Formal Verification of User-Level Real-Time Property Patterns

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Outline

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Real-Time Requirements

Commonly required during the development of concurrent systems

- worst case execution time
- worst case traversal time
- state time duration
- schedulability
- etc.

Core issues for engineers using formal methods

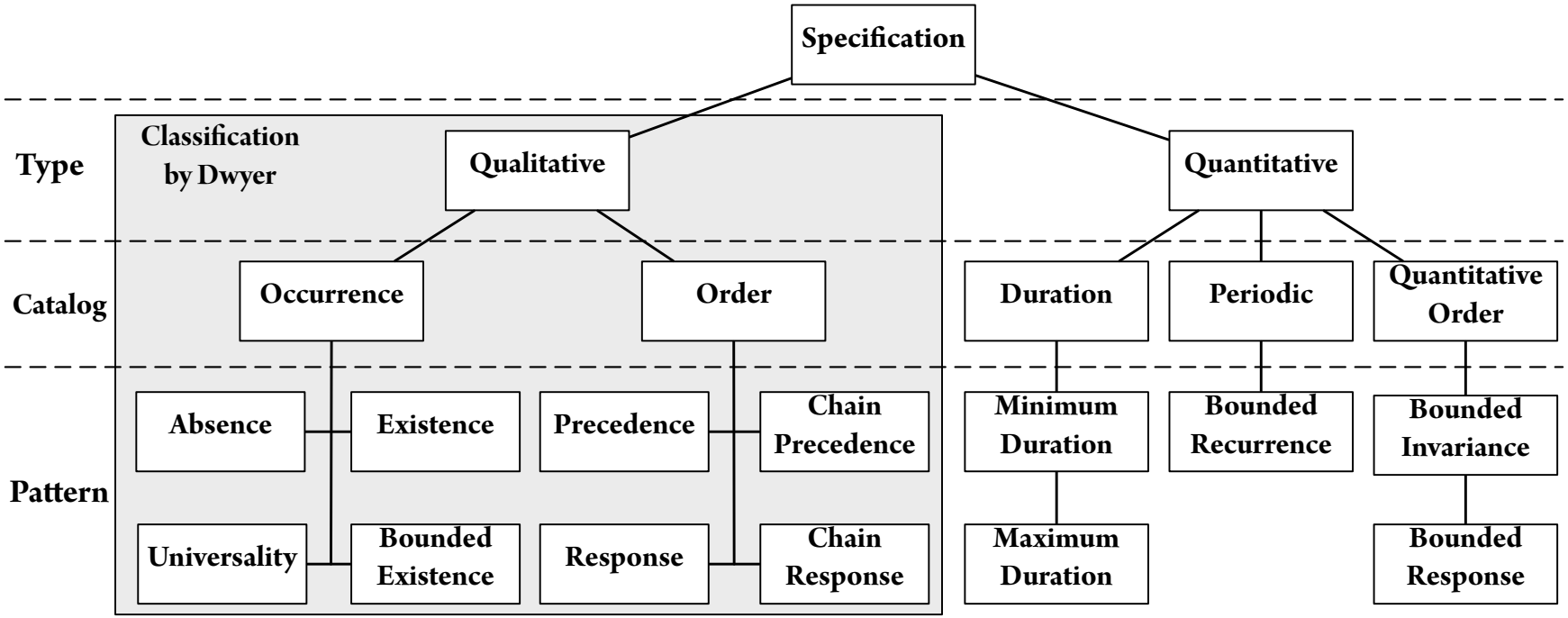
- Ergonomy (user oriented expressiveness) of temporal logics
- Scalability of model checking

Property Pattern Approach

User level expressiveness and Scalability

- Ease the use of formal methods by providing reusable solutions
- Decompose complex problems to simpler ones, with a lower complexity
- Decrease the verification cost
- Qualitative patterns proposed by Dwyer cover 90% temporal requirements.
- Quantitative patterns are extended by Konrad.

Hierarchy of Time Property Patterns



Property-Driven Approach

User level expressiveness and Scalability

Principle

The formal activities in the development process are based on the purpose of property-verification-ease.

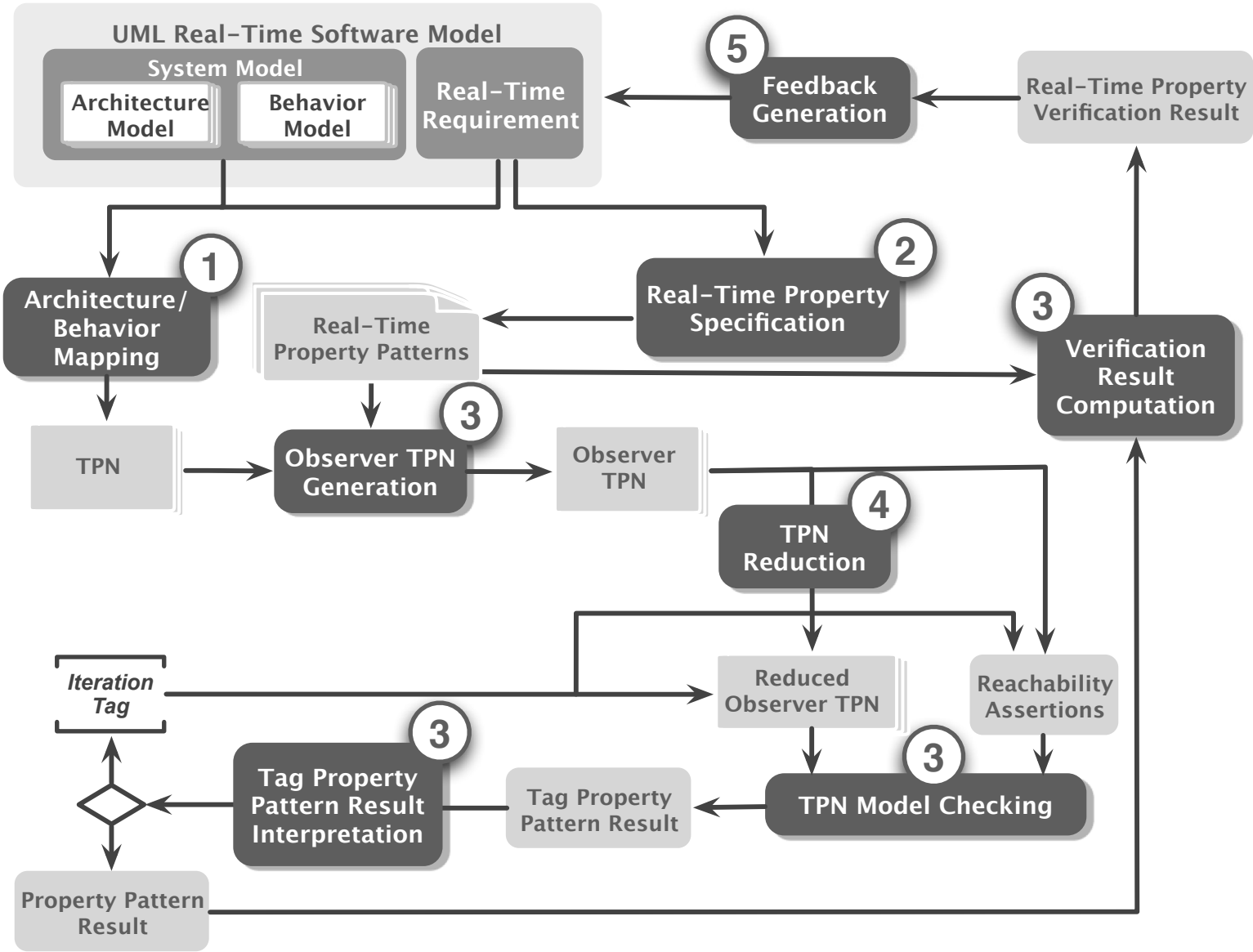
Experiments by B. Combemale

Verification of structural and temporal properties in xSPEM models.
Needs for more scalable methods to verify quantitative properties.

Steps of our work

1. Characterizing properties.
2. Characterizing observable states and events.
3. Expressing real-time properties: property patterns.
4. Defining denotational semantics to Time Petri Net (TPN) + observers and reachability assertions.
5. Reducing state space: property-specific reduction for TPN.
6. Validating model and feedback: automated failure analysis.

Challenge & Property-Driven Verification Framework



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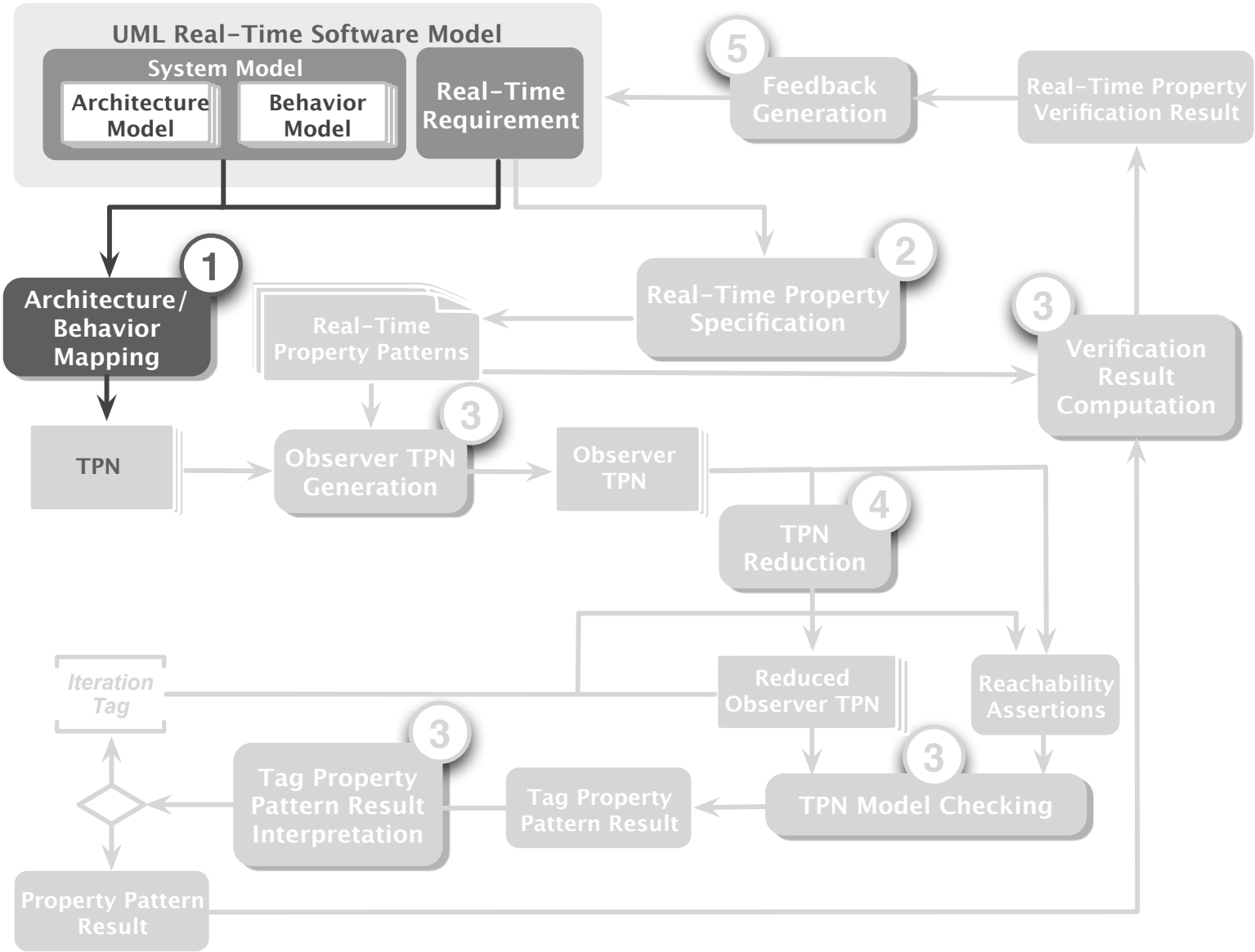

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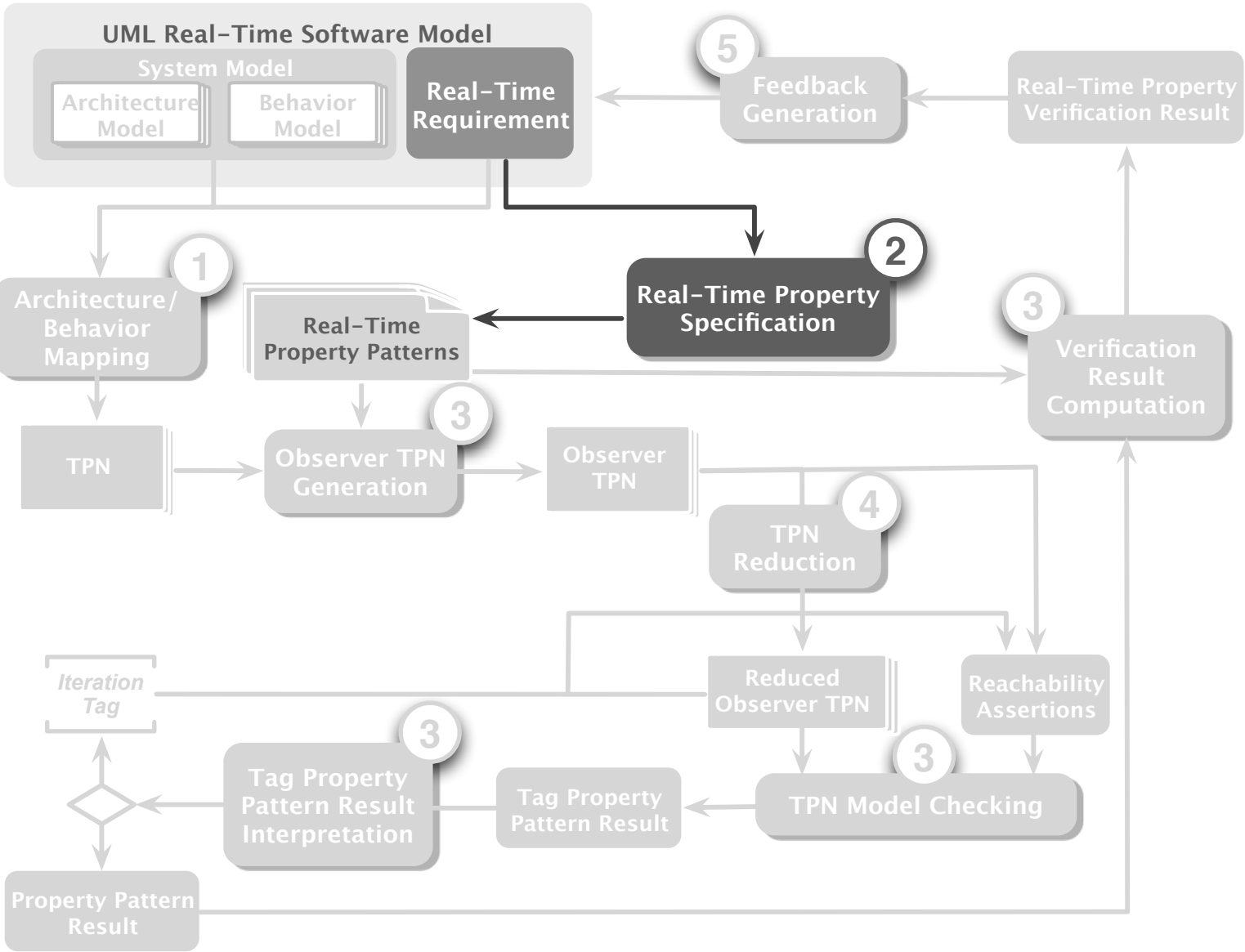

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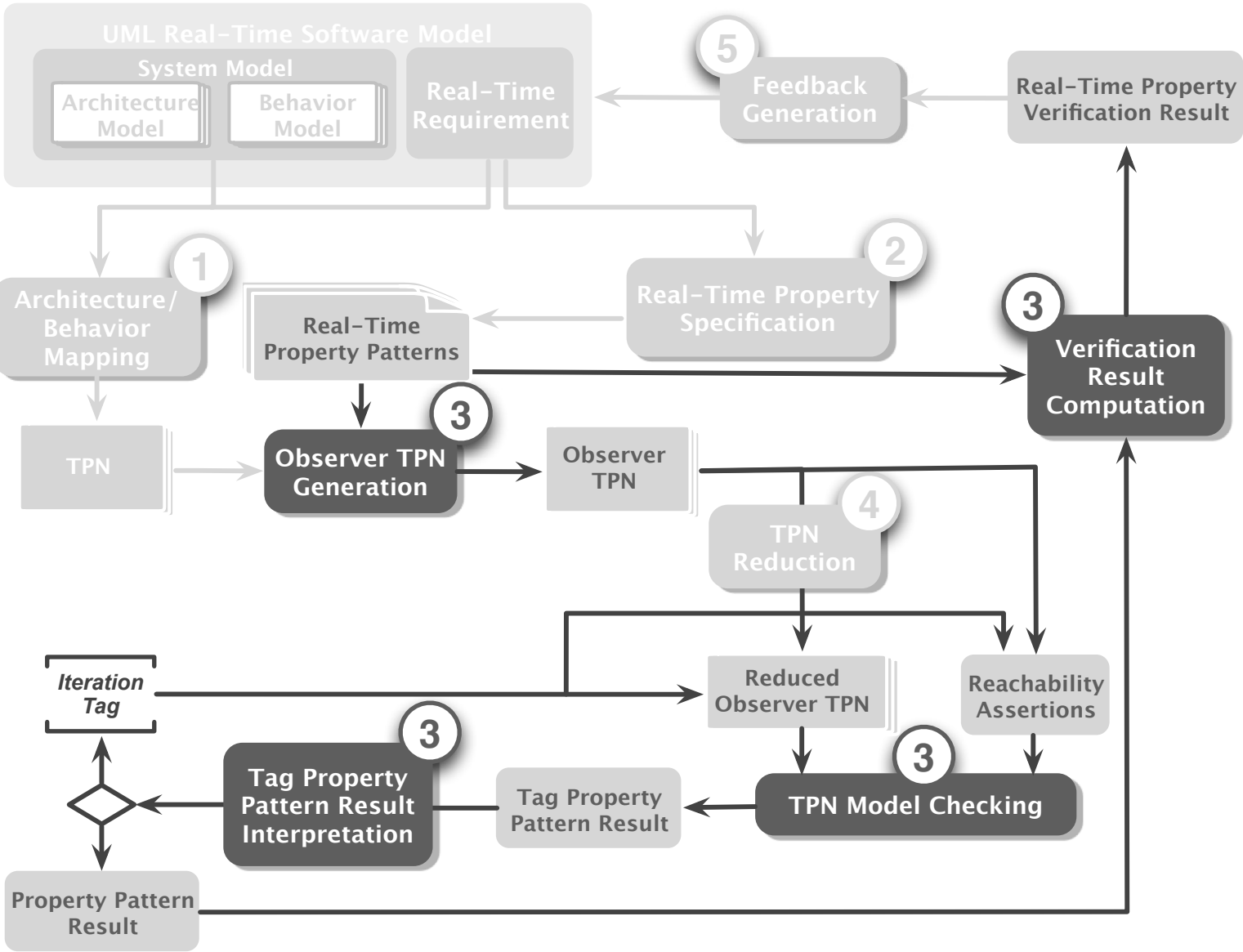

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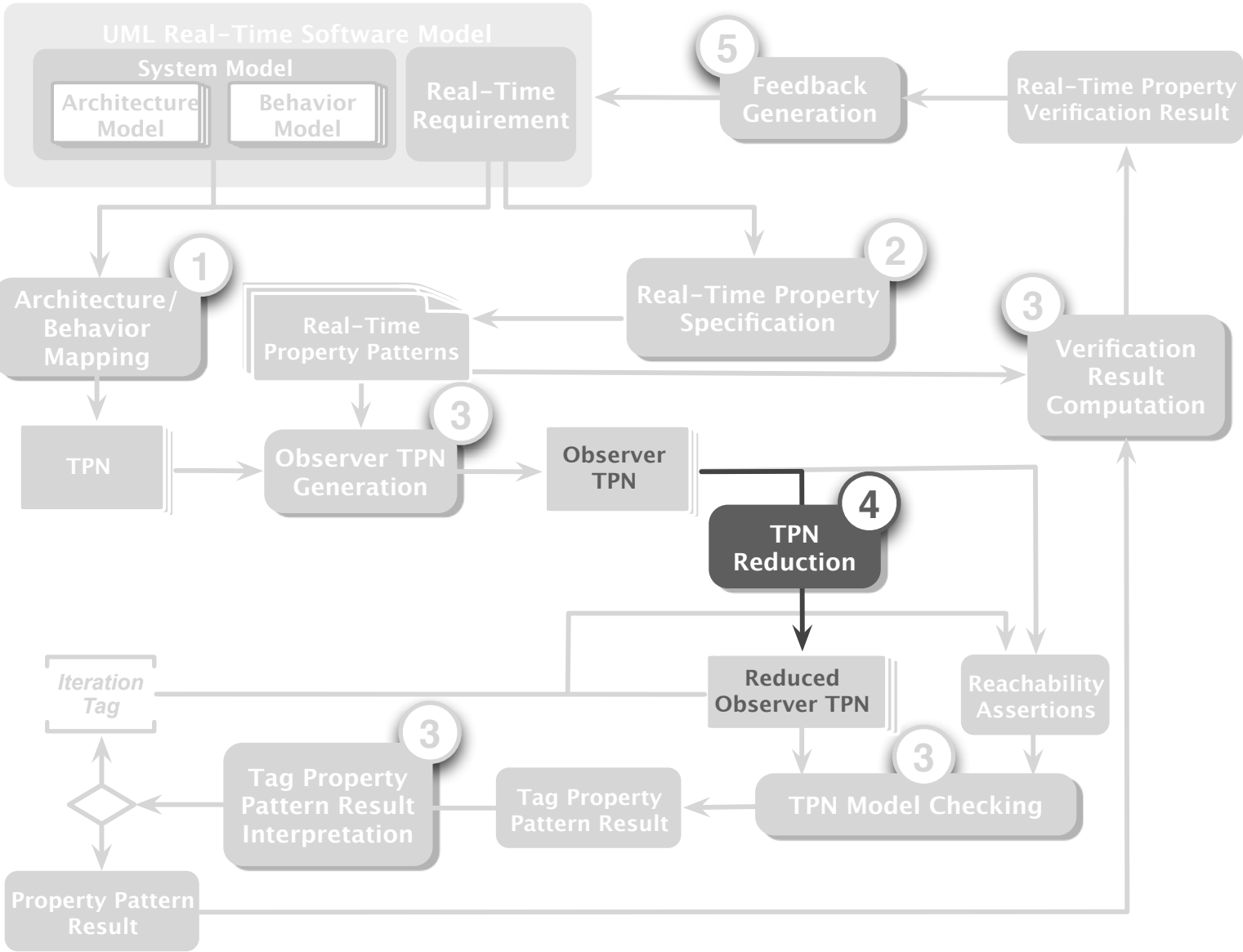

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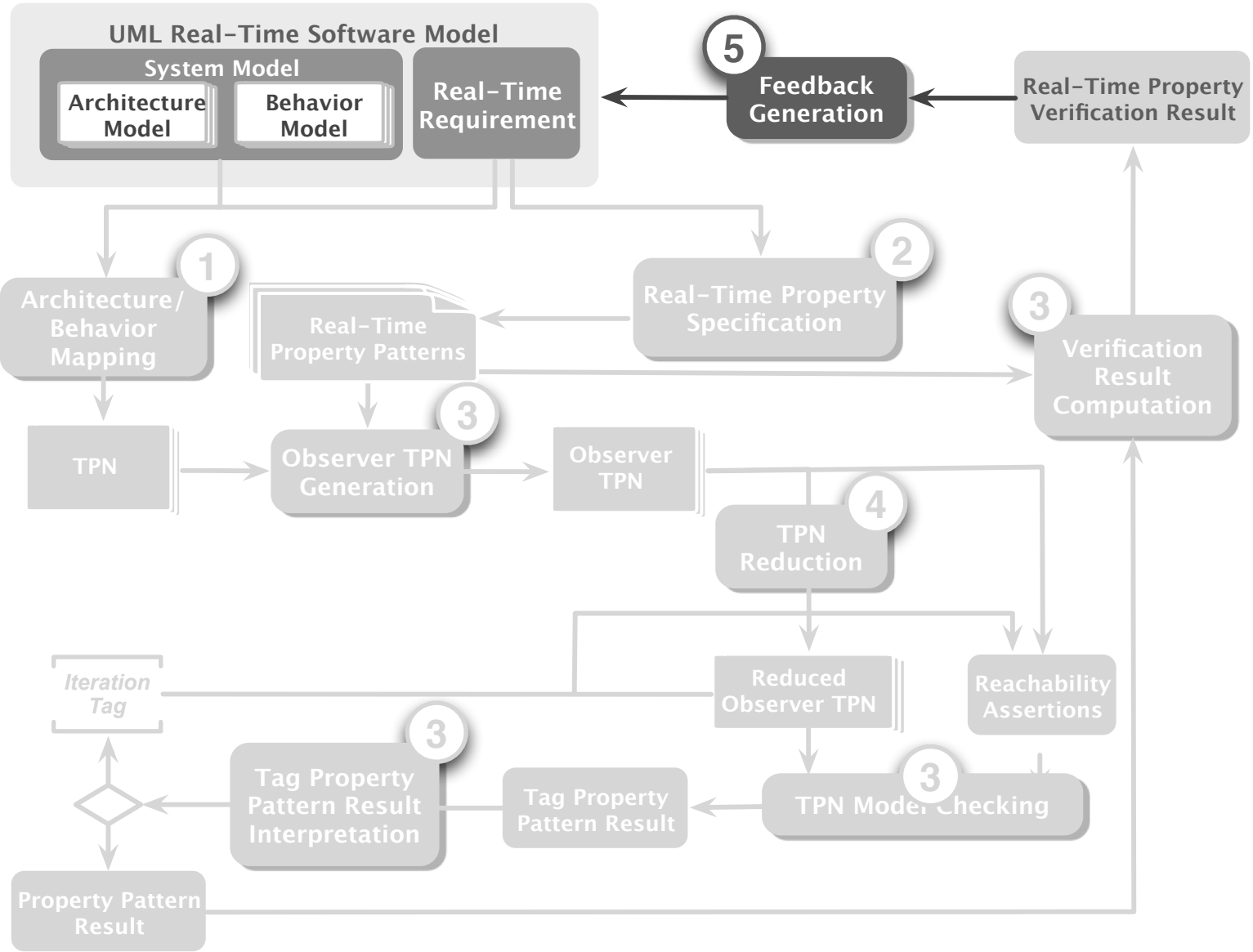

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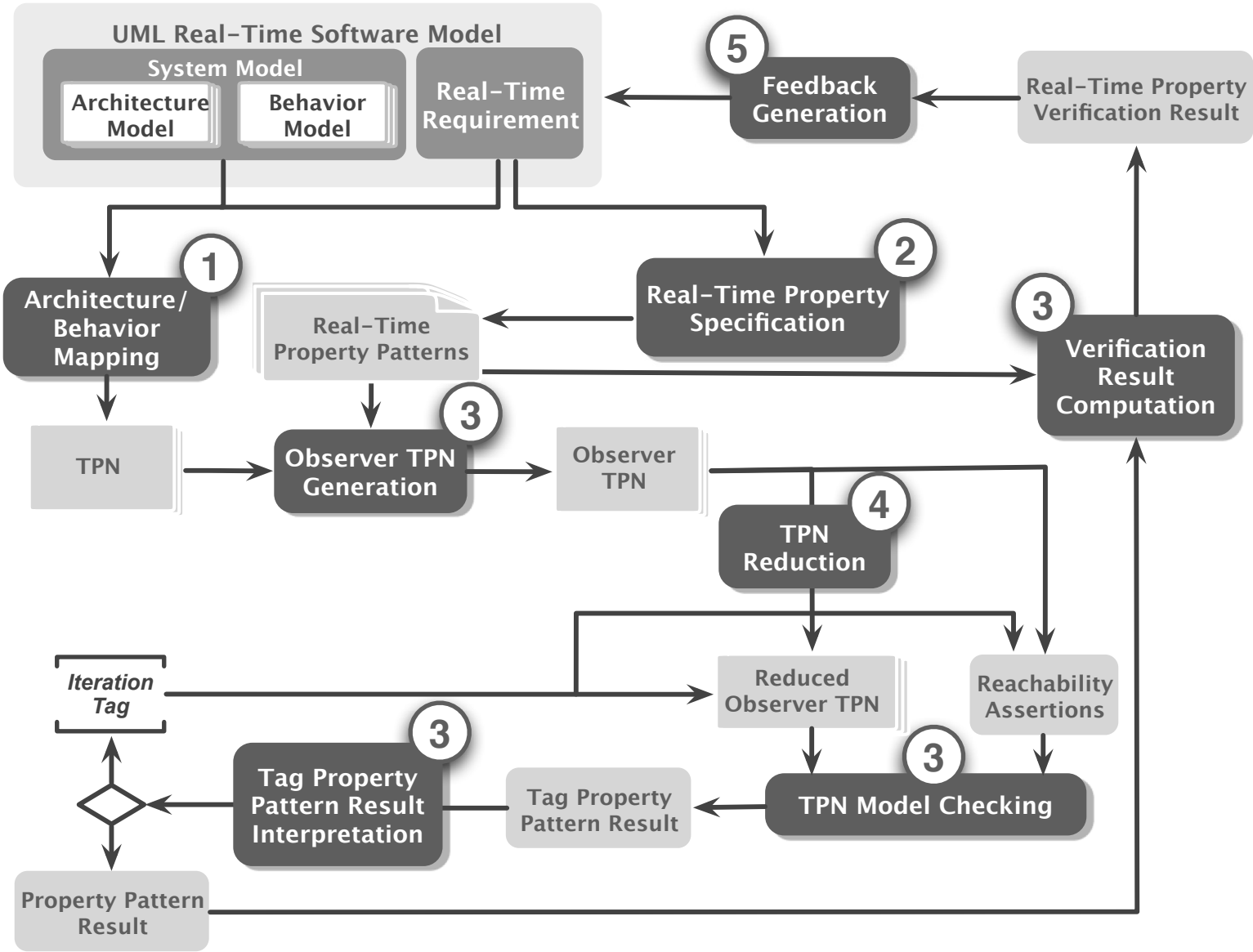

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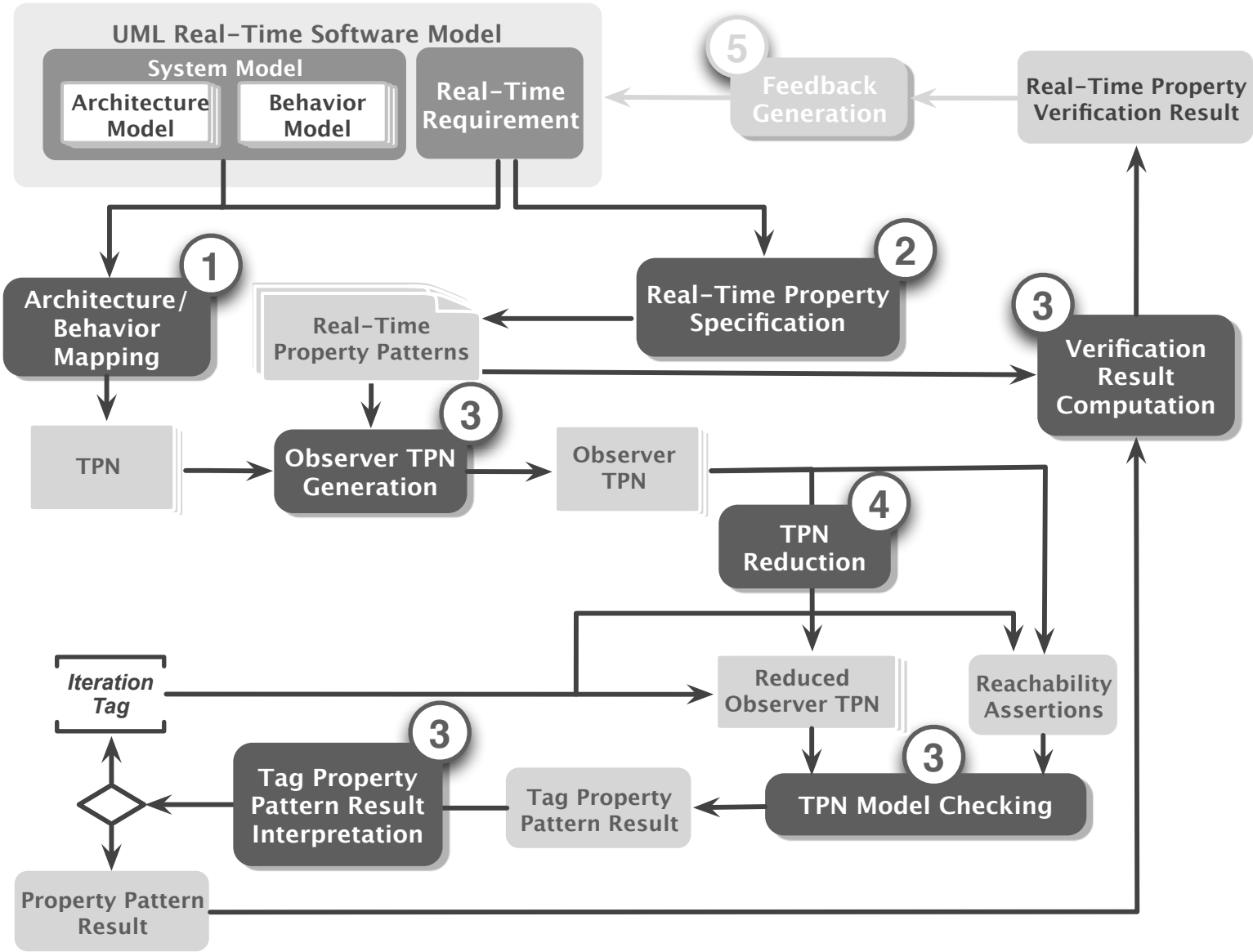
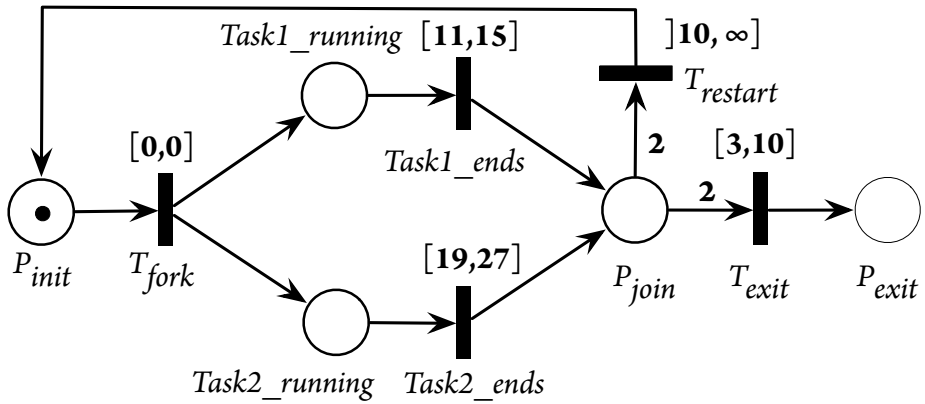


Outline

Time Petri Net

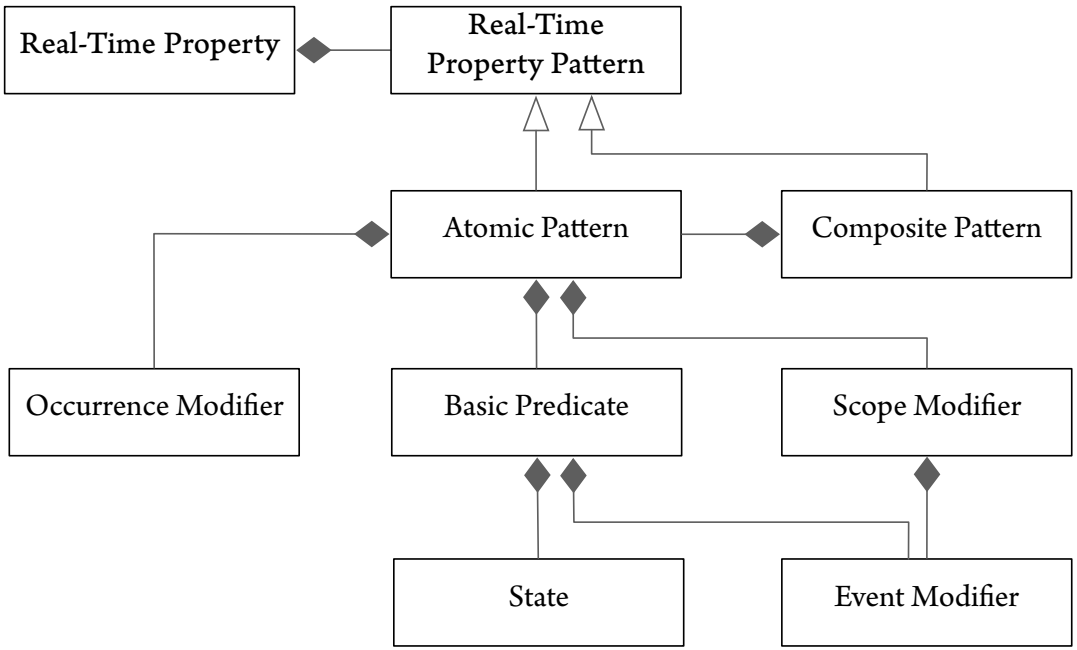


TINA toolset

- Analyze μ-calculus, LTL, CTL properties in TPN.
- Integrate state space abstraction techniques (preserving different types of properties), on-the-fly model checking.
- Data manipulation (*tts*): variable definition and modification.

Outline

Real-Time Property Specification System



Exist A After B Within [bct, wct]

Operator	Occurrence	Basic predicate	Scope
	Absent	B	*global*
or	*Exist*	$A \wedge B$	*between* $(B + bct)$ *and* $(B + wct)$

Outline

Design Principle of TPN/TTS Observers - Structure

Observer Structure

- A TPN/TTS observer is associated to the system through its arcs, joined at the transitions labelled T_A and T_B in components A & B.
- A TTS observer for state-based properties is not composed with the system but simply put in parallel (an operation usually referred to as free product).

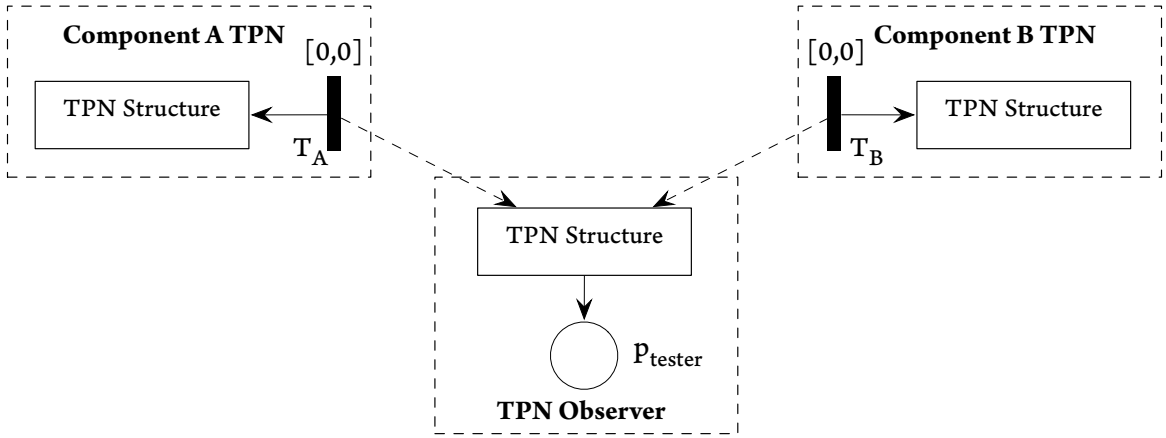


Figure: Observer Structure

Design Principle of TPN/TTS Observers - Soundness

Soundness here means that

- An observer should not impact the system's behavior by introducing extra semantics or removing original semantics
- Observers preserve time divergence, meaning that an observer should not be able to stop the evolution of time (introducing some kind of time deadlocks).

Our approach

- By interacting with the system only by its transitions
- The observers work in a "read-only" mode, guaranteed by the design "linked *from* TPN transitions".

Design Principle of TPN/TTS Observers - Efficiency

Principles

- A system with integrated observers should be able to generate state class graphs with a high-level abstraction (i.e. marking abstraction for TINA)
- The generating state space of a single observer shall be as small as possible.
- The checking of each property pattern shall be independent to promote parallel computation.

Elementary Observers - Basic Event Modifiers

Event modifier: an atomic element, or a composite one.
Example: *t unit of time after event* E^{i-k}.

- E^i (the i^{th} occurrence of event E);
- E^{i-k} (the event delayed k times from the current event E^i);
- $E^{i-k} + t$ (the event delayed t *u.t.* from current event E^{i-k}).

Generic observer structure for event modifiers

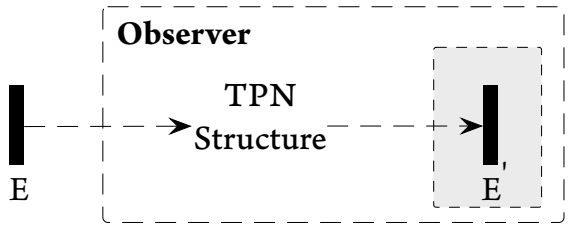


Figure: Observer Structure of Event Modifiers

Elementary Observers - Basic Predicates

- The specification of basic predicates relies on events and states
- An event can be a single event modifiers or a composition of several event modifiers.
- A set of basic predicates used by our property patterns has been defined
- The generic TPN structure of predicate observers is defined as Fig. 3
- The transition E_M is an event, and the predicate is assessed using the observer and a set of *mmc* assertions.

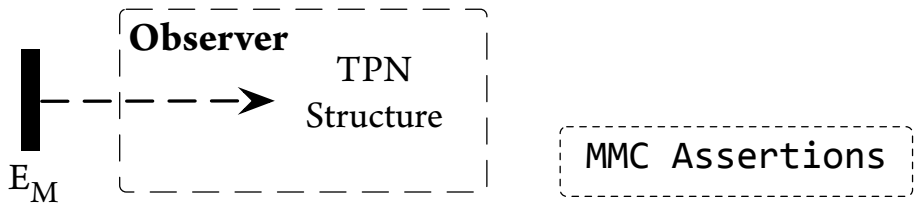


Figure: Predicate Observer Pattern

Elementary Observers - Basic Scope Modifiers

Basic scope modifiers include

- Global
- Before E_i
- After E_i,
- Between E_a and E_b
- Others are compositions of the basic ones.

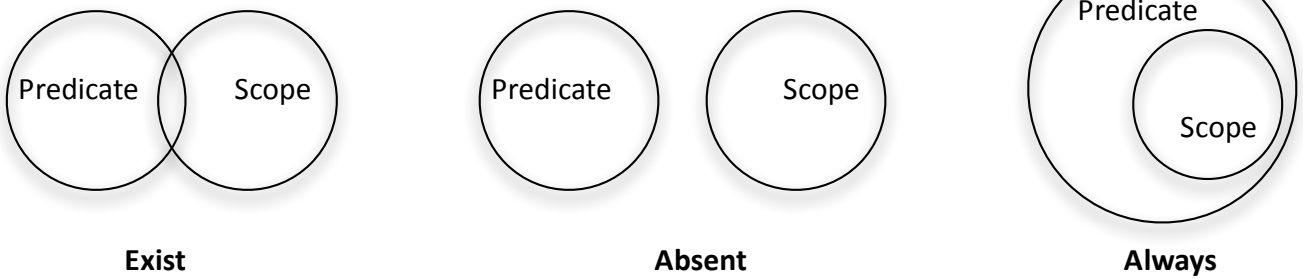
Elementary Observers - Occurrence Modifiers

Assume in the state class graph

- P: set of states that match the predicate,
- S: set of states that match the scope,
- $P \wedge S$: set of states that match both the predicate and the scope.

Occurrence

- **Exist** *Predicate* in *Scope*: $\begin{cases} P \wedge S \neq \emptyset & \text{if S} \neq \emptyset; \\ True & \text{if S} = \emptyset. \end{cases}$
- **Absent** *Predicate* in *Scope*: $P \wedge S = \emptyset$
- **Always** *Predicate* in *Scope*: $P \wedge S = S$



Example of Real-Time Property Verification

Two concurrent processes are modeled in TPN. Both execute only once. The target property $\mathcal{P}$ is *Always* E_A *After* E_B *Within* $[1, 2]$.

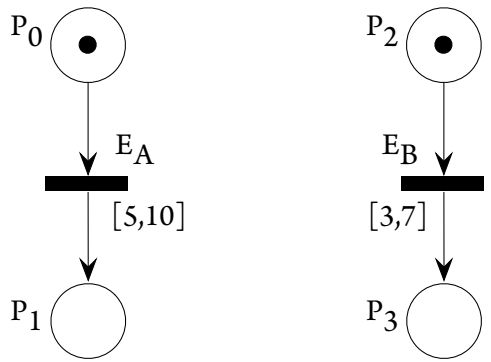


Figure: Observer-based Verification Example

Example of Real-Time Property Verification

The scope *Between* $E_B + 1$ *and* $E_B + 2$ is observed by using a composite observer with three parts:

- **obs$_1$** for event modifier $E_B + 1$,
- **obs$_2$** for event modifier $E_B + 2$,
- **obs$_3$** for scope modifier *Between* $E_B + 1$ *and* $E_B + 2$

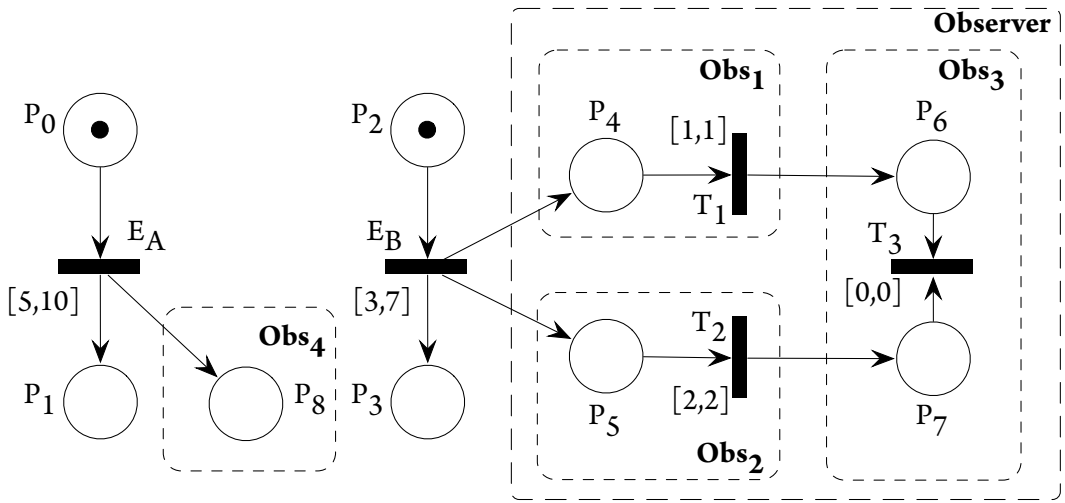


Figure: TPN Observers for the Example

Example of Real-Time Property Verification

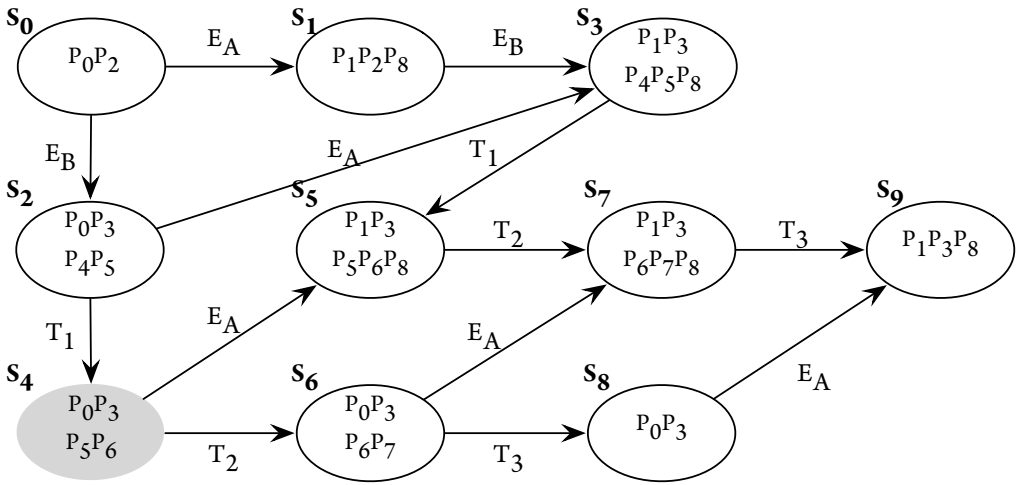


Figure: Reachability Graph of Verification Example

Very good scalability with Avionics IMA-AFDX systems (GALS – Globally Asynchronous Locally Synchronous)

Outline

Conclusion

Existing pattern systems

- target expressiveness of real-time requirements
- leave the verification related issues to the users
- Do not guarantee the efficiency of verification

Our pattern system

- Atomic patterns corresponding to elementary observers
- End-user real-time requirements are compositions of these patterns
- Automatic generation of composite observers for composite properties
- Positive outcome on the verification cost
- Integrated in our UML-MARTE real-time verification framework

Future work

- Still more experiments
- Mechanisation and proof of correctness

Thanks for your attention!