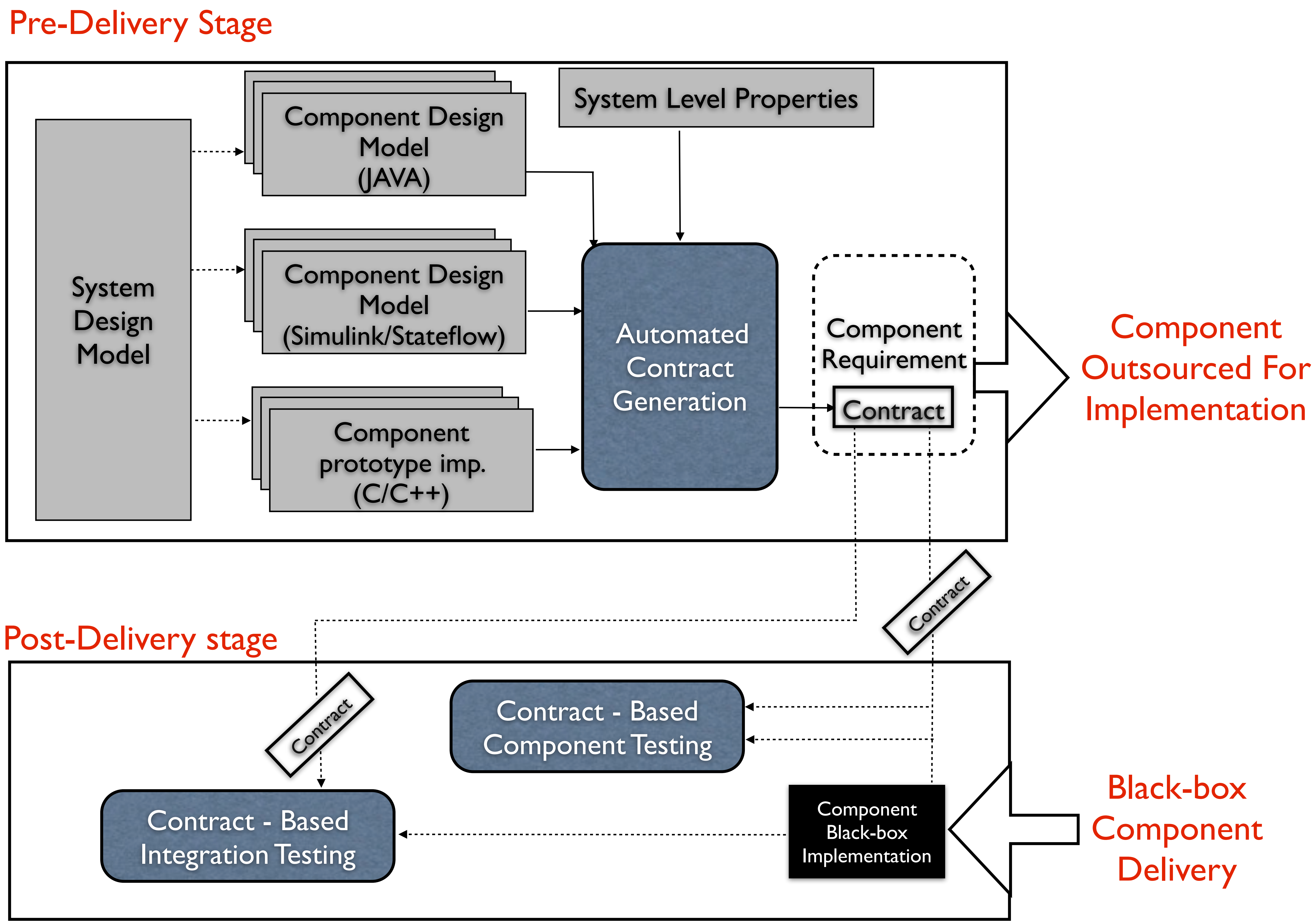

Pre-delivery verification stage

Pre-delivery Verification Stage

How to generate formal contracts from models and prototypical code?

1. Define a notion of a component contract
   - system property based
   - allows obtain a higher degree of assurance
2. Design a uniform intermediate modeling formalism
   - to facilitate the integration of different techniques
   - to target heterogeneous in-house system prototypes
3. Develop (semi)-automated techniques to generate contract from models and prototypical code

Notion of a Formal Contract

- Contracts as a method to organize and integrate component-based systems
- Specify precisely the information necessary to reason about a component interactions
- Contracts specify I/O behavior of a component:
  - Define the component guarantees provided that its environment obey certain assumptions.

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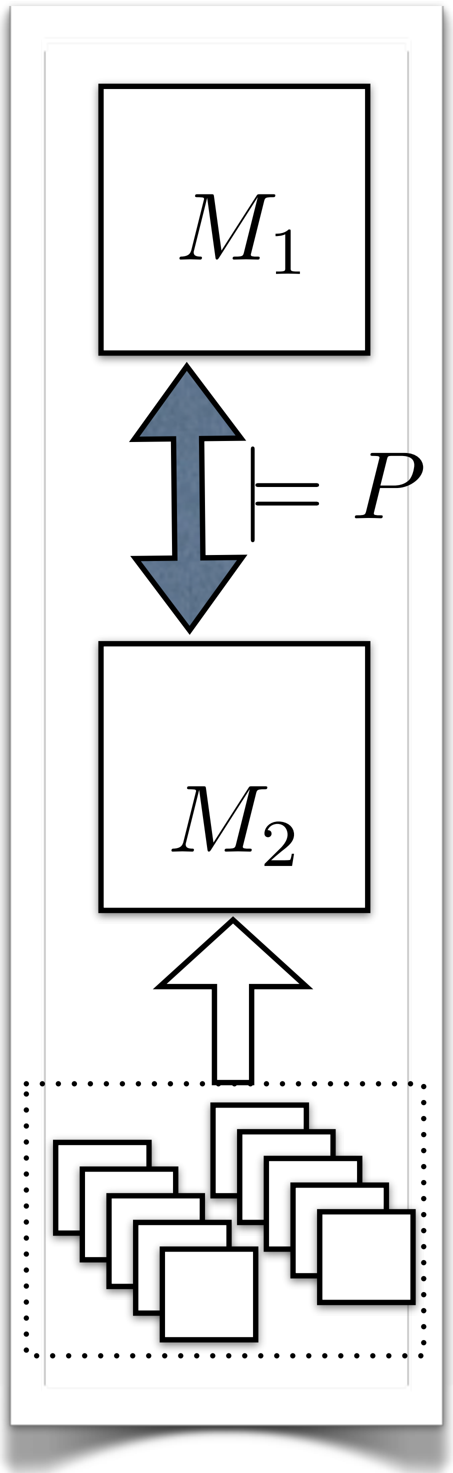
Different notions of formal contract, e.g.:

- Othello: Trace-based contract framework [Tonetta et. al.]
- AGREE: Contract language for AADL [Cofer et. al.]
- ACSL, JML, SPARK, etc : Contract in Programming Languages.

Compositional Verification



- Check P on entire system: too complicated (e.g. many states)
- Use system's natural decomposition into components to break-up the verification task
- Check components in isolation: $M_1 \models P$?
- ... typically a component is designed to satisfy its requirements in specific contexts

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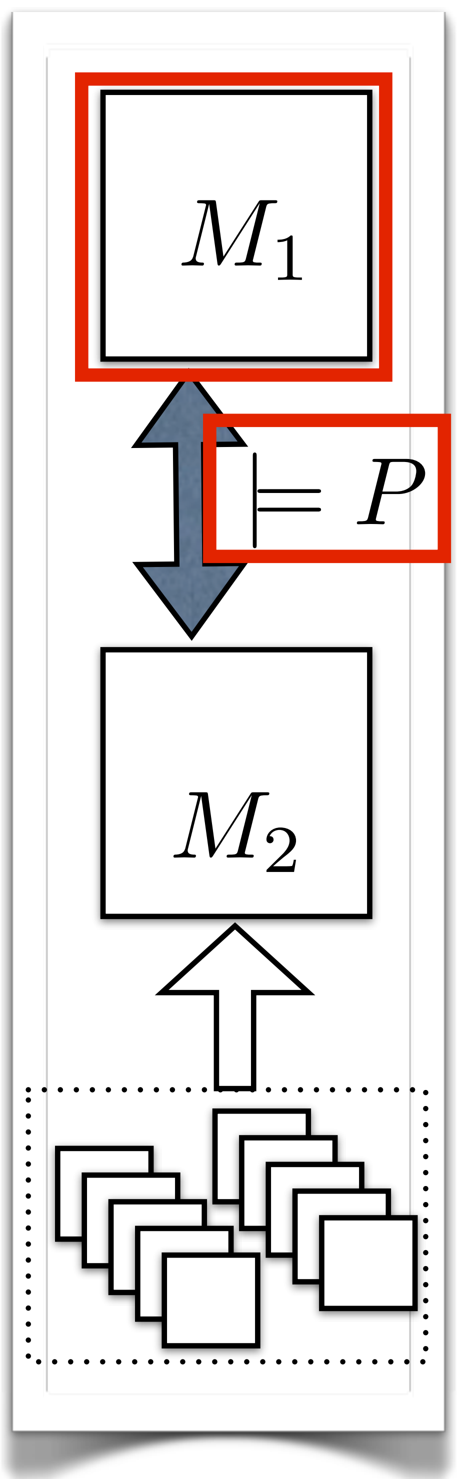

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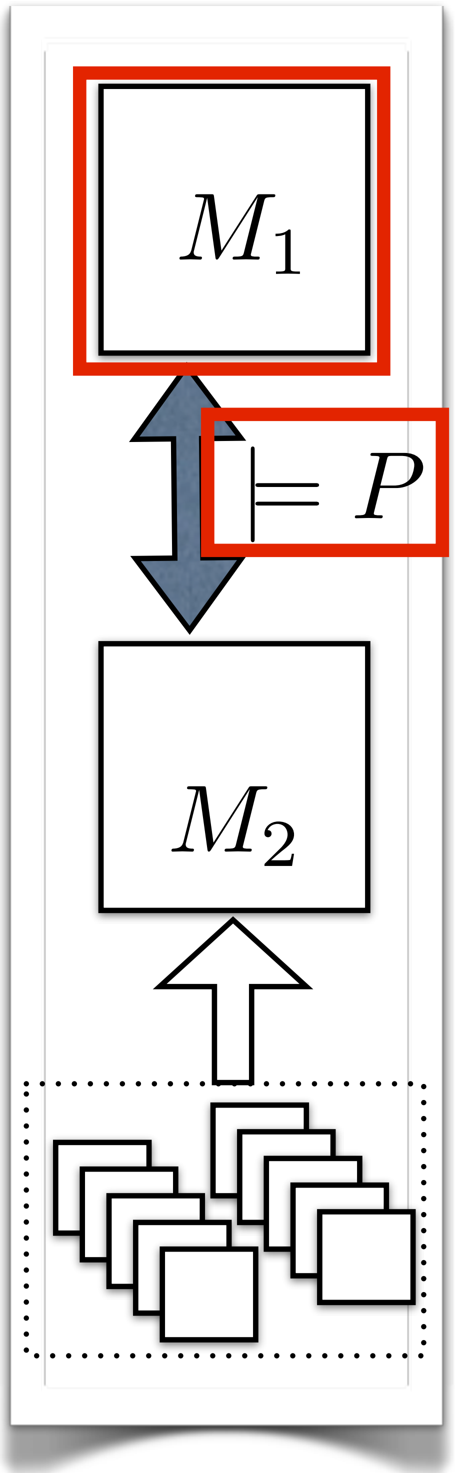

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- Assume-Guarantee reasoning
- *Misra & Chandy 81, Jones 83, Pnueli 84, Pasareanu 01*

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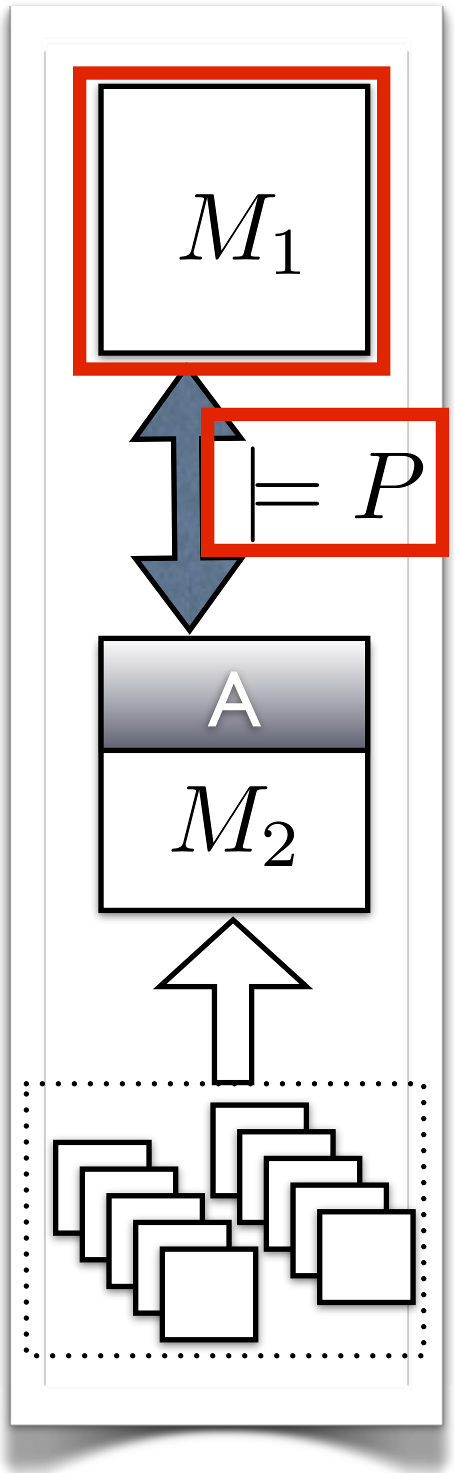

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  - introduces assumption A representing M_1's context

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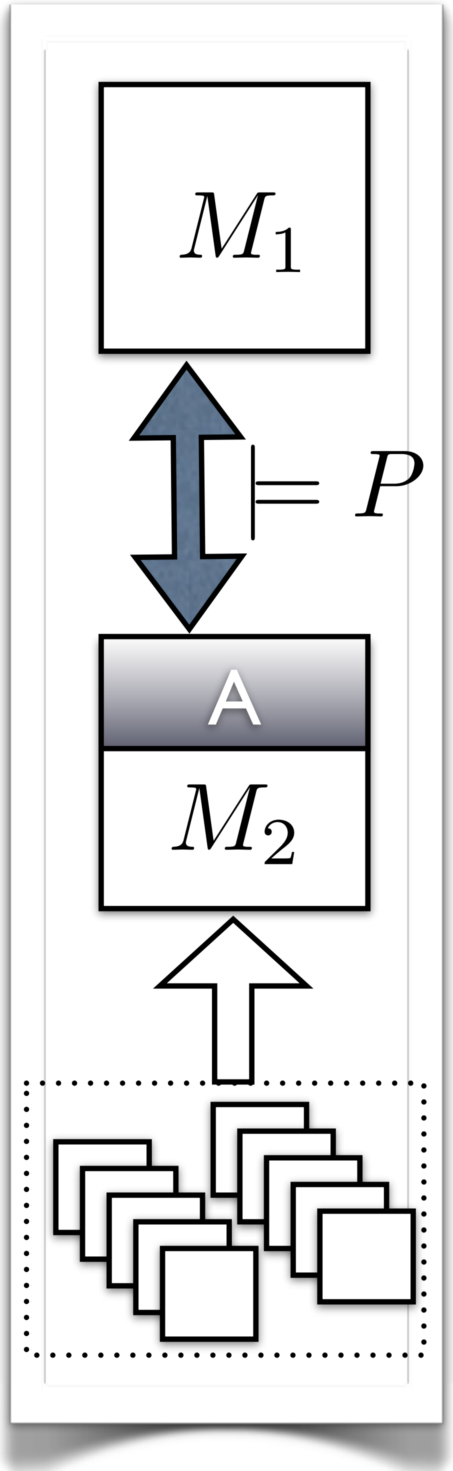

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Simplest assume-guarantee rule (*Asym*)

$$\frac{\begin{array}{l}1.\ \langle A \rangle\ M_1\ \langle P \rangle \\ 2.\ \langle true \rangle\ M_2\ \langle A \rangle\end{array}}{\langle true \rangle\ M_1 \| M_2\ \langle P \rangle}$$

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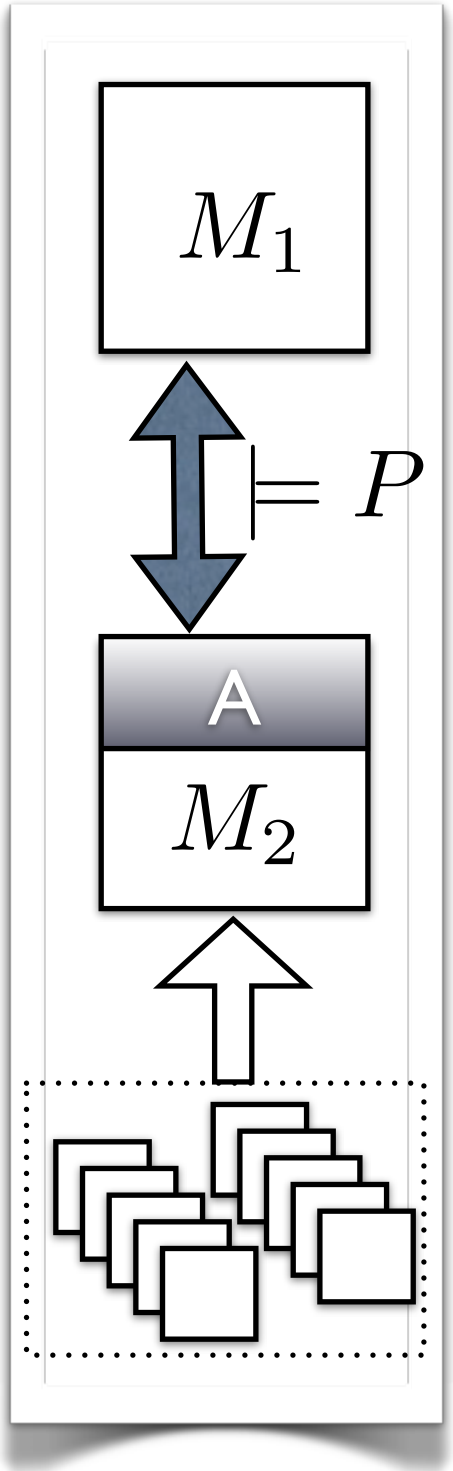

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* Cobleigh et. al "*Learning assumption for compositional verification*". TACAS'01
* Emmi et. al "*Assume Guarantee Verification for Interface Automata*". FM'08
* Giannakopoulou et. al "*Symbolic Learning of component interfaces*". SAS'12
* Howar et. al "*Hybrid learning: interface generation through static, dynamic, and symbolic analysis*" ISSTA'13.

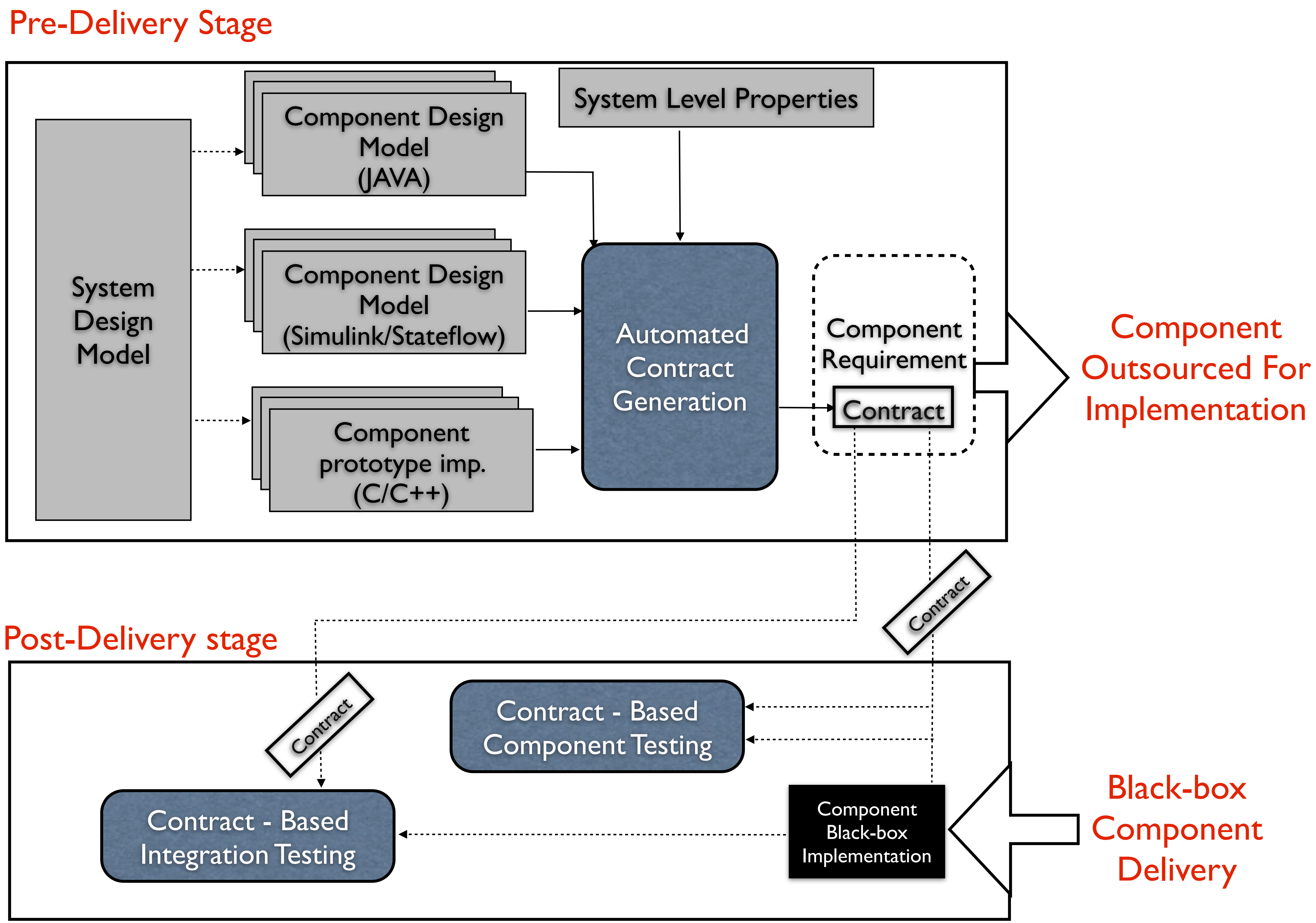
Compositional Verification

Example of assumptions (*)

- no file "close" before "open"
- access to shared variable "X" must be protected by lock "L"
- *(rover executive)* whenever thread "T" reads variable "V", no other thread can read "V" before thread "T" clears it first
- *(spacecraft flight phases)* a docking maneuver can only be invoked if the launch abort system has previously been jettisoned from the spacecraft

(*) C. Pasareanu slides on compositional verification from SSFT 2012

Two Stage solution for virtual integration



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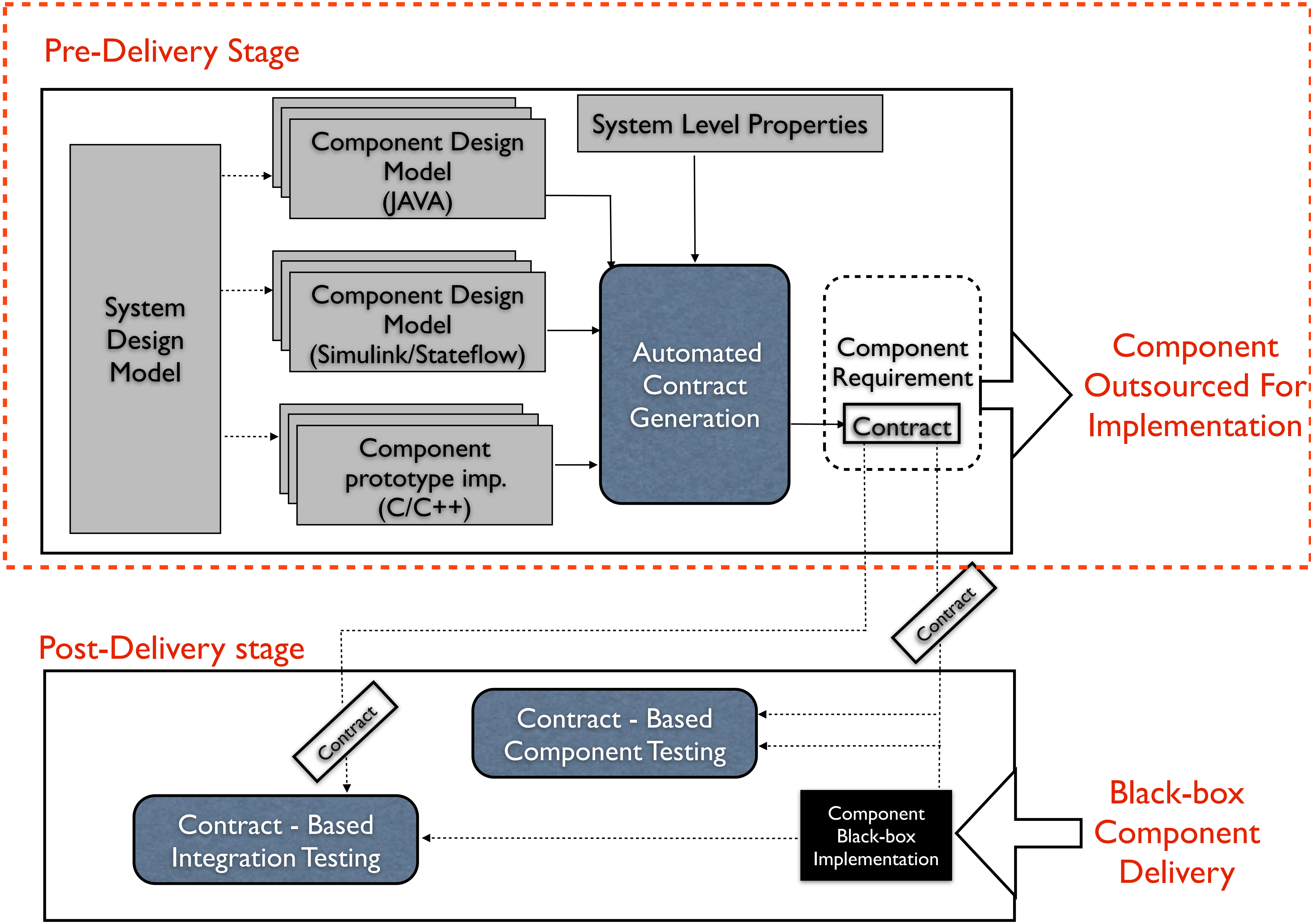
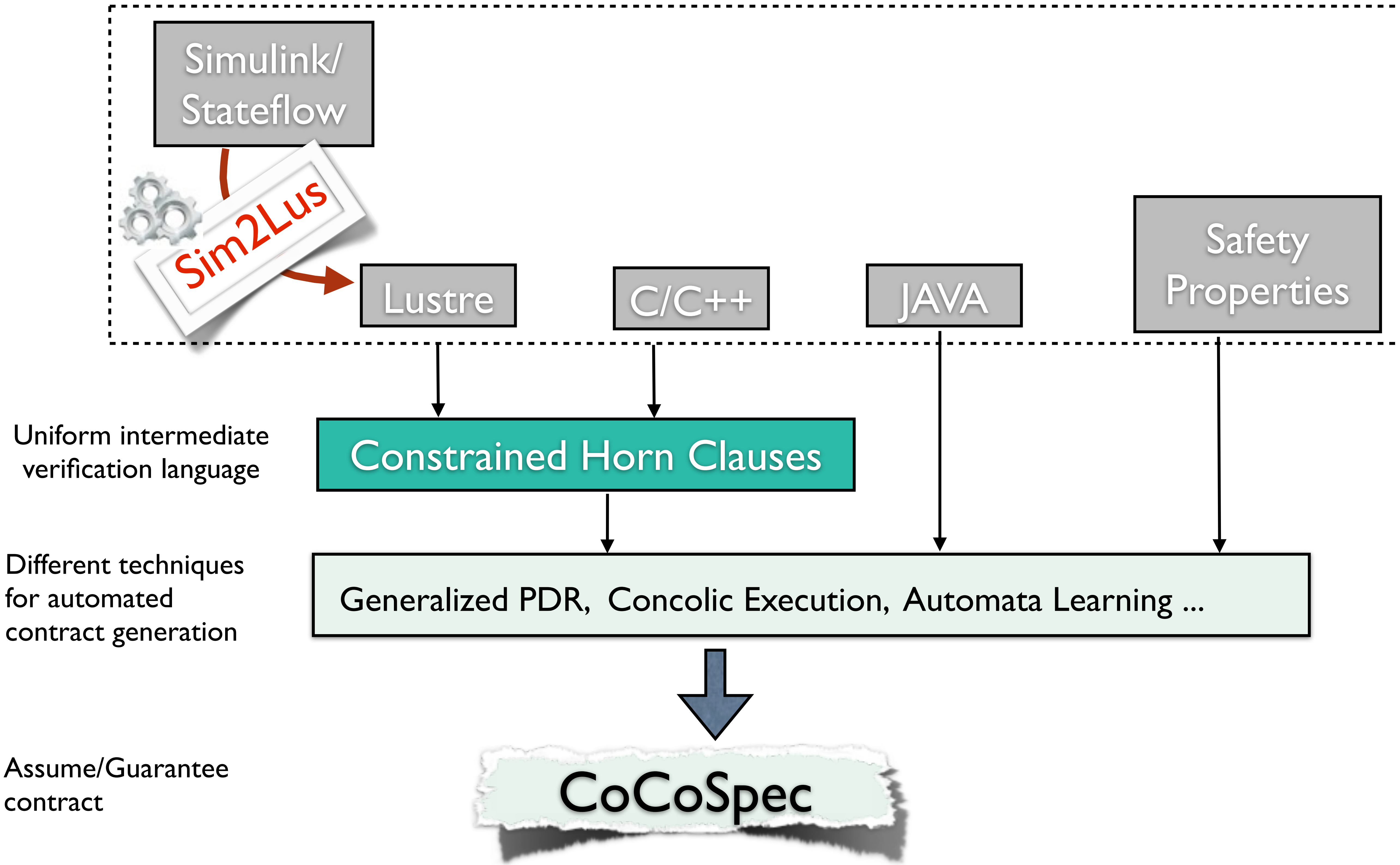


Pre-delivery Verification Stage

Our current approach:



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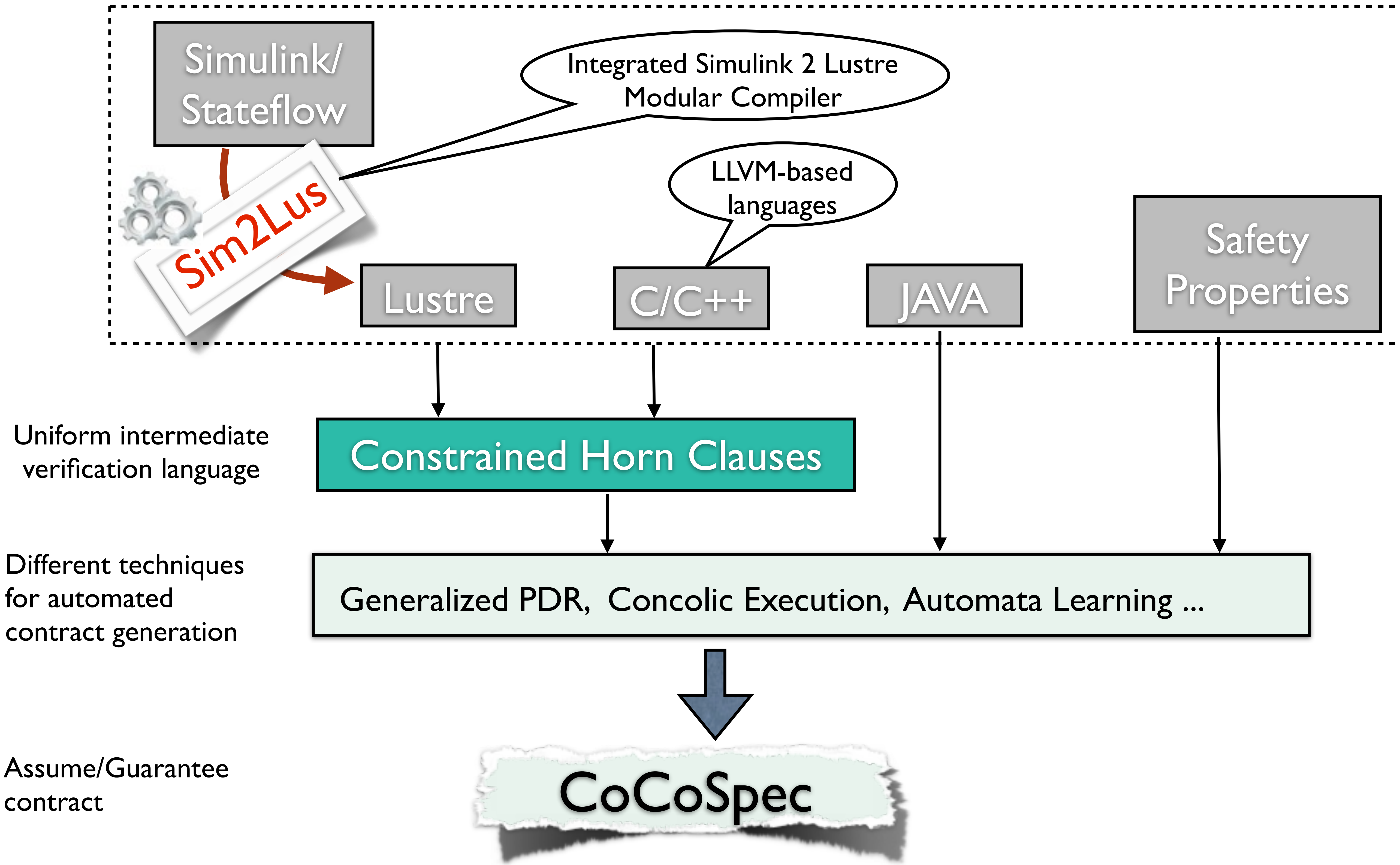

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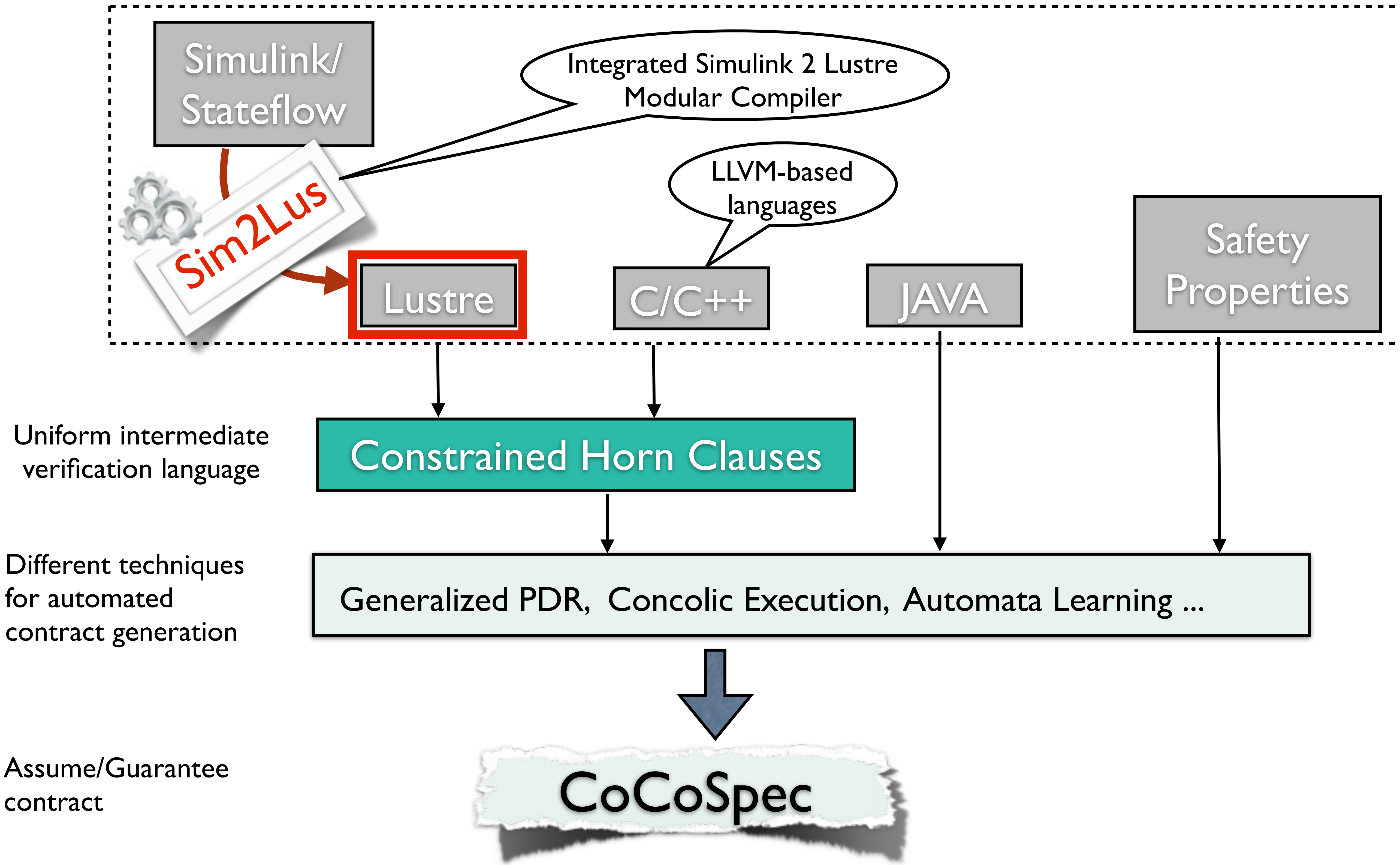


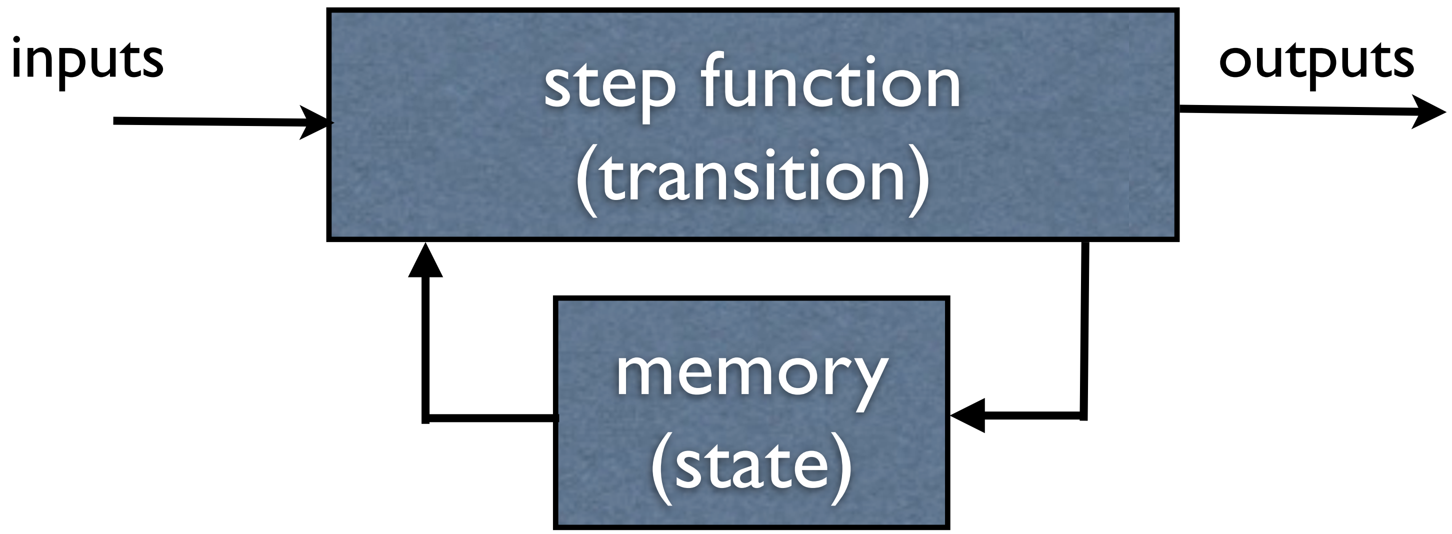
Lustre

- Declarative and deterministic specification language
- Lustre programs = systems of equational constraints between input and output streams

```
node therm_control (actual: real; up, dn: bool )
        returns (heat, cool : bool)
 var desired, margin : real;
 let
    margin = 1.5;
    desired = 21.0 → if dn then (pre desired) − 1.0
                     else if up then (pre desired) + 1.0
                     else (pre desired);
    cool = (actual − desired) > margin;
    heat = (actual − desired) < −margin;
 tel
```

Lustre

- A Lustre program models an I/O automaton



Implementing a Lustre program

- Read inputs
- Compute next state and outputs
- Write outputs
- Update state

Repeat at every trigger
(external event)

Lustre

A Lustre program is a collection of nodes: $L = [N_0, N_1, \ldots, N_m]$

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$$\bigwedge_{i \in \mathbb{N}} v_i = \rho(s_i)$$

- $v_i \in \mathcal{O}_i \cup \mathcal{L}_i$ and $Vars(si) \subseteq \mathcal{I}_i \cup \mathcal{O}_i \cup \mathcal{L}_i$
- s_i arbitrary Lustre expression including node calls $N_j(u_1, \ldots, u_n)$
- ρ function maps expression to expression

$$a \to b \text{ is projected as } \begin{cases} a \text{ in } Init_i \\ b \text{ in } Trans_i \end{cases}$$

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- A safety property P is any Lustre expression over the main node N_0

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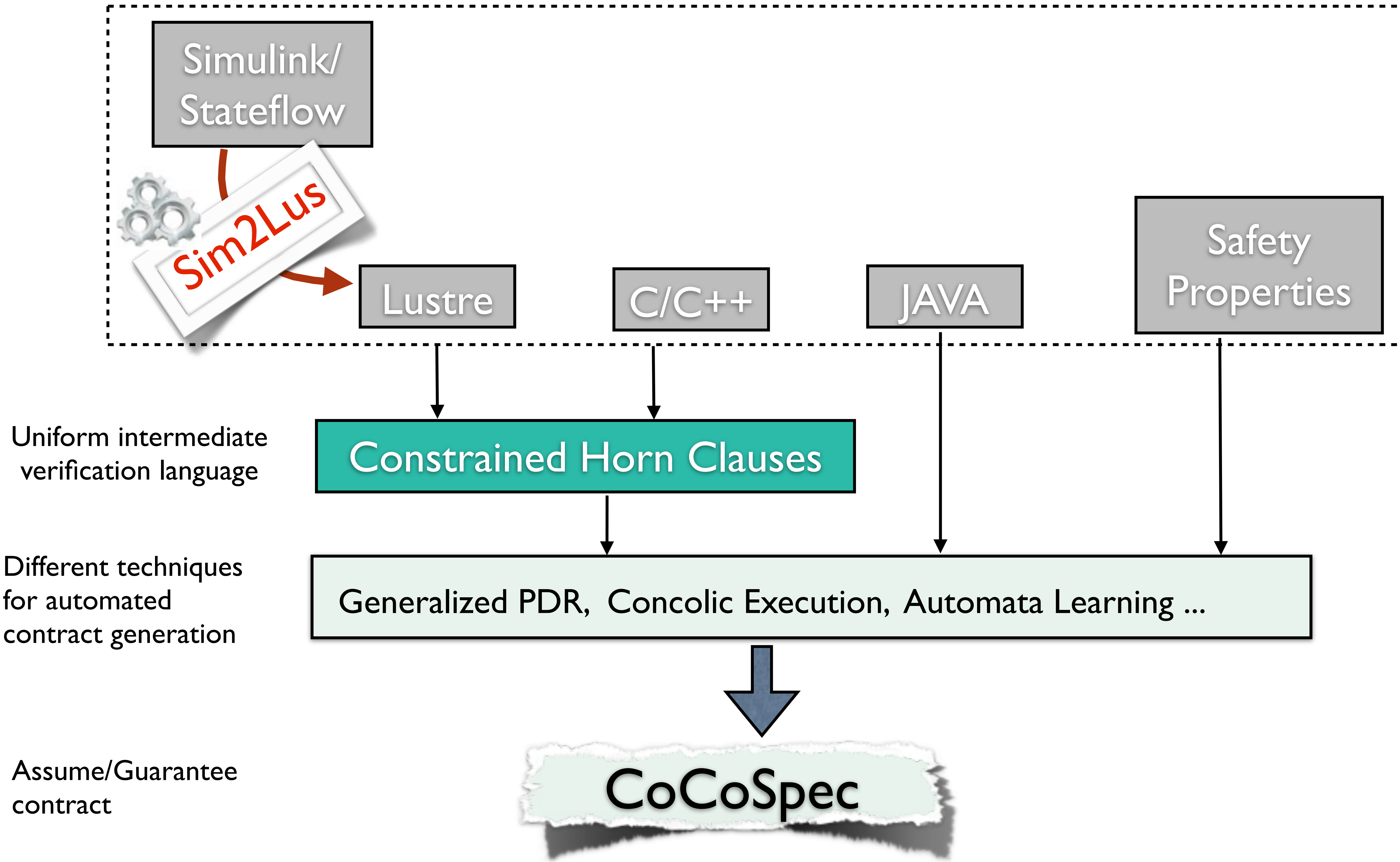

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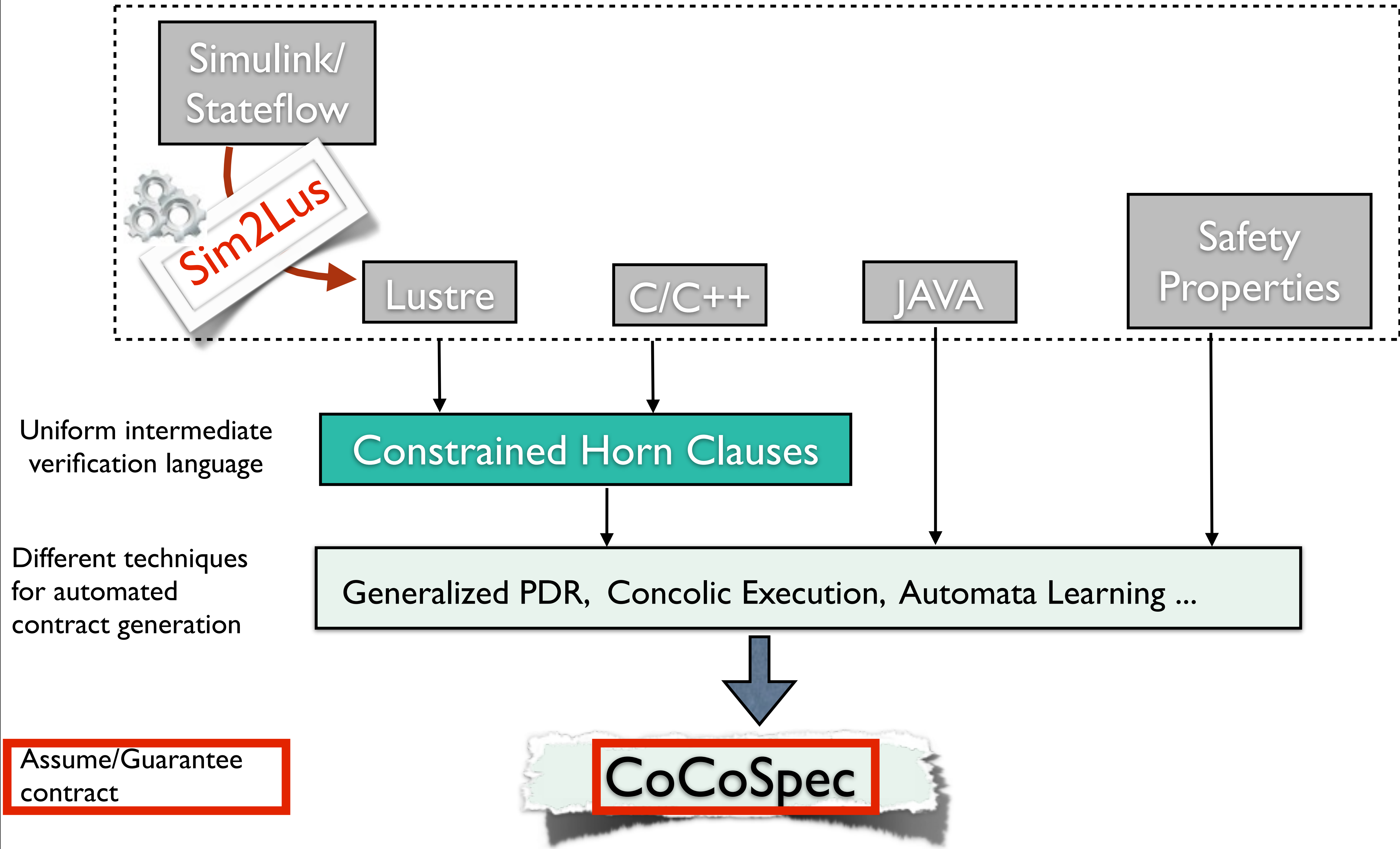

Assume-Guarantee contracts

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- an assumption $\mathcal{A}$: how the component must be used
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$$(\Box \mathcal{A}) \Rightarrow (\Box \mathcal{G}) \quad \text{holds for } C$$

In practice, usually weakened to

$$(\mathit{hist}\ \mathcal{A}) \Rightarrow \mathcal{G} \quad \text{is an invariant of } C$$

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If component C' uses C, then $\mathcal{A}_{cs}$ ($\mathcal{A}$ at call site) must always be true:

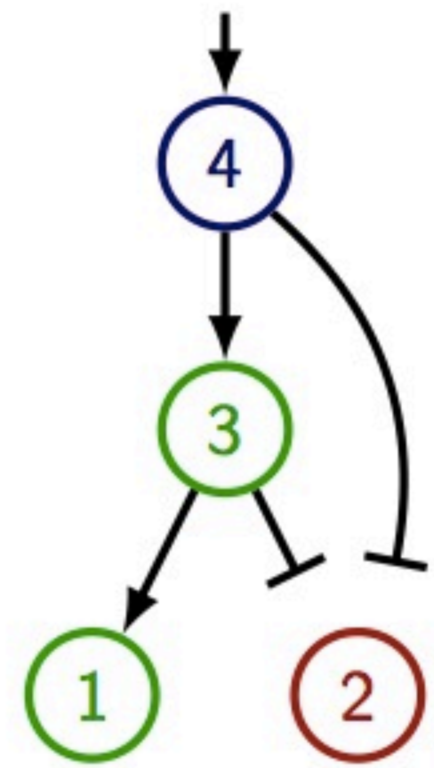
$$\mathcal{A}_{cs} \quad \text{is an invariant of } C'$$

Assume-Guarantee contracts

Improves scalability of the verification of hierarchical systems by abstracting components by their contract.

The analysis is bottom-up:

- *leaves* are analyzed as usual, which can succeed or fail.
- for *nodes*, we first abstract the subcomponents, which can succeed, or fail.
  In case of failure we can restart the analysis after (soundly) refining the abstraction, possibly several times.



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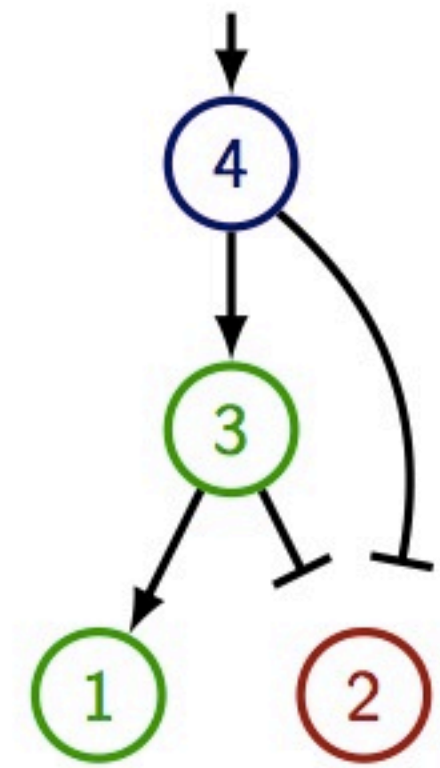
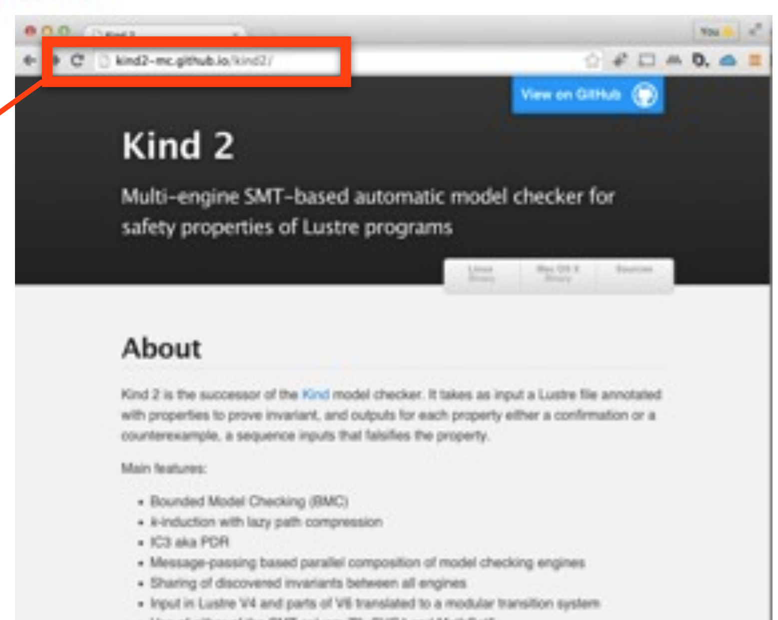


Implemented in Kind2: a multi engine model checker for Lustre programs

http://kind2-mc.github.io/kind2/



CoCoSpec

- An Assume/Guarantee-based Contract Language on top of Lustre

A CocoSpec contract is a pair $\langle \mathcal{A}, \mathcal{G} \rangle$

Assumption — how the component must be used:

$$\mathcal{A} \equiv \vee \; (require_i)$$

Guarantee — how the component behaves:

$$\mathcal{G} \equiv \wedge \, (require_i \Rightarrow ensure_i)$$

CoCoSpec

- An Assume/Guarantee-based Contract Language

```
node component(n1, n2:int; chaos:bool)
              returns (out: bool; corrupted, warning:bool) ;
--!contract : contr       ;

let
  -- Implementation.
tel

contract contr(n1, n2:int; chaos:bool)
              returns (out: bool; corrupted, warning:bool) ;
let
  require (-7 <= n1) and (7 <= n1); -- n1 legal input
  require (-11 <= n2) and (11 <= n2); -- n2 legal input
  ensure (-42 <= out) and (42 <= out); -- out is bounded
tel
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contract inhibited(on, off: bool) returns (active: bool) ;
var
  act_raise: bool ; last_act_raise: int ;
let
  active_raise   = false -> active and not pre active ;
  last_act_raise = 0     -> if pre active_raise then 1
                            else 1 + pre last_act_raise ;
  require last_act_raise <= n ;
  ensure  active ;
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ghost variable

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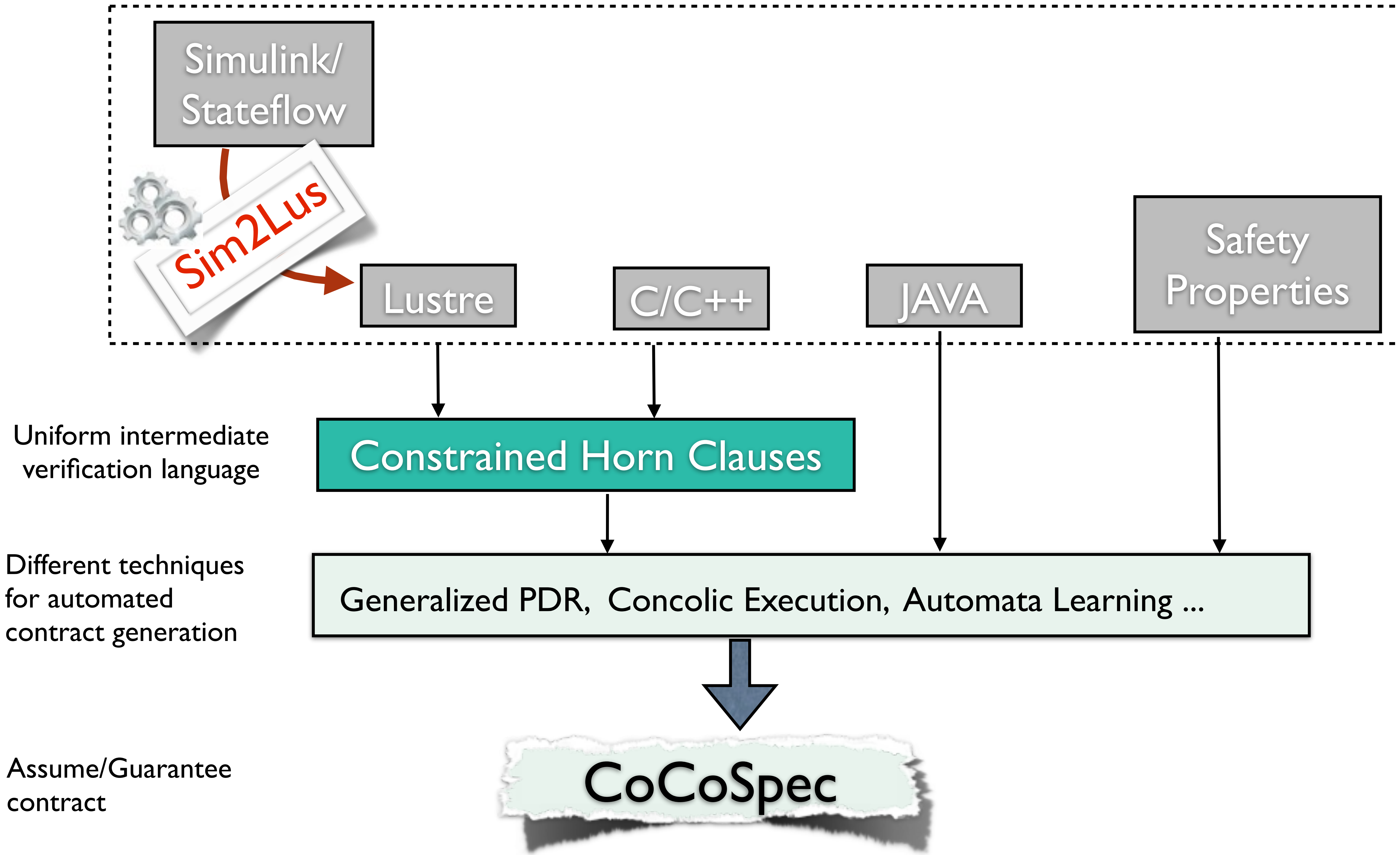

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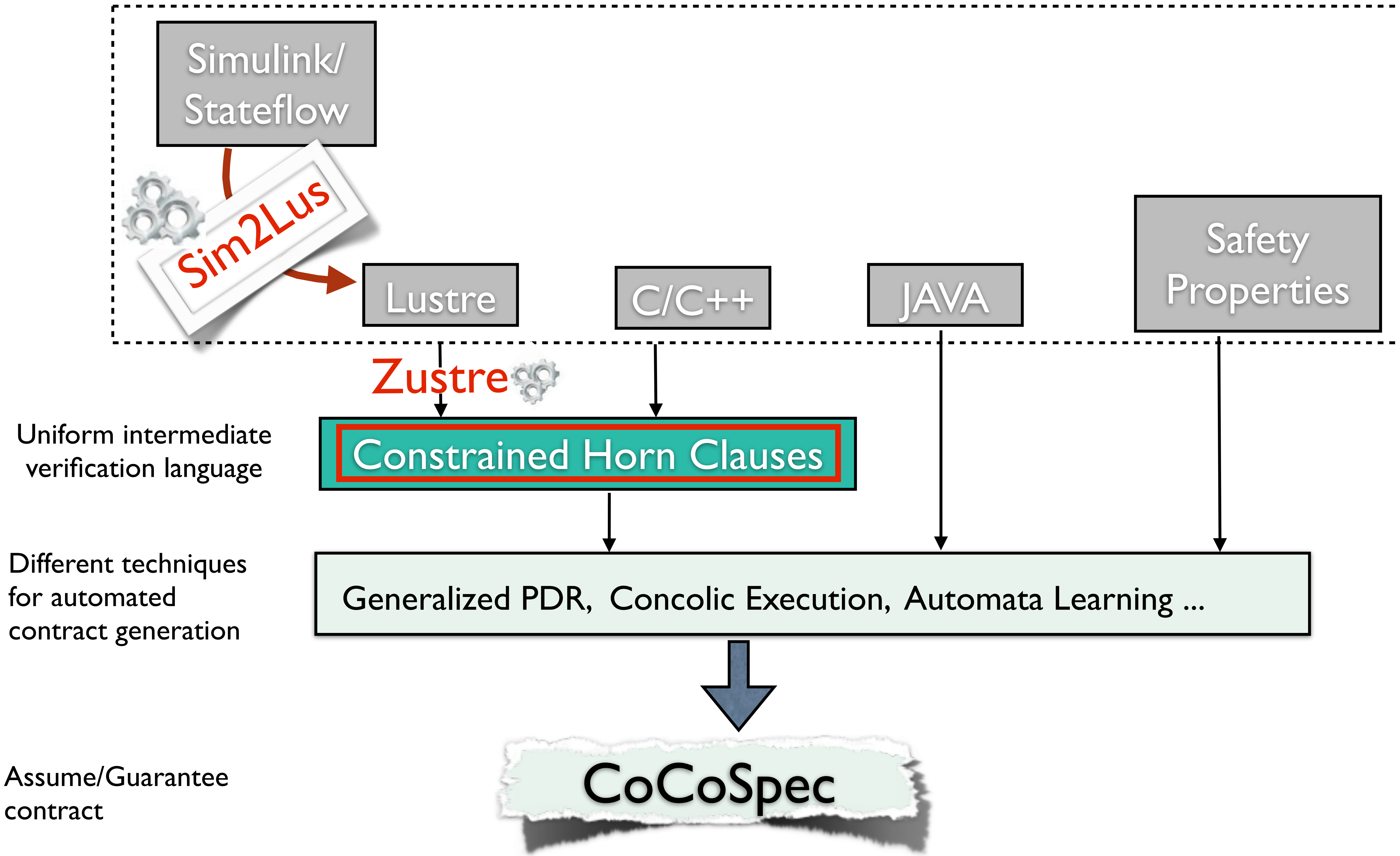
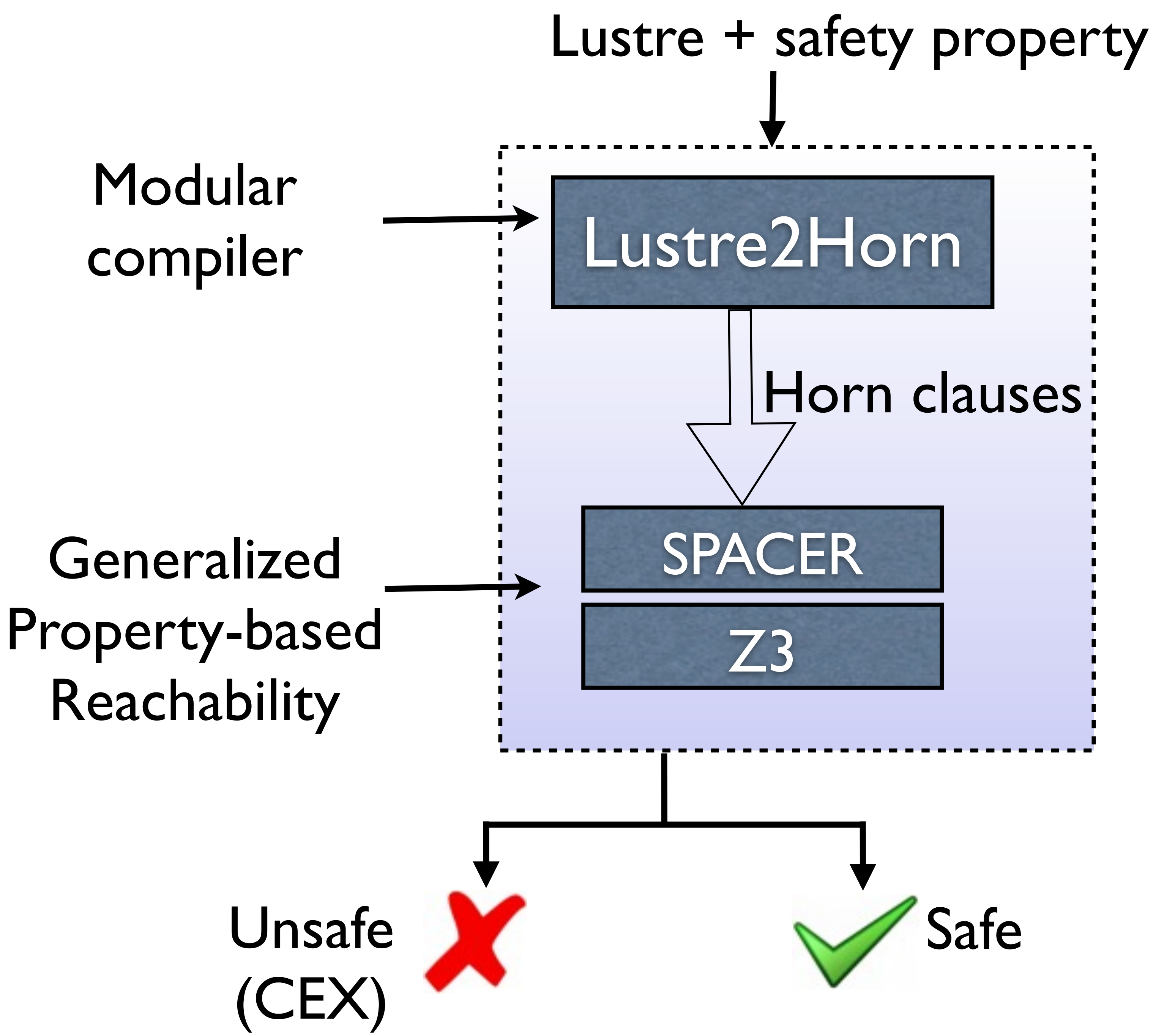


Zustre

A verification engine and CoCoSpec generator for Lustre program



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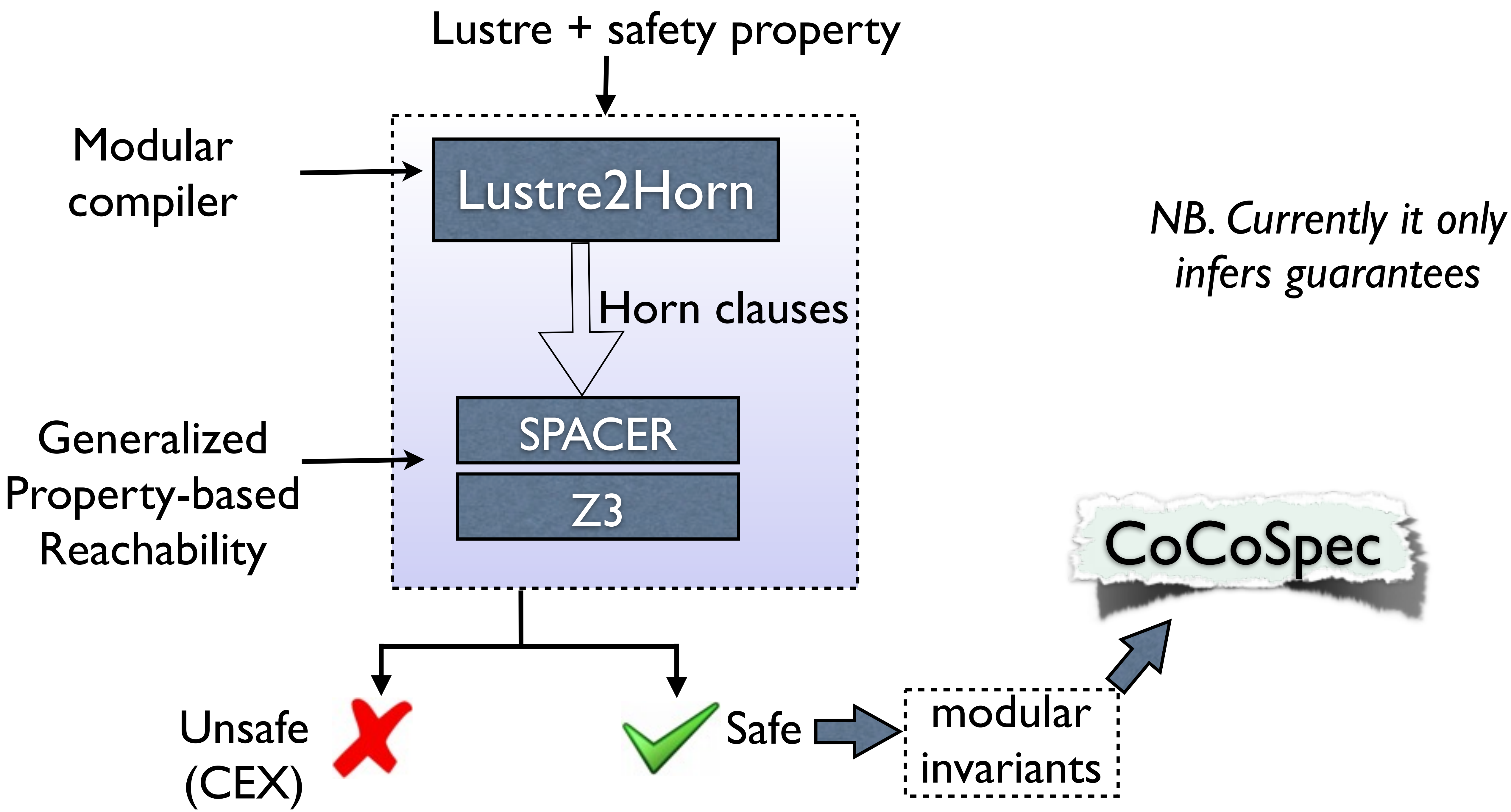

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Constrained Horn Clause

Constrained Horn Clause

- A fragment of First Order Logic.
- A uniform way to represent transition systems for verification.

$\mathcal{F}$: set of function symbols
$\mathcal{P}$: set of predicate symbols
$\mathcal{V}$: set of variables

Constrained Horn Clause (CHC) is a formula:

$$\forall \mathcal{V} \cdot (\phi \wedge p_1[X_1] \wedge \cdots \wedge p_n[X_n] \rightarrow h[X]), \text{ for } n \geq 0$$

ϕ : constraint over $\mathcal{F} \cup \mathcal{V}$ with respect to some background theory
e.g. arithmetic, arrays, SMT
$X_i, X \subseteq \mathcal{V}$: (possibly empty) vectors of variables
$p_1, \ldots, p_n, h$: n-ary predicates
$p_i[X_i]$: application $p(t_1, \ldots, t_n)$ of an n-ary predicate symbol

Example 1

```
node therm_control (actual: real; up, dn: bool )
          returns (heat, cool : bool)
 var desired, margin : real;
 let
    margin = 1.5;
    desired = 21.0 → if dn then (pre desired) − 1.0
                     else if up then (pre desired) + 1.0
                     else (pre desired);
    cool = (actual − desired) > margin;
    heat = (actual − desired) < −margin;
 tel
```

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```

$$[\ margin = 1.5 \\ \wedge\ desired = 21.0 \\ \wedge\ cool = actual - desired > margin \\ \wedge\ heat = ...] \Rightarrow TC_{init}(actual, up, dn, heat, cool, desired)$$

Initial states

$$[\ margin = 1.5 \\ \wedge\ desired' = ite(dn\ (desired - 1.0)\ (ite...)) \\ \wedge\ cool = actual - desired' > margin \\ \wedge\ heat = ...] \Rightarrow TC_{trans}(actual, up, dn, heat, cool, desired, desired')$$

Transition relation

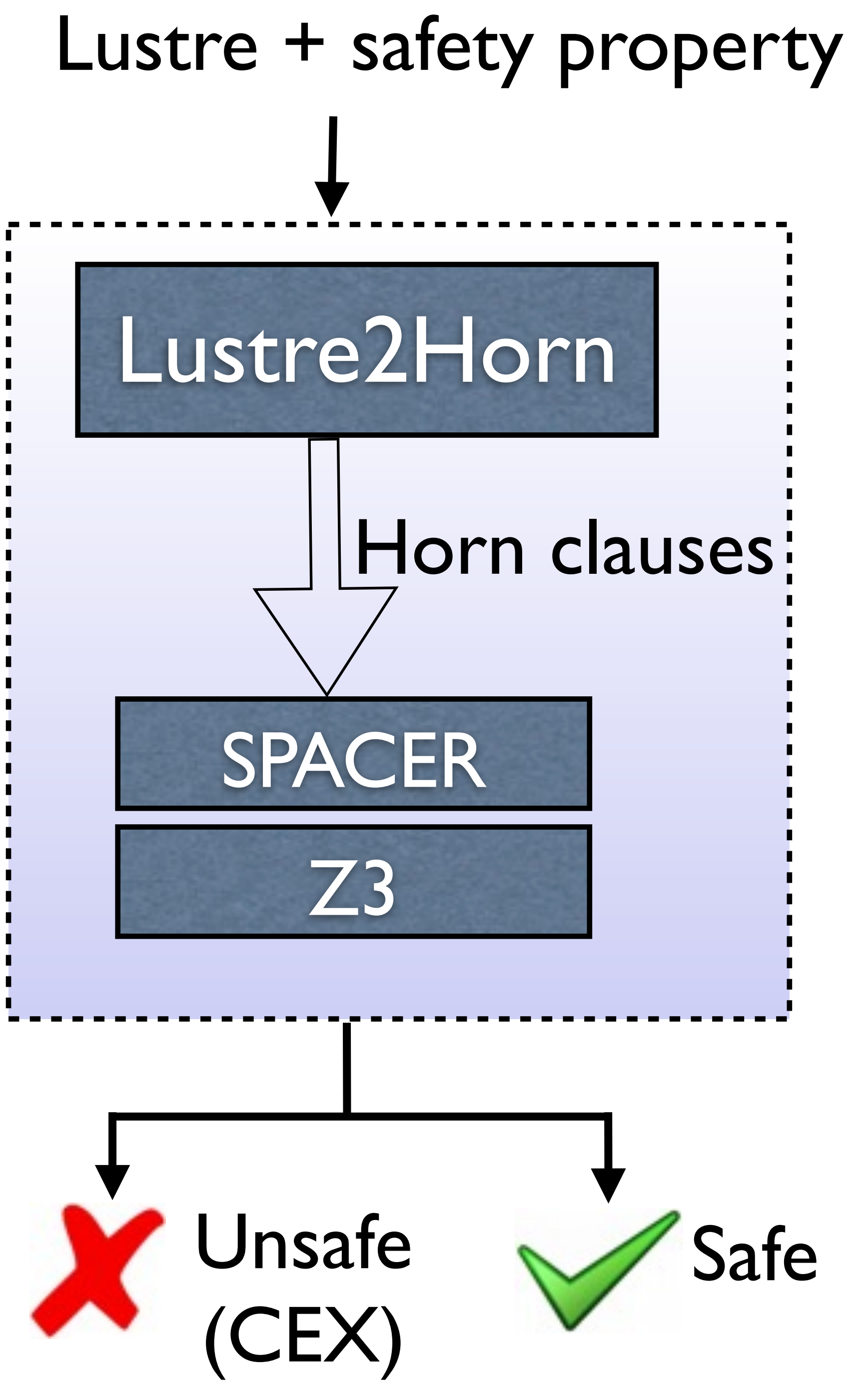
$$TC_{init}(actual, up, dn, heat, cool, desired) \Rightarrow Loop(actual, up, dn, heat, cool, desired)$$

$$Loop(actual', up', dn', heat', cool', desired) \\ \wedge\ TC_{trans}(actual, up, dn, heat, cool, desired, desired') \\ \Rightarrow Loop(actual, up, dn, heat, cool, desired')$$

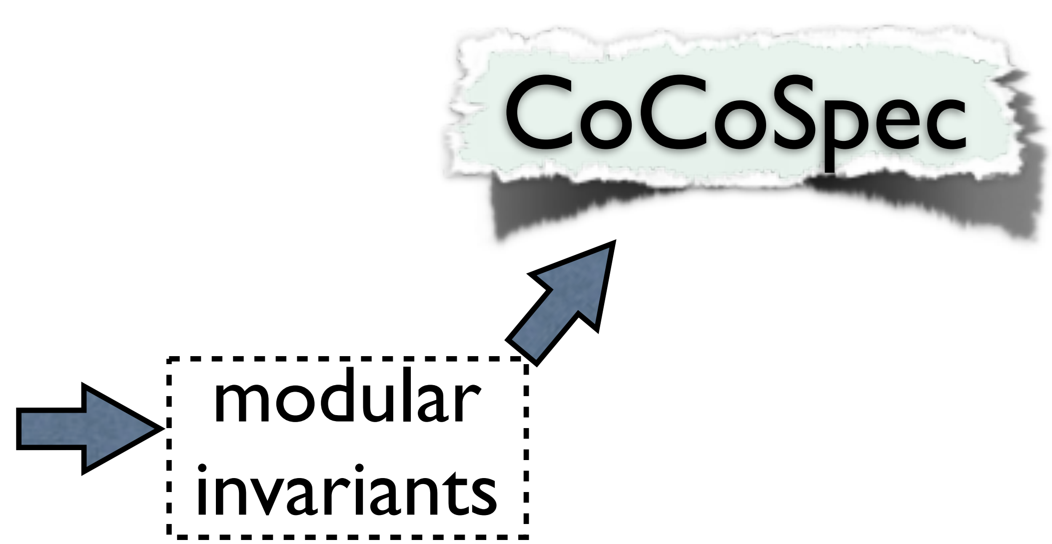
Loop

Zustre

A verification engine and CoCoSpec generator for Lustre program



- $N(\mathcal{I}, \mathcal{O}, \mathcal{S}, \mathcal{S}') = \bigwedge \varphi$: an invariant for a node N
- **Modular invariants** : invariants for each node



From Horn Clauses to CoCoSpec

```
node Sofar( X : bool ) returns ( Y : bool );
let
  Y = (true -> pre Y) and X;
tel

-- assignment other

node Store( Delta : int ) returns ( Total : int );
var Prev : int;
let

  Prev  = 0 -> pre Total;
  Total = if Delta < 0 and Prev > 0  then Prev+Delta
     else if Delta > 0 and Prev < 10 then Prev+Delta
     else Prev;
tel



node top( Delta : int ) returns ( OK : bool );
var Total : int;
    S: bool;
    -- Delta_const :  int;
let
  -- Delta_const = Delta -> pre Delta_const;
  Total = Store( Delta );

  S =  Sofar( -1 <= Delta and Delta <= 1 );
  OK = S => 0 <= Total and Total <= 20;
  --!PROPERTY :  OK=true;
  --!MAIN:true;
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```
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    Not(Not(Sofar.Y) == Sofar.X))
And(Not(Sofar.Y == Or(Not(Sofar.__Sofar_2_c), Not(Sofar.X))),
    Not(Not(Sofar.__Sofar_2_x) == Sofar.Y))
```

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```
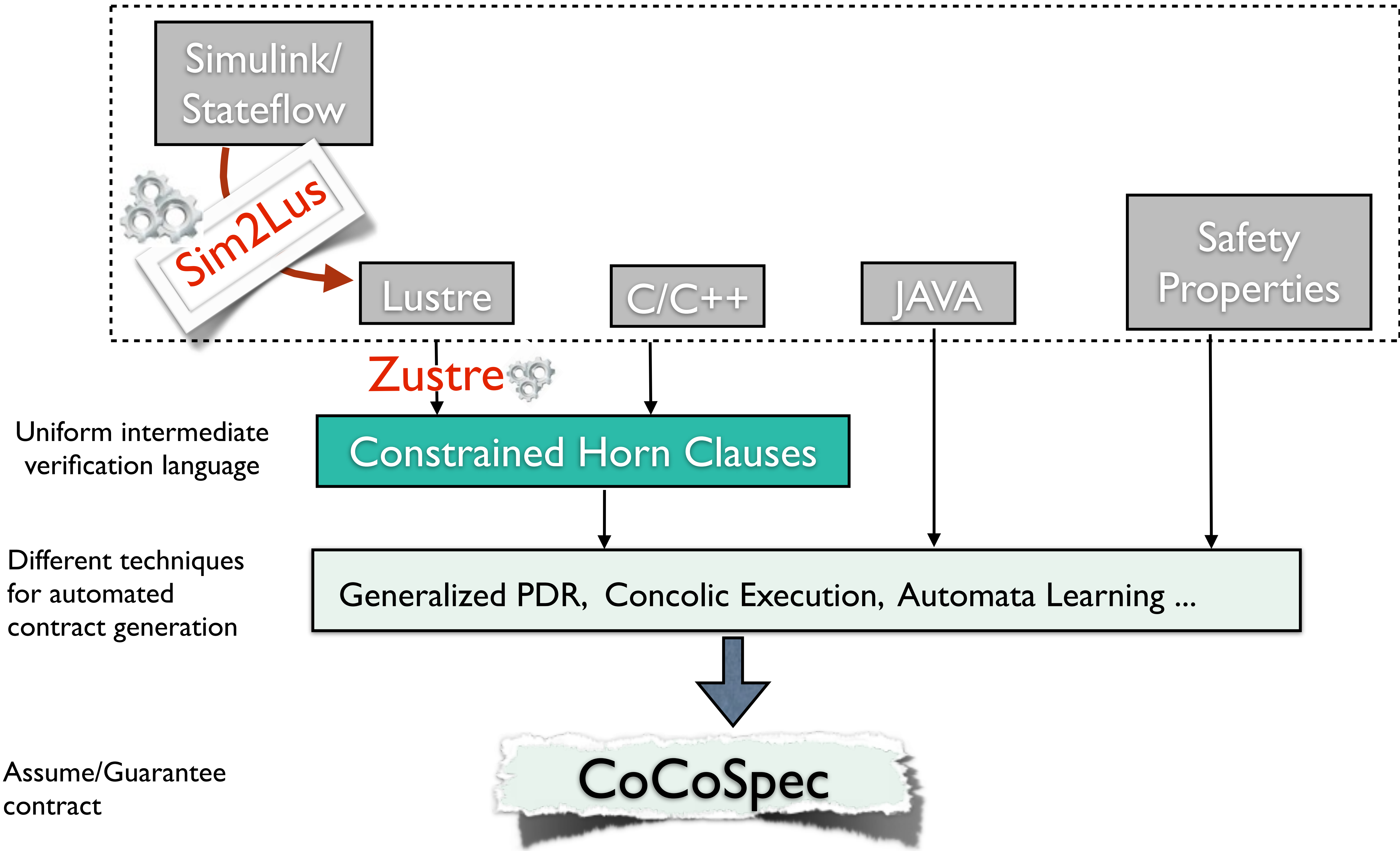

```
contract Sofar (X:bool) returns (Y:bool);
 let
   ensure (Y = X) -> (Y = (pre(Y) and  X));
 tel
```

NB. We use Z3 tactics to simplify (manipulate) formulas

Pre-delivery Verification Stage

Our current approach:



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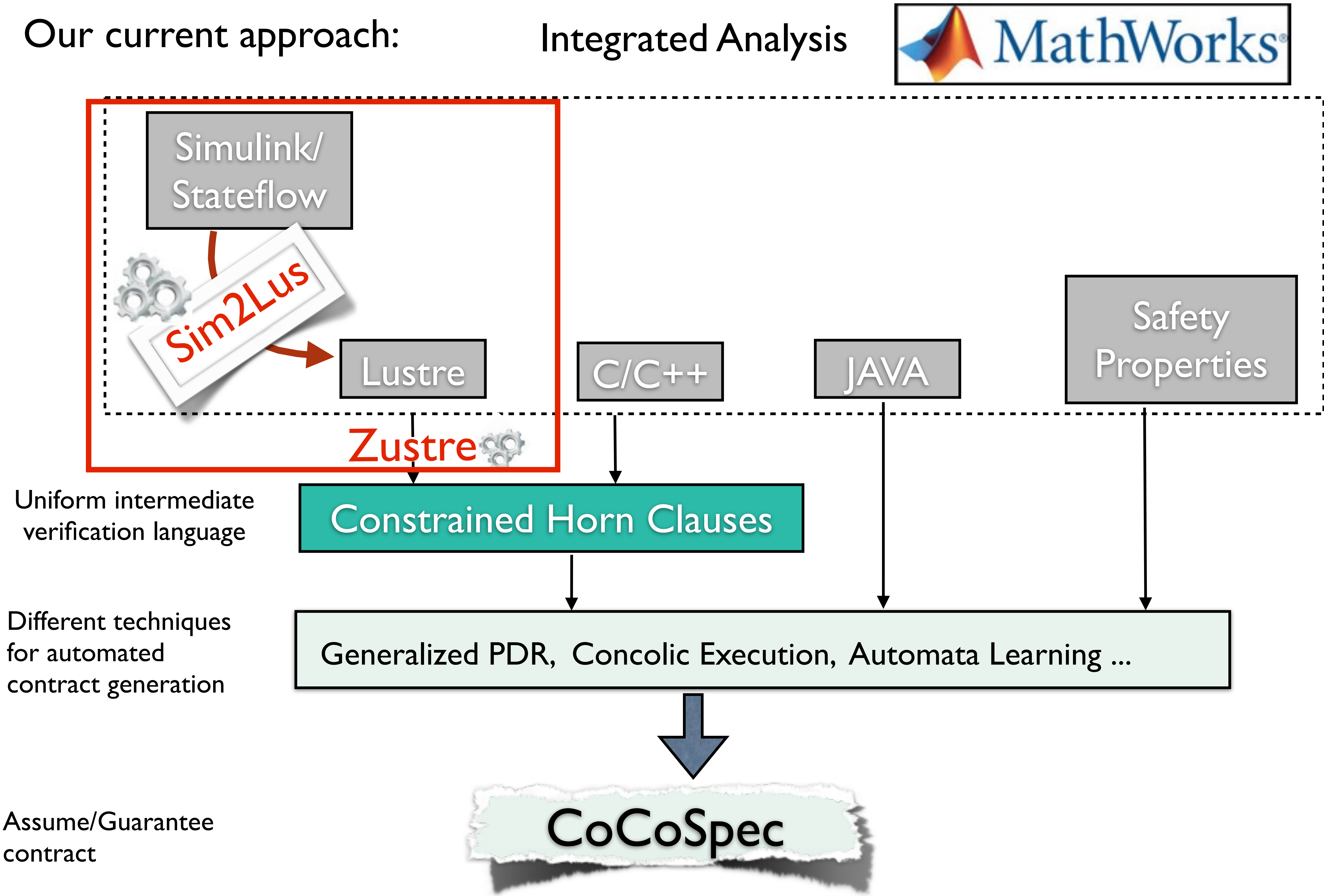
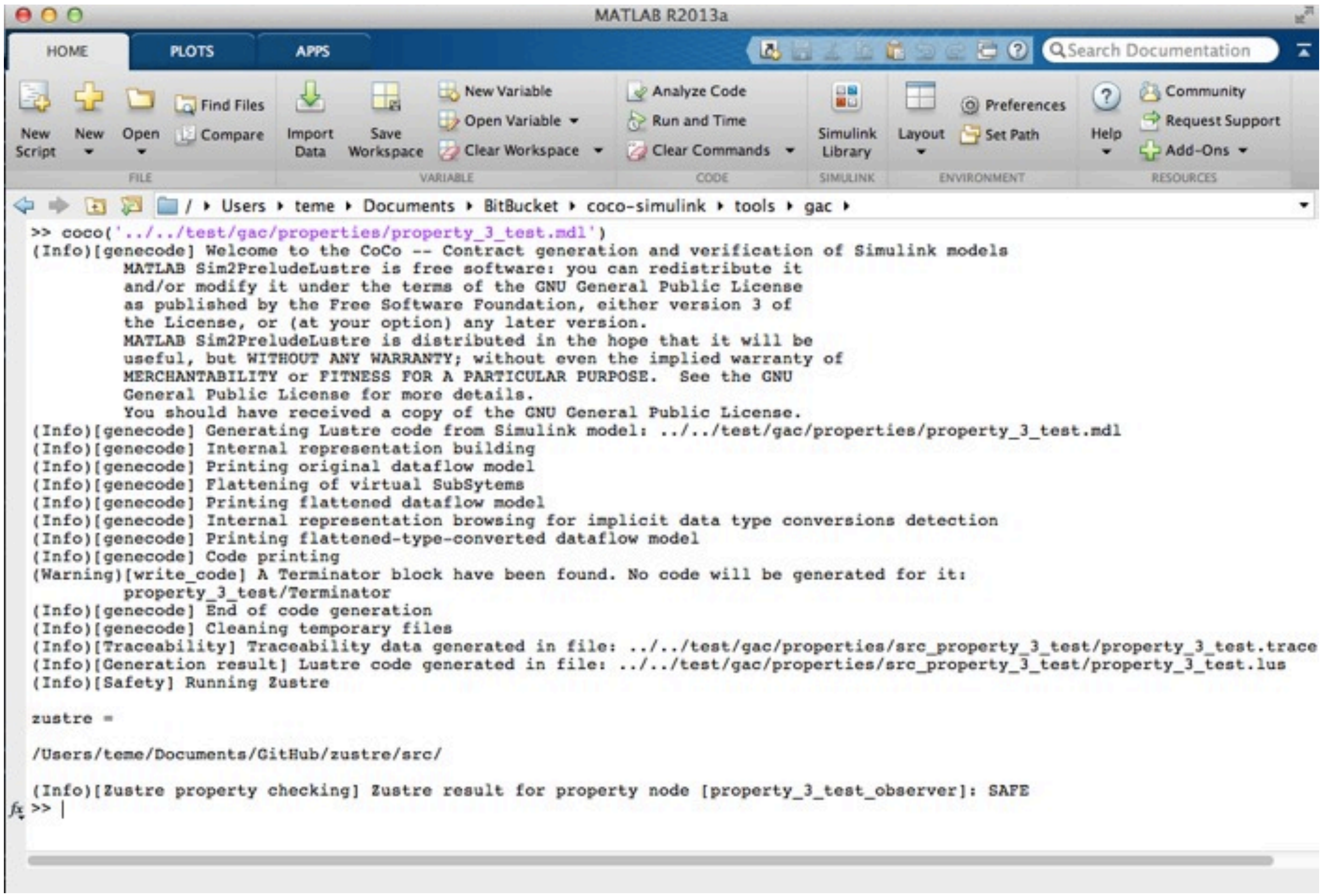


Integrated Analysis Framework



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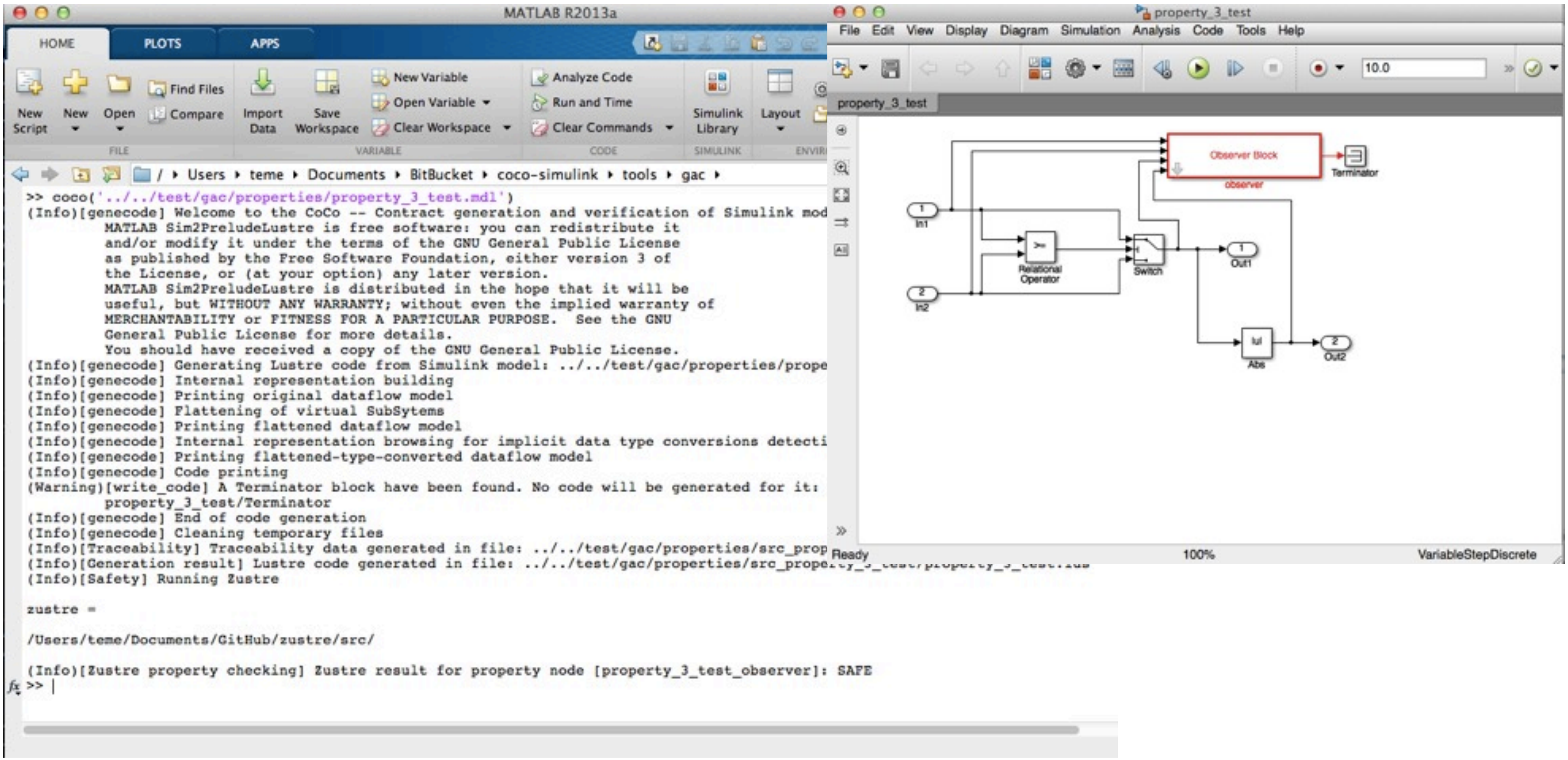
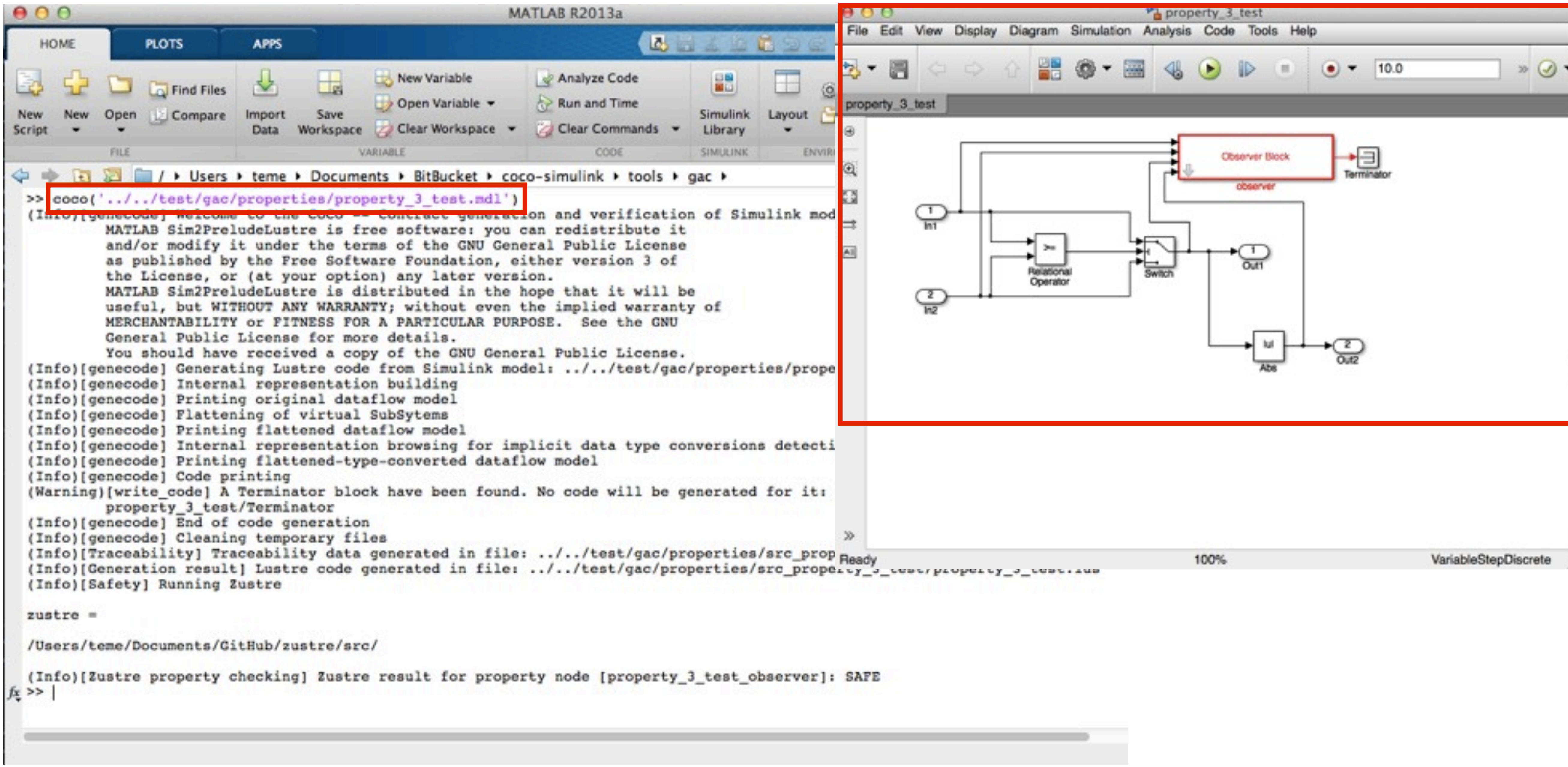


Specify safety properties
using synchronous observers

Integrated Analysis Framework



Specify safety properties
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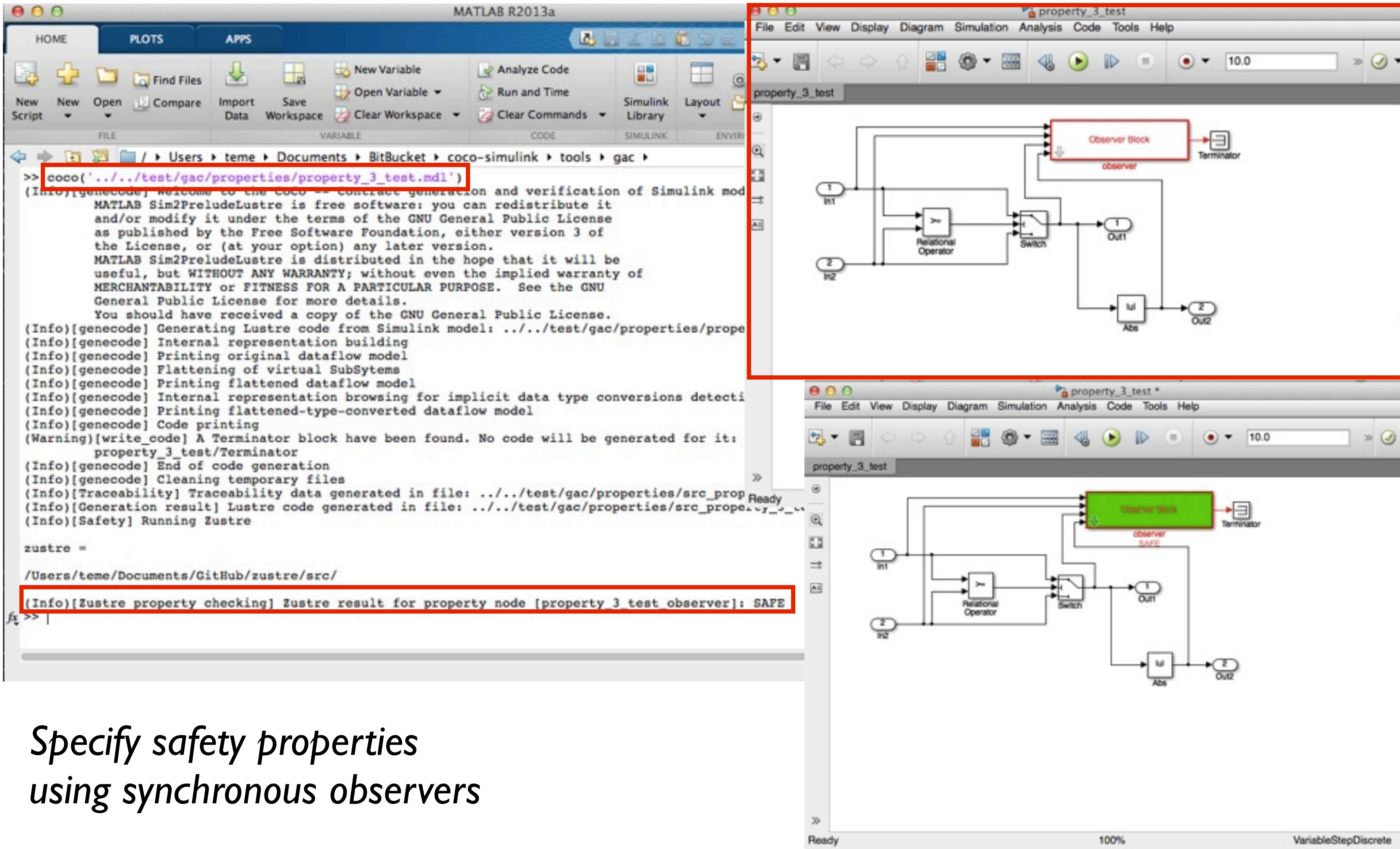
Integrated Analysis Framework

MathWorks



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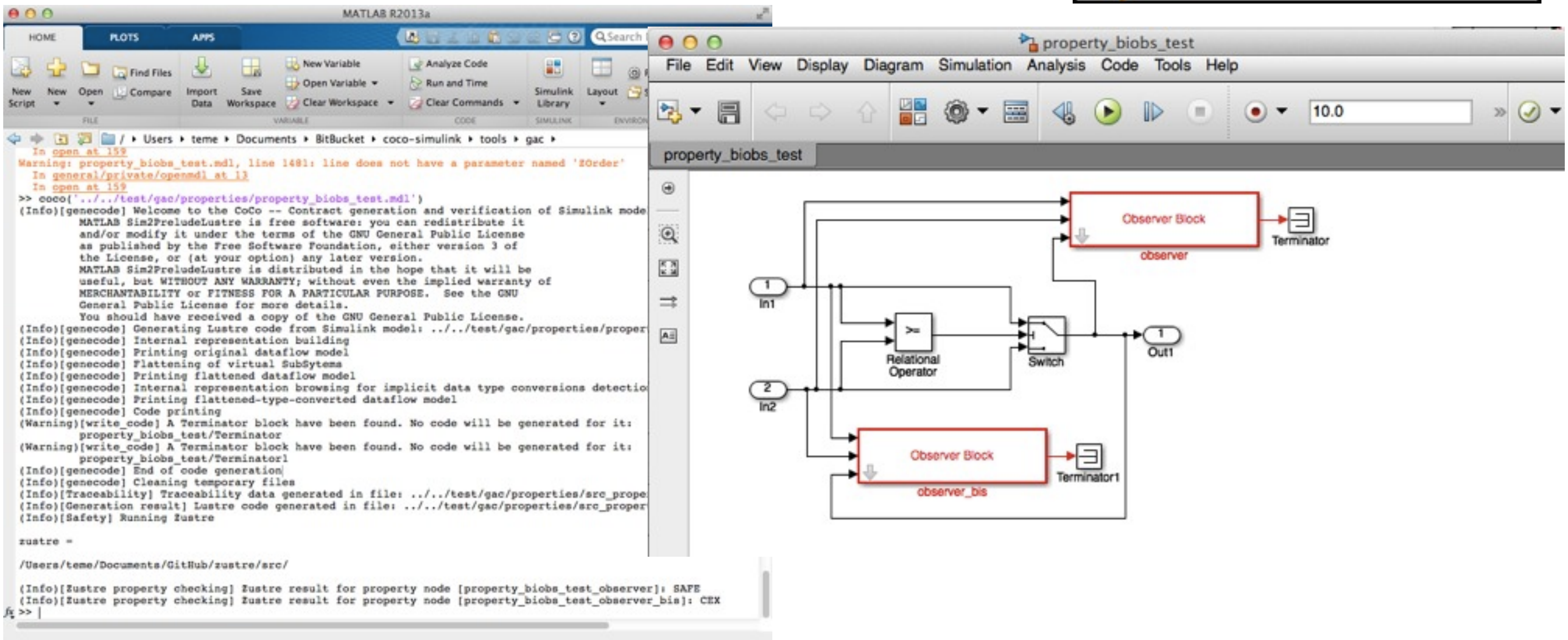

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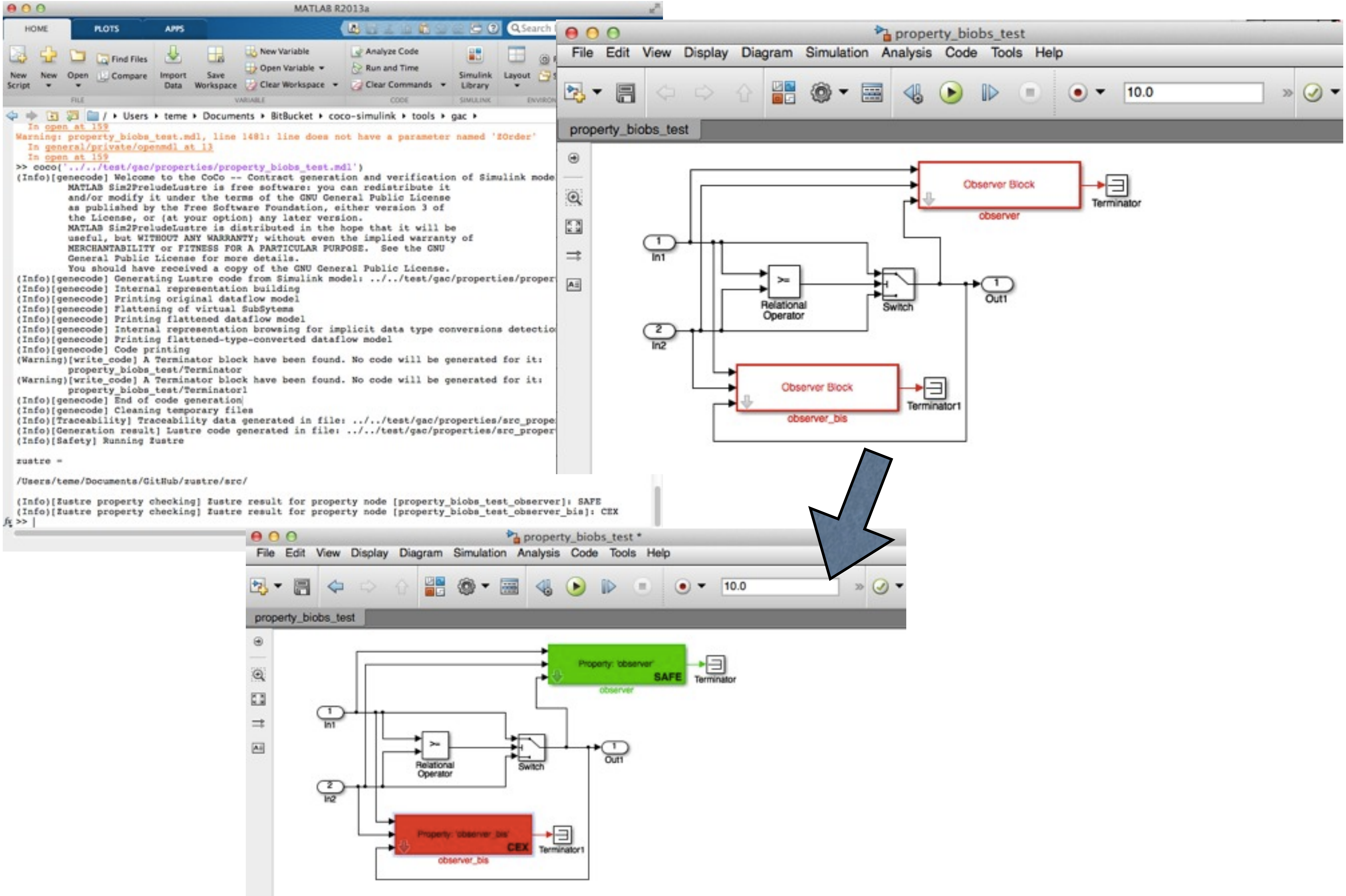

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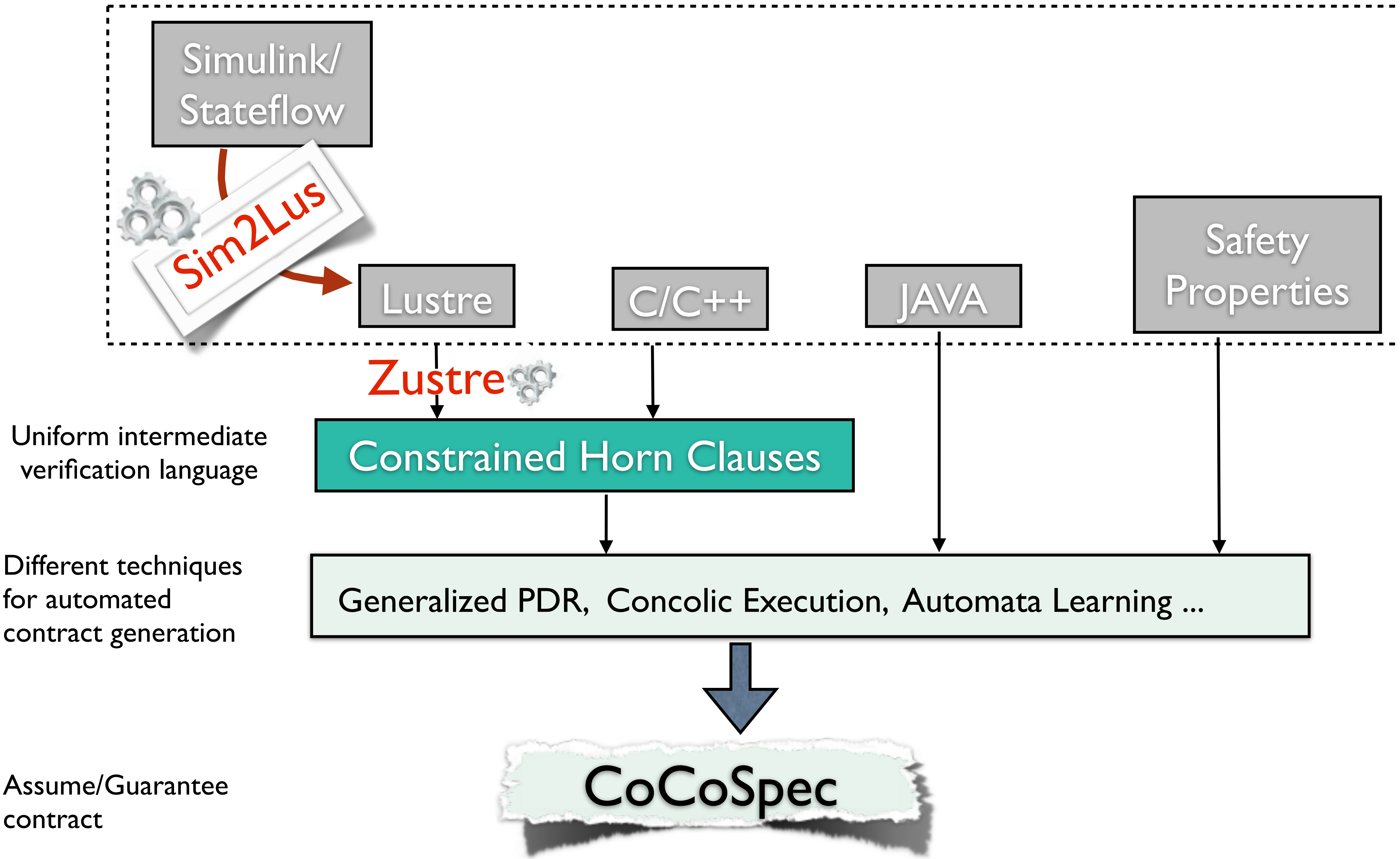

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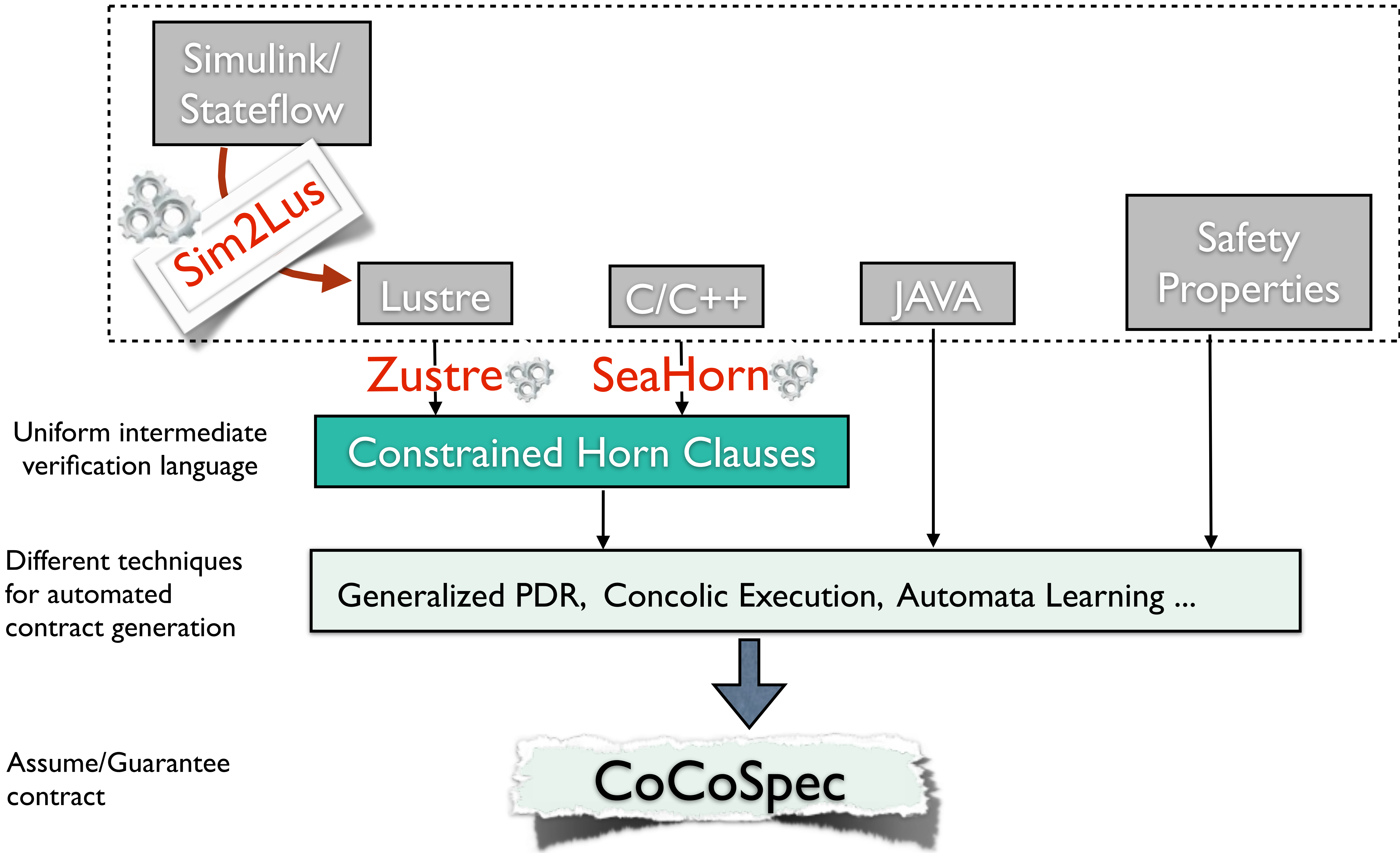
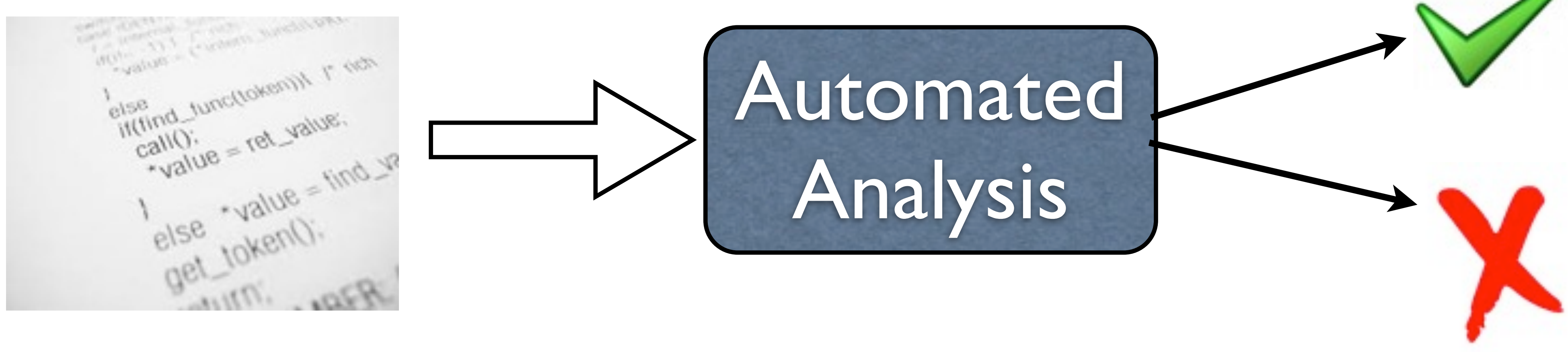


SeaHorn

A framework for verifying LLVM-based programs

Program
+ Safety properties



NB. (i) Current version targets C programs
(ii) and does not generate CoCoSpec

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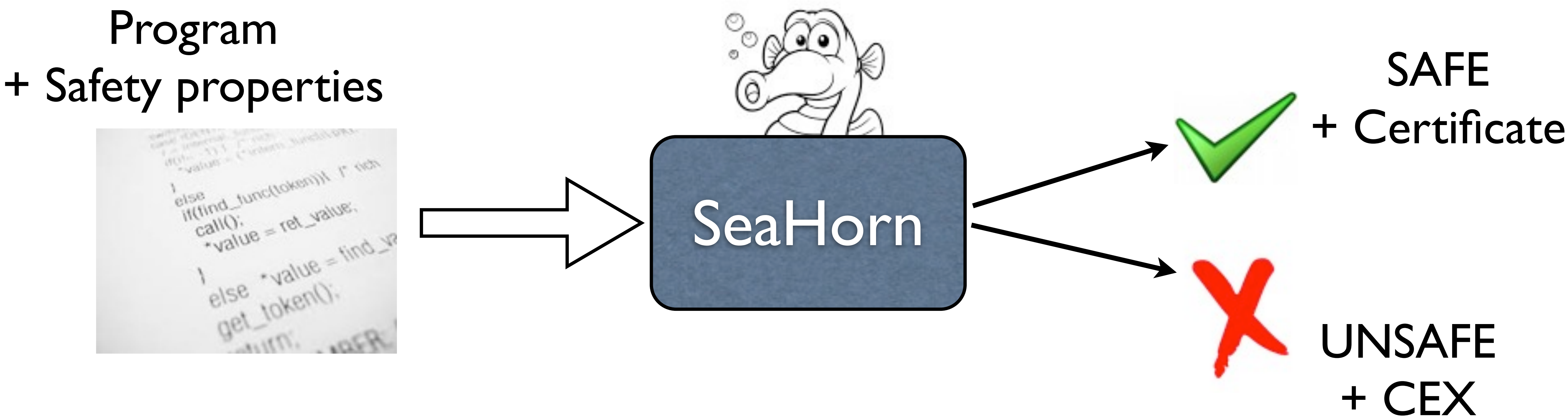

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A framework for verifying LLVM-based programs

Dr. Arie Gurfinkel
(SEI / CMU)

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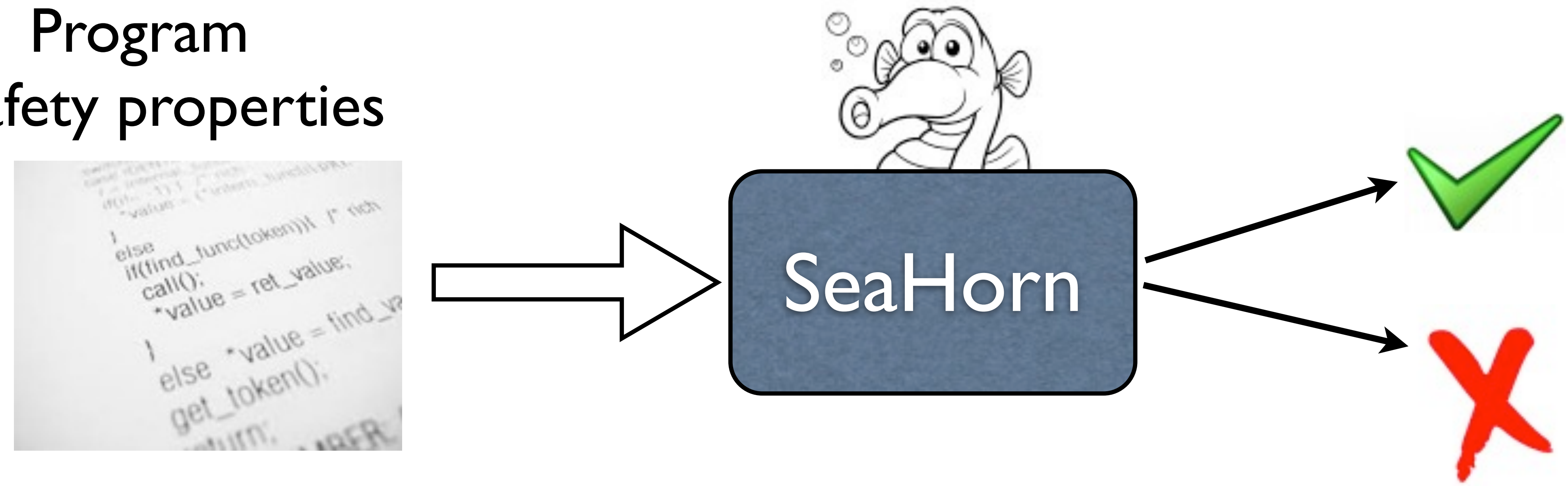

SAFE
+ Certificate

UNSAFE
+ CEX

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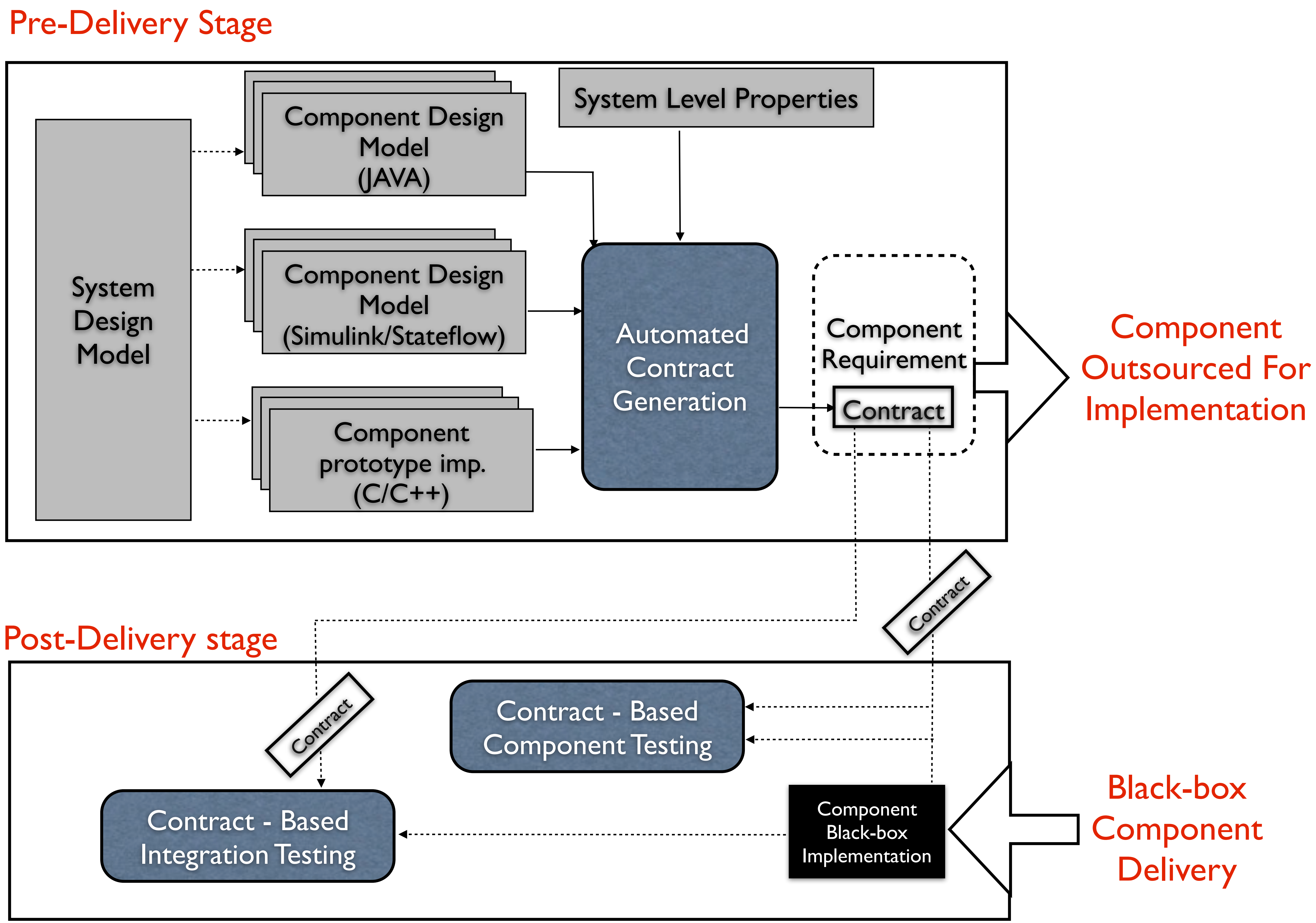
Post-delivery verification stage

Two Stage solution for virtual integration



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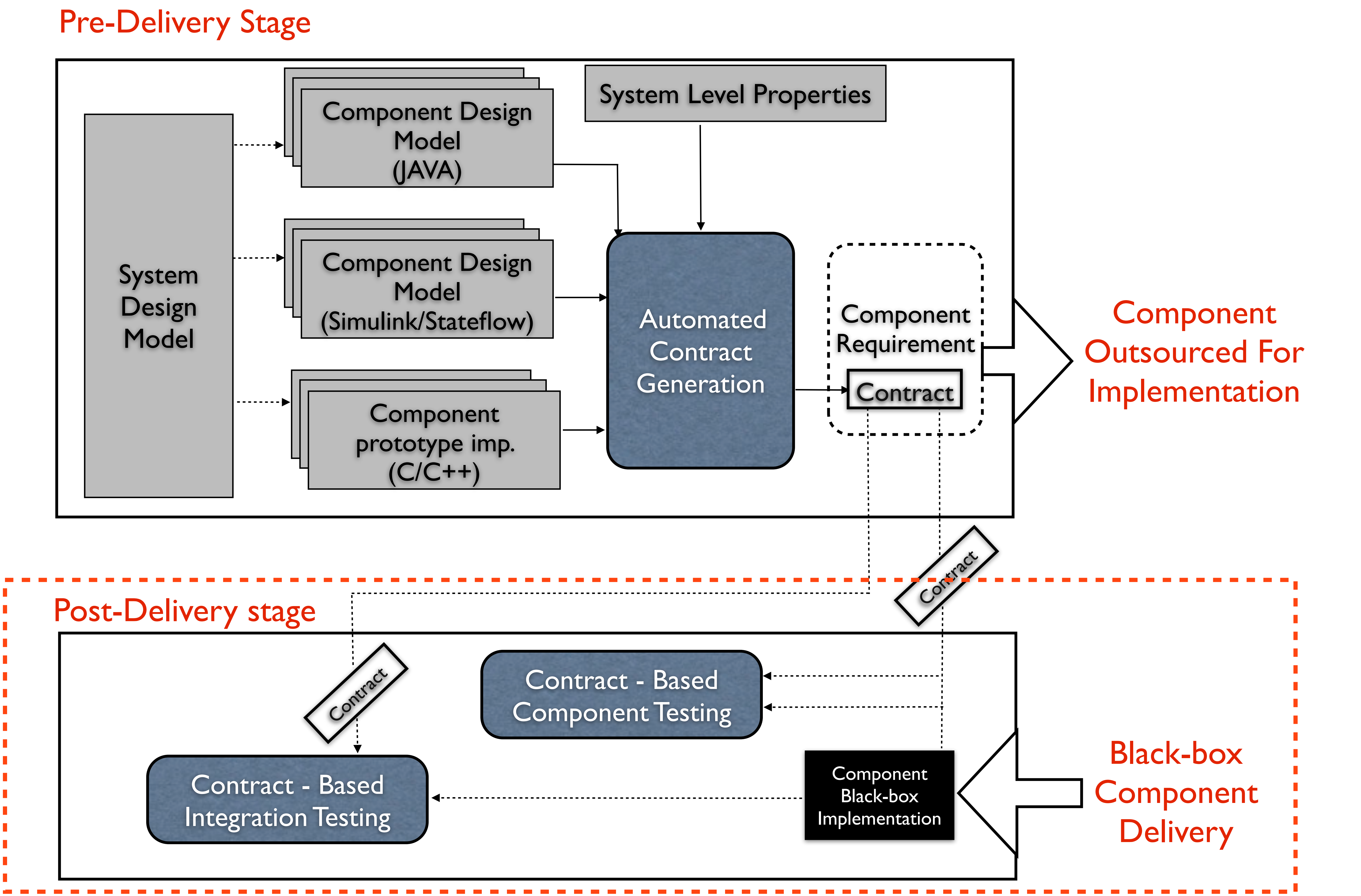

Post-delivery Verification Stage

Component Black-box Implementation $\models^{?}$ CoCoSpec

Contract-based test generation

- Test generation via Bounded Model Checking
- Coverage and mutation oriented
- TestEAS: test execution and analysis system

Test generation via BMC

Components are represented as transition systems:

- s is the vector of state variables of the system
- $\mathcal{I}(s_0)$ is the init predicate, true if s_0 is initial
- $\mathcal{T}(s_i, s_{i+1})$ is the transition predicate, true if s_{i+1} is a successor of s_i

Given a test objective $\mathcal{O}(s)$, we can query an *SMT solver* for a trace of k states leading to it:

$$\mathcal{I}(s_0) \wedge \mathcal{T}(s_0, s_1) \wedge \cdots \wedge \mathcal{T}(s_{k-2}, s_{k-1}) \wedge \mathcal{O}(s_{k-1})$$

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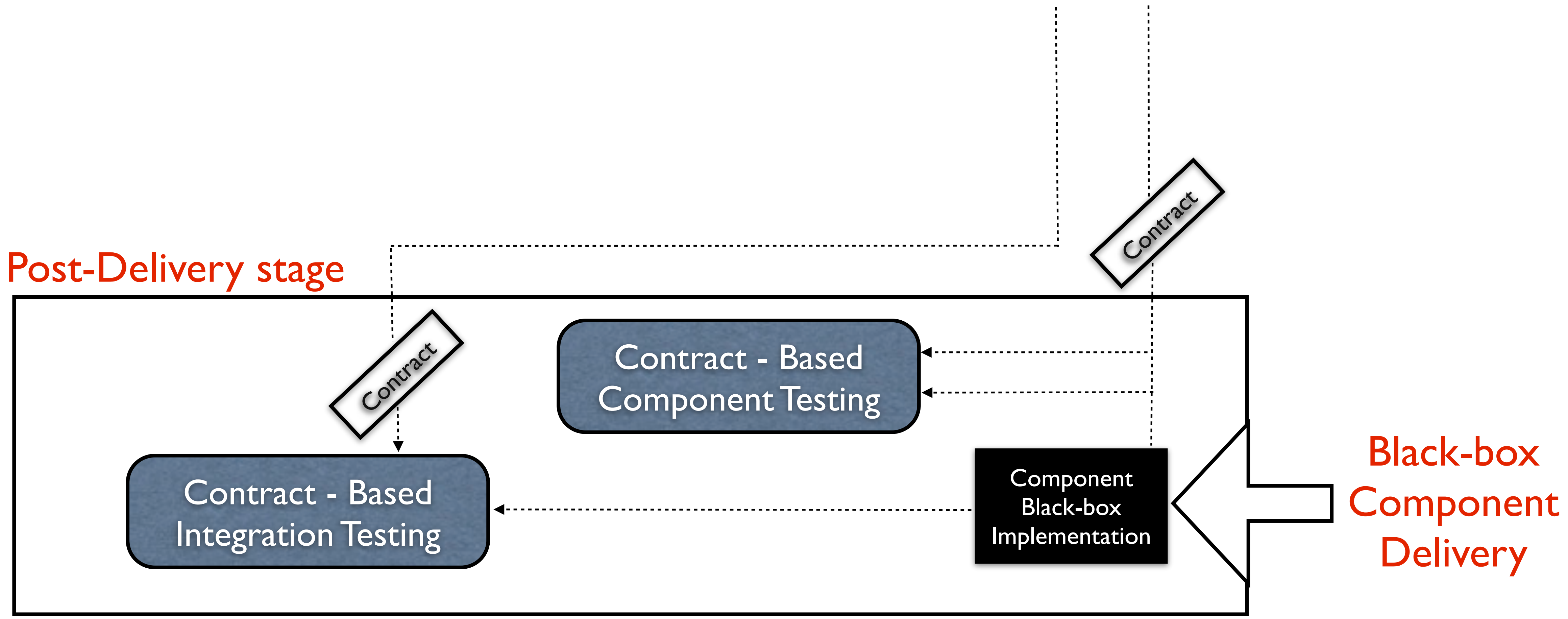
- Coverage-oriented: the set of test cases are generated to realize some coverage criterion on the source file, *e.g.* (O)MC/DC.
- Mutation-based: alter the syntax of the source code and generate test cases failing on (*killing*) the mutants.

Post-delivery Integration testing



A. Cimatti et al :"*A property-based proof system for contract based design*". In SEAA 2012.

W. Damm et al :"*Using contract-based component specifications for virtual integration and architecture design*". In DATE 2011.

E. Kesseler et al :"*Assessing COTS software in a certifiable safety-critical domain*". In Information Systems Journal 2008.

A. Benveniste et al :"*Multiple Viewpoint Contract-based Specification and Design*". In FMCO 2007.

Post-delivery integration testing

- pre-delivery:
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Post-delivery integration testing

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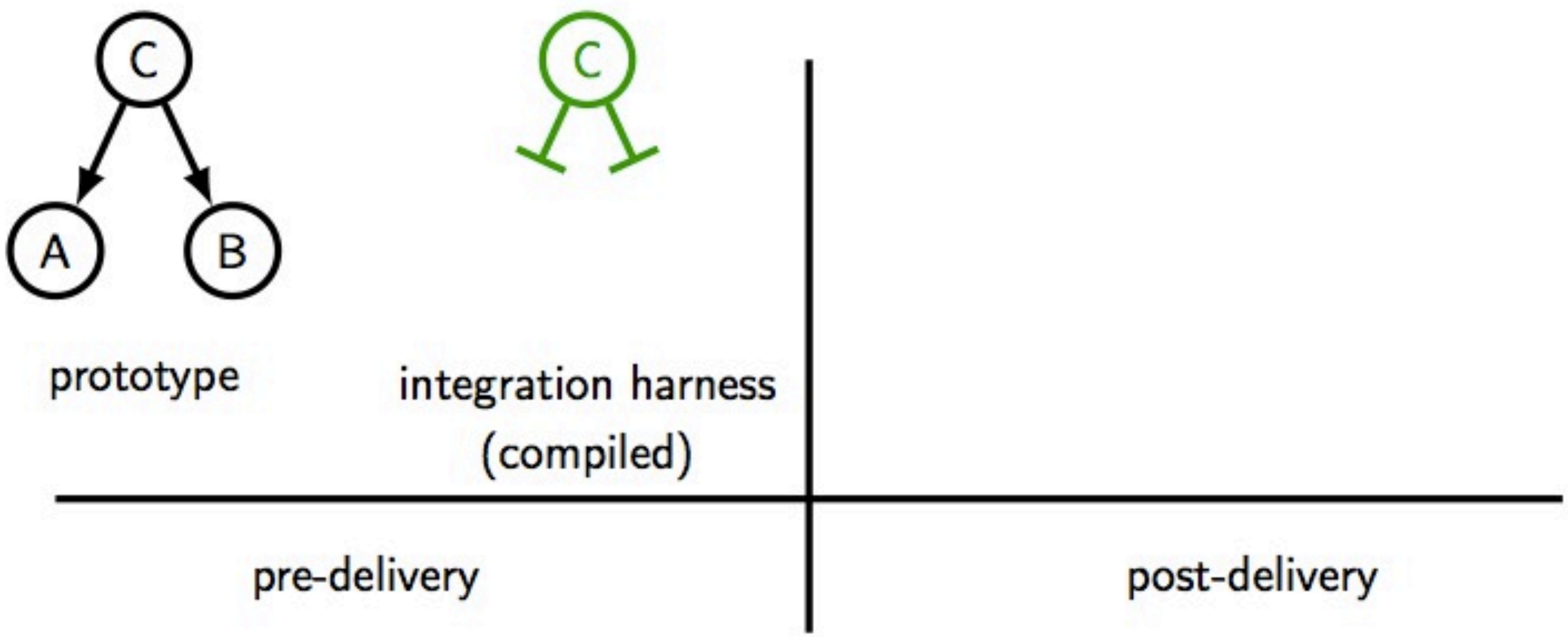

Post-delivery integration testing

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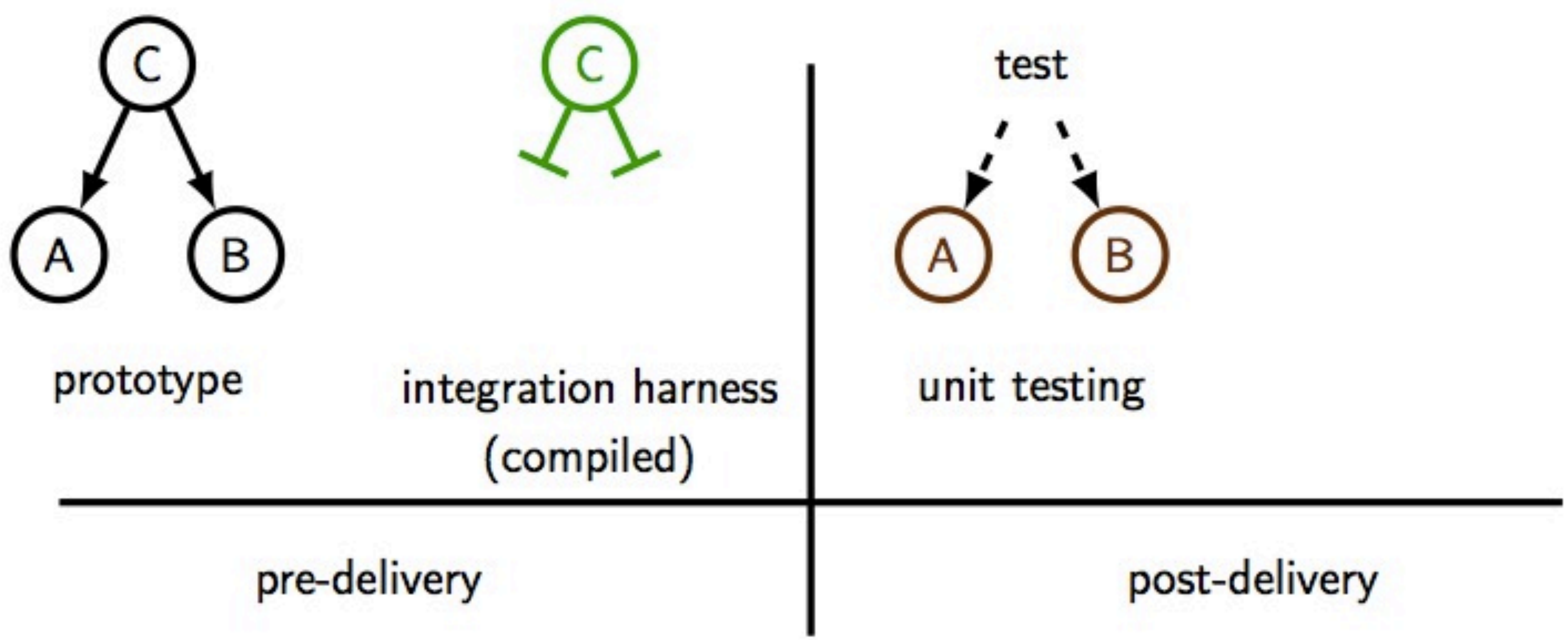
- post-delivery:
  - unit testing of the binaries,



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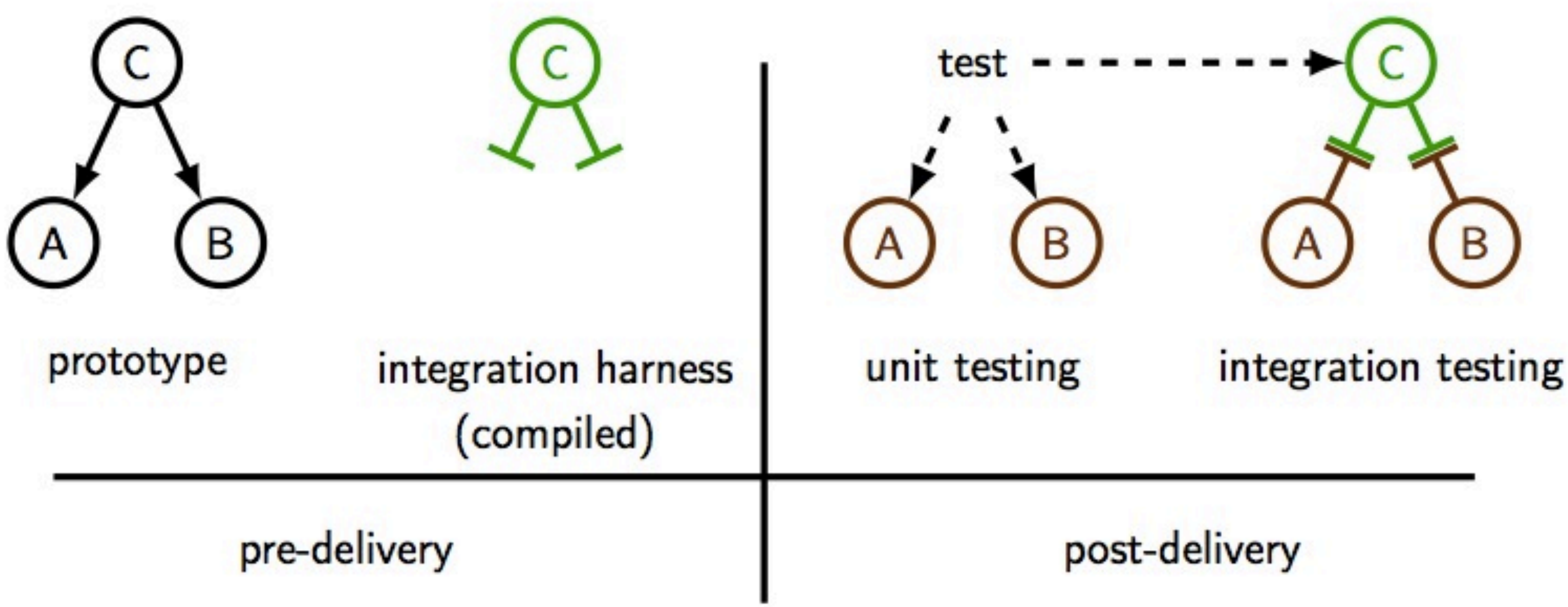

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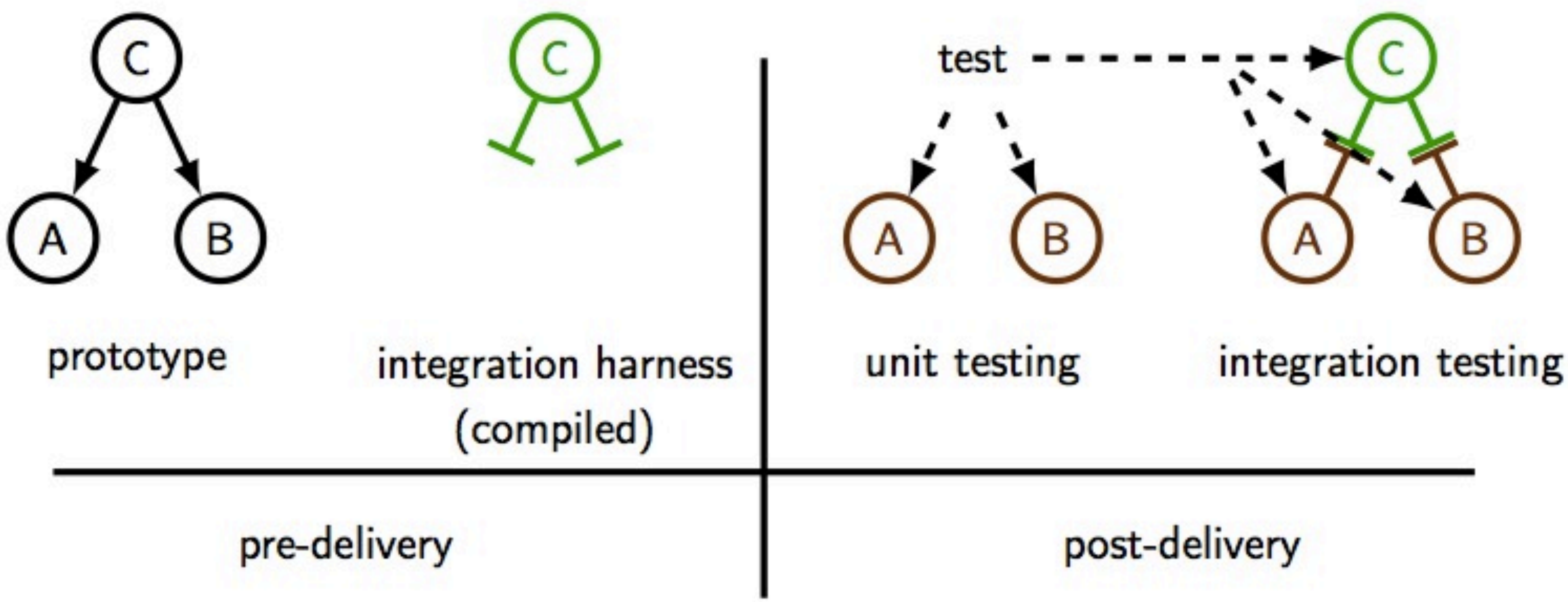

FCS Case Studies

Transport Class Model (TCM)

The TCM – a twin-engine tube and wings configuration aircraft simulation, scaled up from the Generic Transport Model (GTM).

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UAV-sized (wingspan ~6ft) version of a plane with geometry similar to a transport -class aircraft

Intended as an experimental platform for controls and health management system

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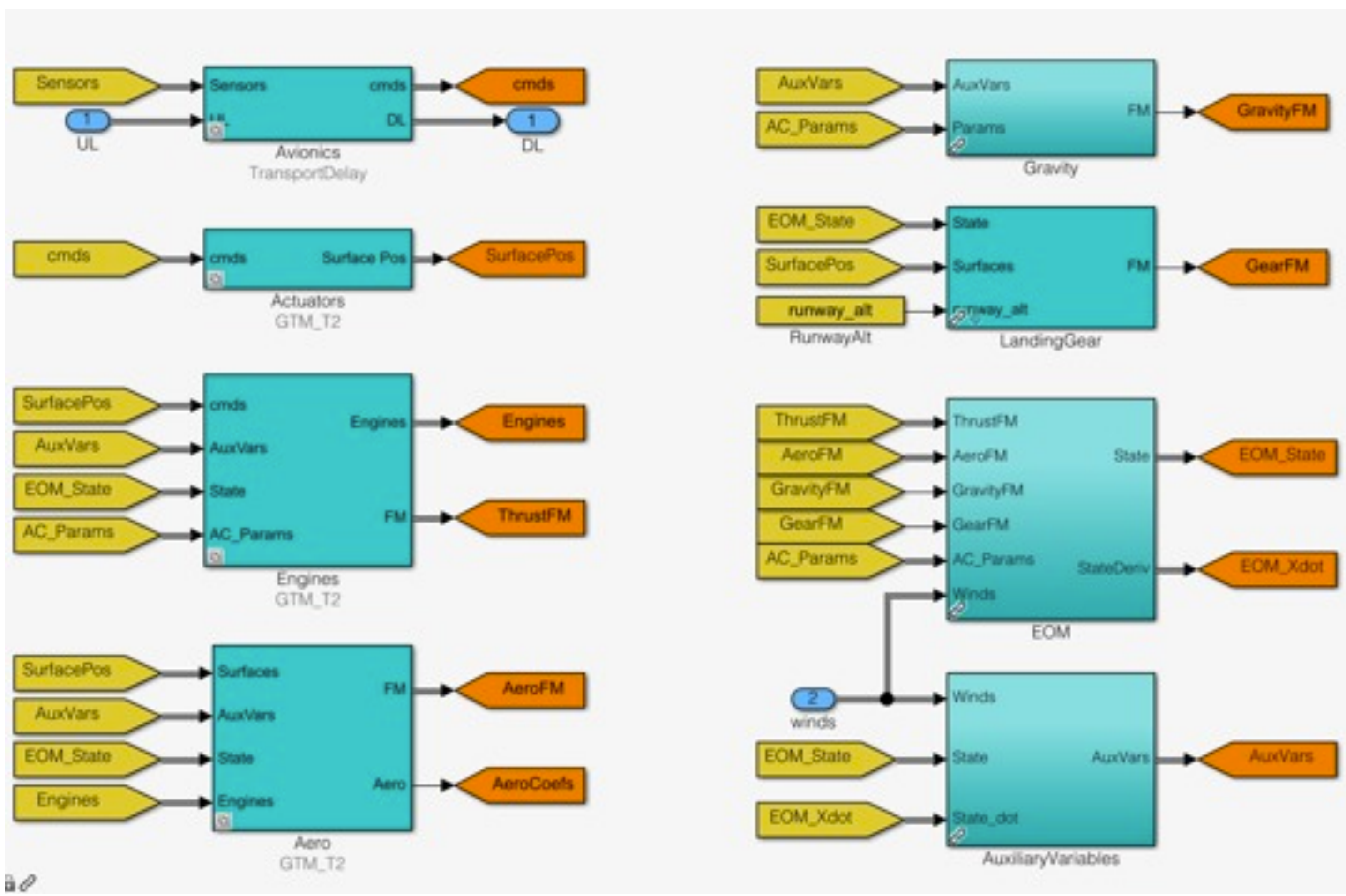
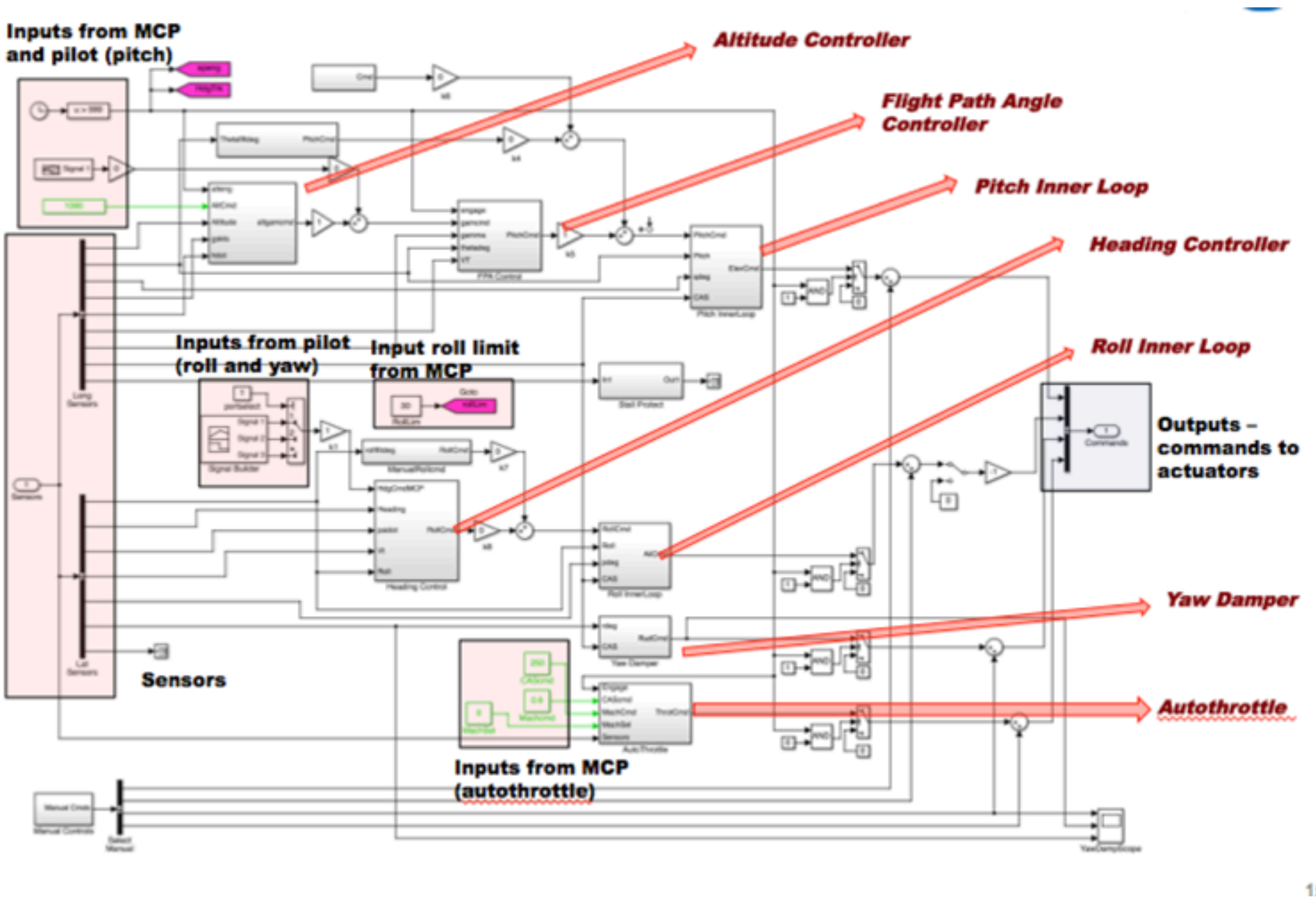


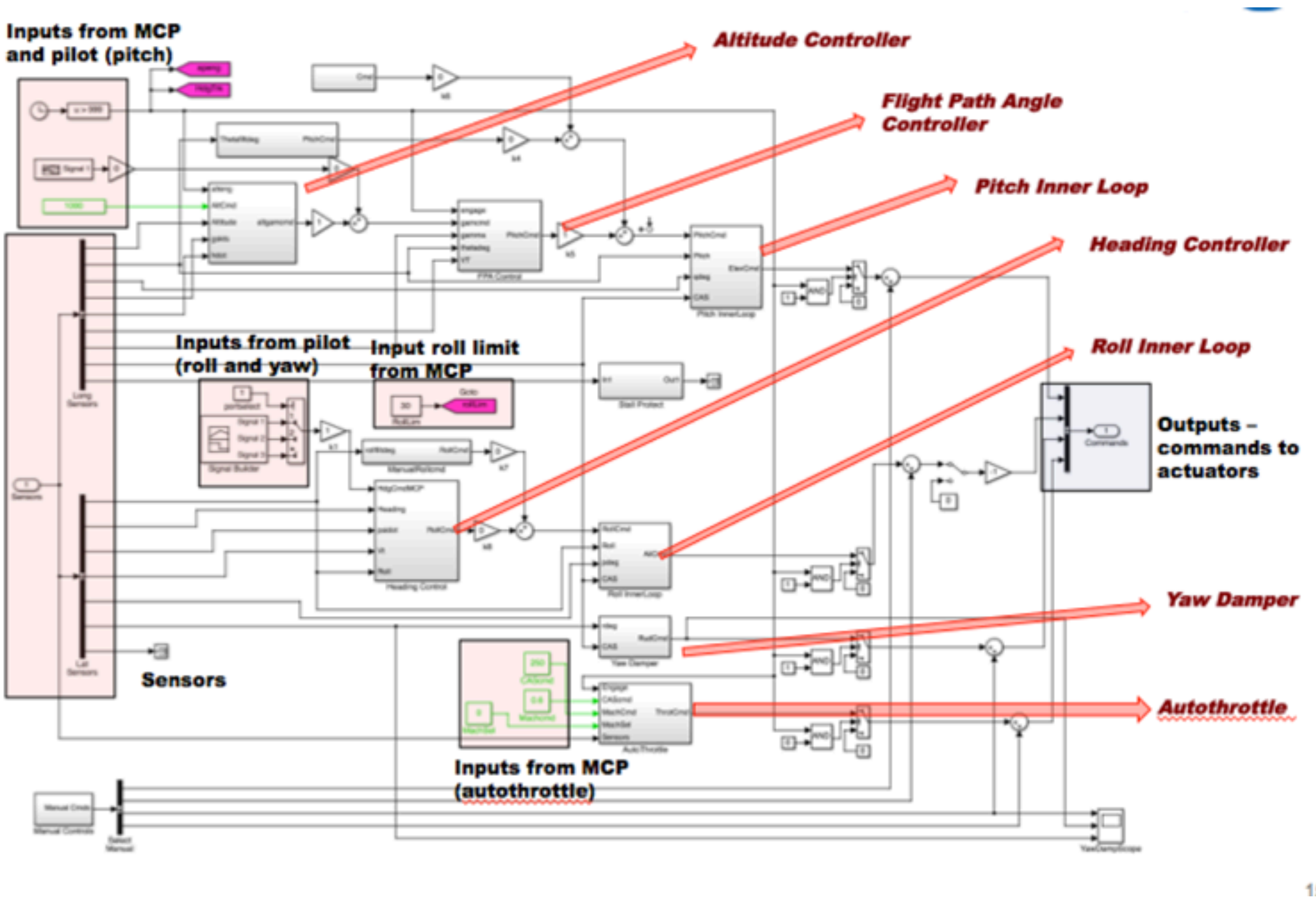
Intended as an experimental platform for controls and health management system

Simulink simulator for the avionics (transport delay), actuators, engines, landing gear, aero, sensors (including noise) ...

TCM Autopilot



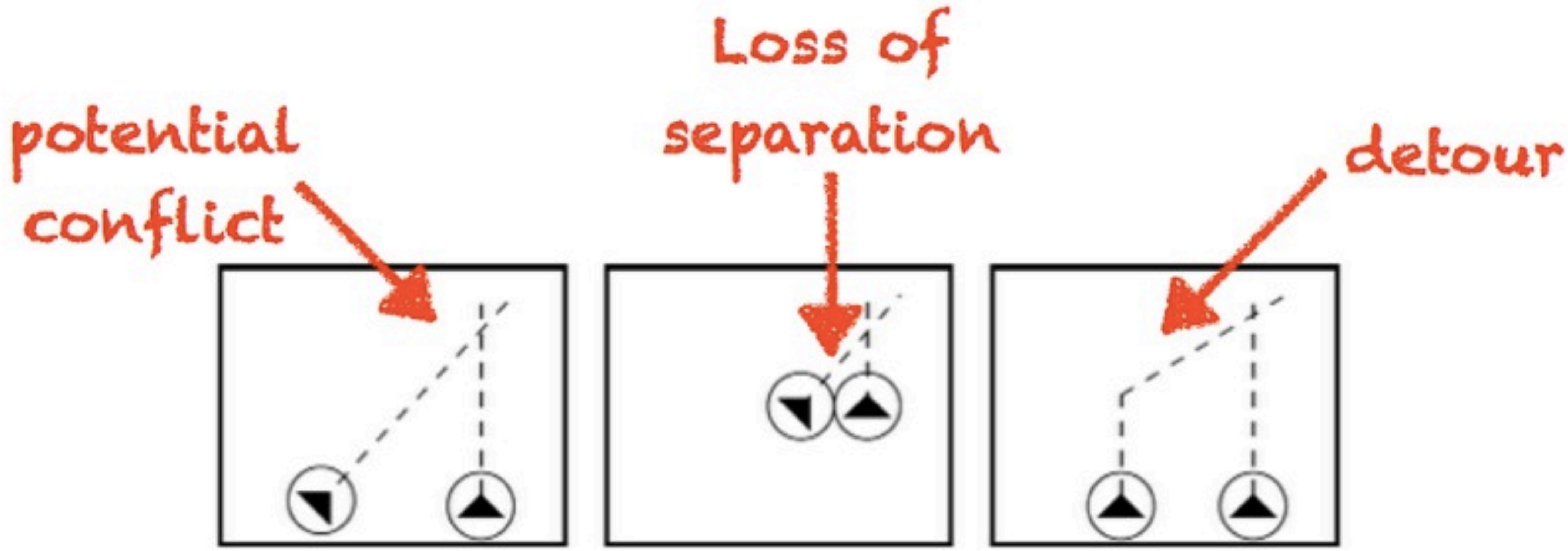
TCM Autopilot



Kahsai et. al. "*Verifying the safety of a flight critical software*". FM'15.

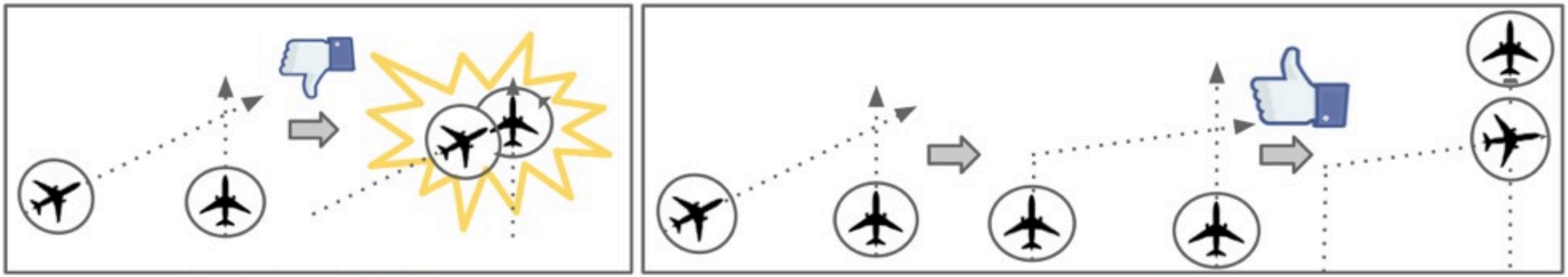
- Safety verification via model checking
- Manual decomposition of 'hard' safety properties

NextGen Air-Traffic Control



- NextGen. New national airspace system in the US.
- Air-Traffic Control. Separation assurance: resolution of potential future conflicts between aircrafts.
- Loss of Separation. Two airplanes come closer than a specified safe distance (horizontally or vertically)

NextGen Air-Traffic Control



Unresolved conflict Resolved conflict

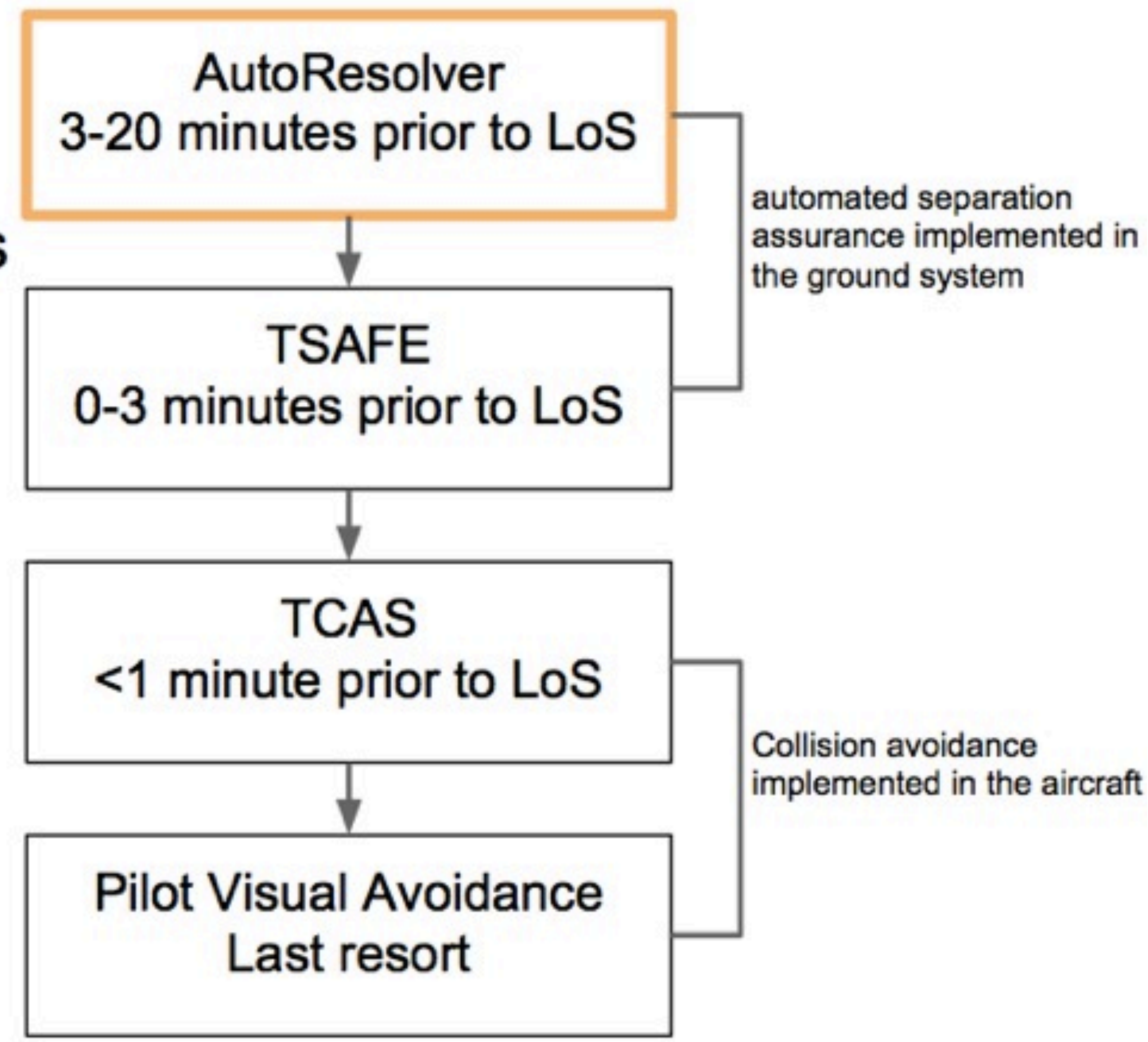
- Air-traffic control. Provides separation assurance by resolving potential future conflicts between aircraft
- Loss of separation. Airplanes come closer than a specified safe distance (horizontally and vertically)

NextGen Air-Traffic Control

NextGen component. 3-20 min time horizon

Java prototype developed at NASA Ames

- 2,500 classes, 150kloc (w/ ACES)
- 150 classes, 65kloc (w/o ACES)
- (+ NASA Worldwind, etc.)



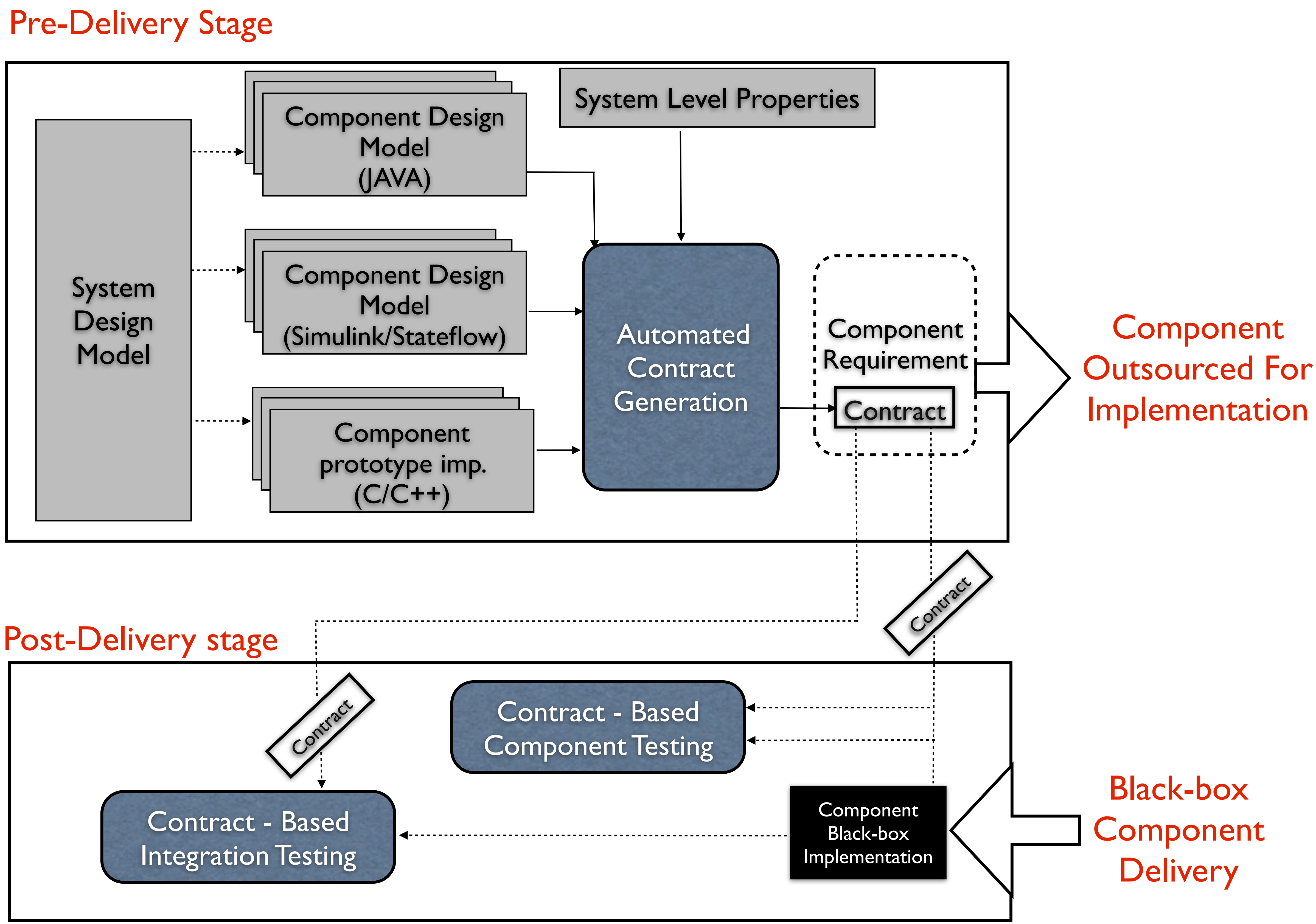
Summary

This talk ....

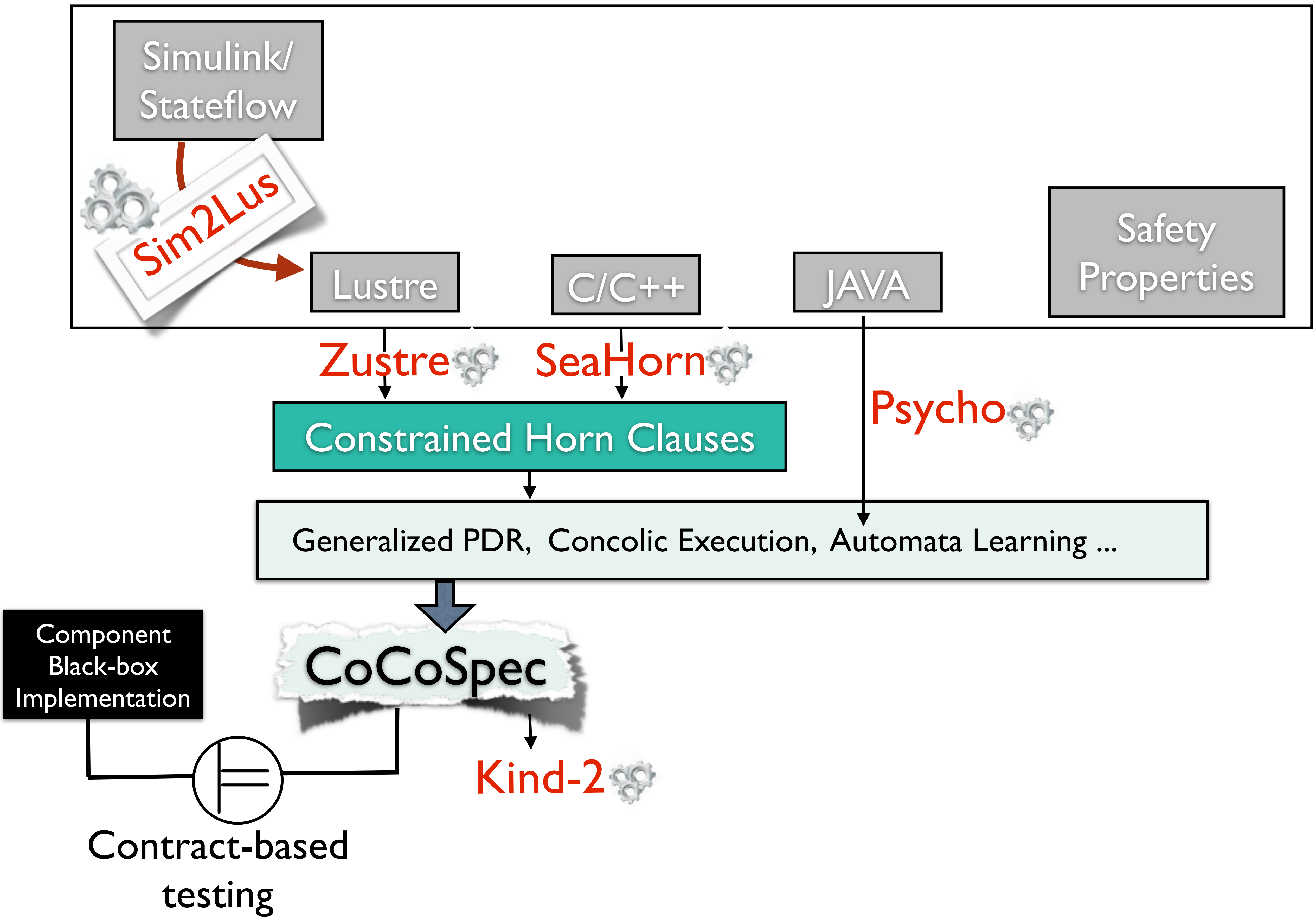
.... outsourcing in flight critical software

.... virtual integration of outsourced components

Two Stage solution for virtual integration



tools tools and tools



Thank you

Contact information

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web (work): http://ti.arc.nasa.gov/profile/tkahsaia/
web (personal): http://www.lememta.info/