From Model-Based Design to Formal Verification of Adaptive Embedded Systems

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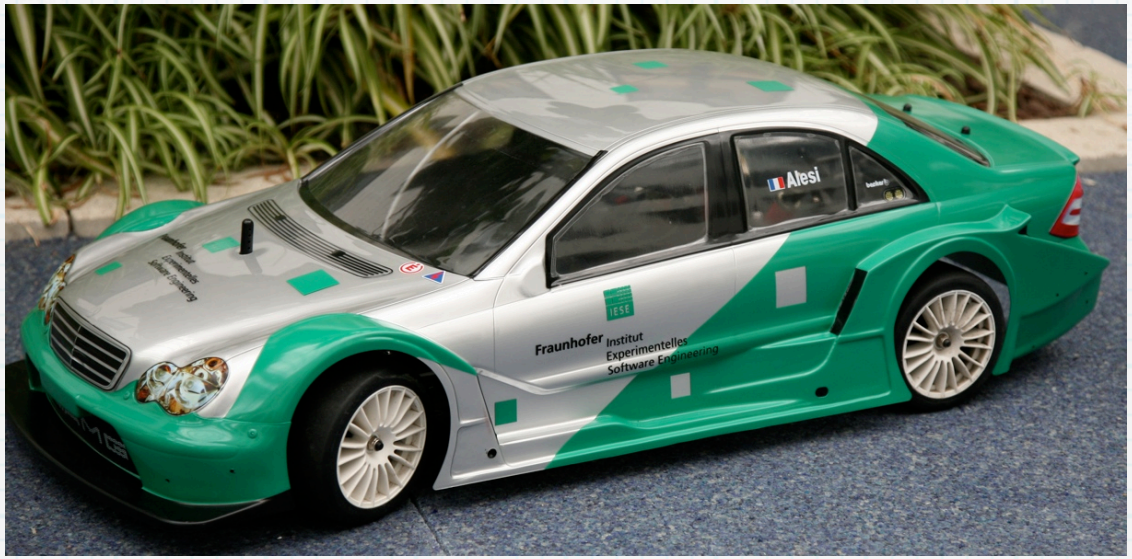
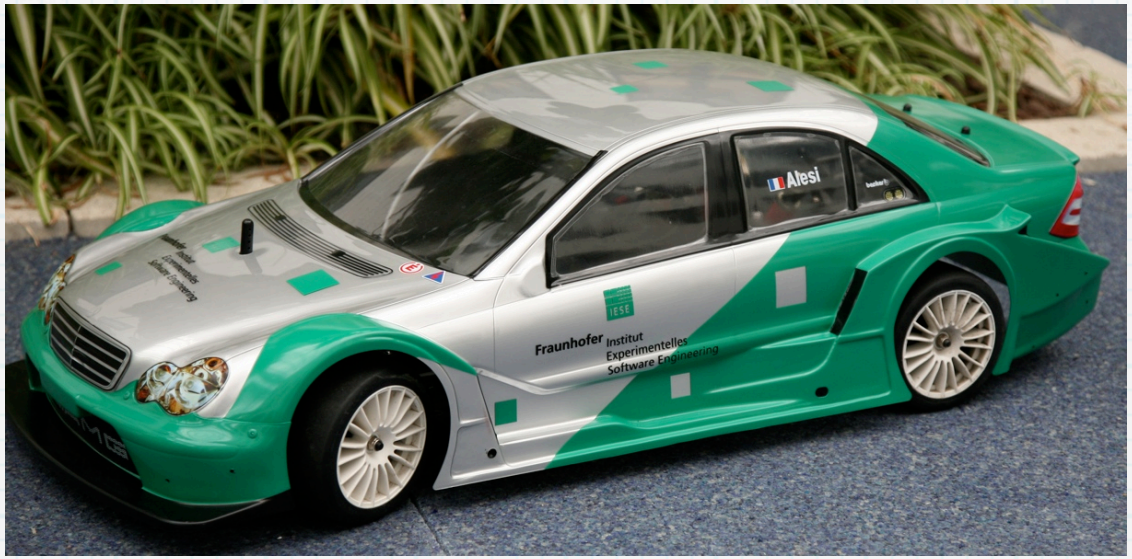
Technische Universität Kaiserslautern
SoFTeX Arbeitsgruppe Softwaretechnik
DASMOD Dependable Adaptive Systems and Mathematical Modeling

Self-Adaptive Systems



Self-Adaptive Systems

HW - Fault
SW - Fault



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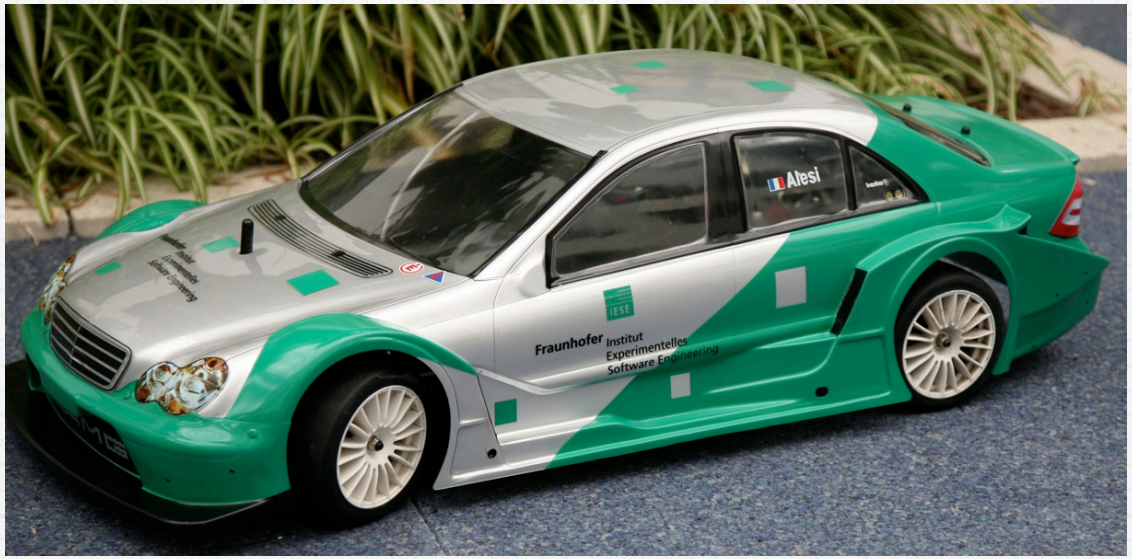
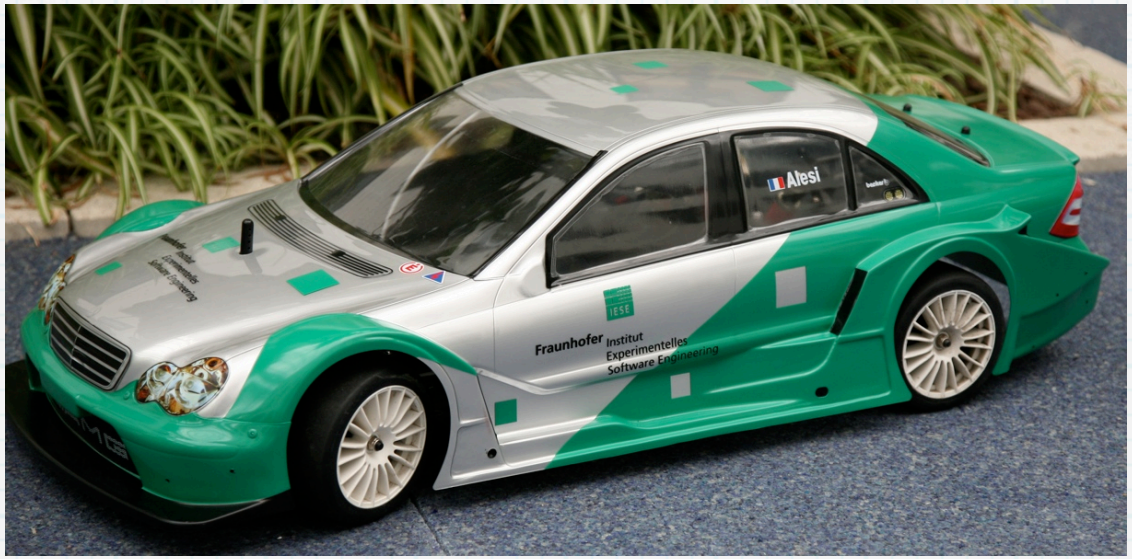


HW - Fault
SW - Fault

Runtime adaptation

Self-Adaptive Systems



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Runtime adaptation

Degrade functionality to remain operational by switching to different predetermined configuration

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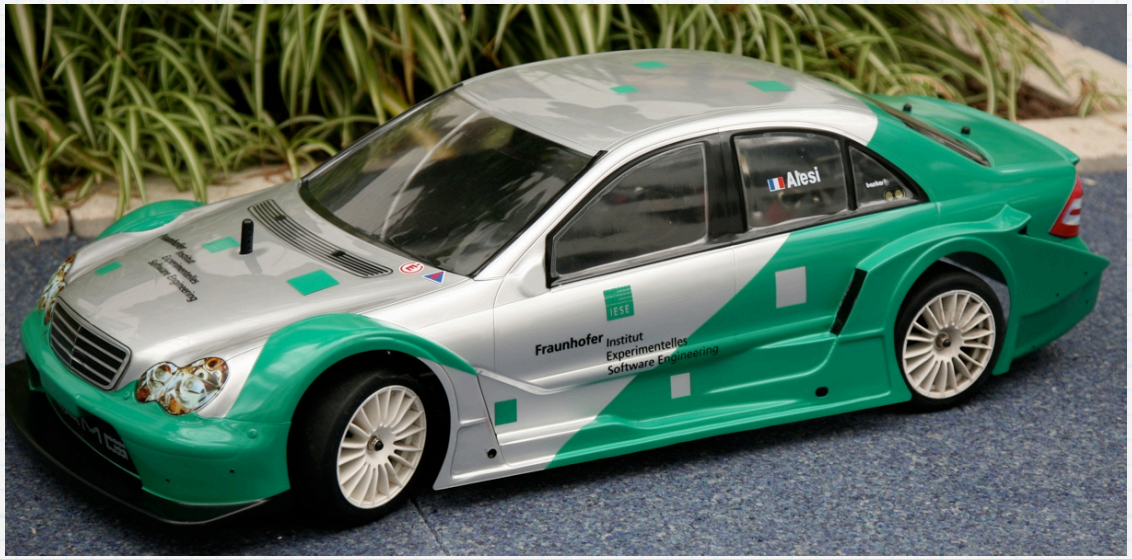

HW - Fault
SW - Fault

Safety
Survivability

Runtime adaptation

Degrade functionality to remain operational by switching to different predetermined configuration

Adaptive Systems Development

Adaptation increases design complexity, since

- **decentralized adaptation mechanism**
- **reconfiguration triggers reconfiguration**
- **complex interdependencies**

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Solution:

- **Model-Based Design of Adaptive Systems**
- **Integrated with Formal Verification of Adaptation Behaviour**

Integration - Outline

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Modelling Concepts for Adaptive Systems

Integration - Outline

Modelling Concepts for Adaptive Systems

Verification Tools

System Properties

Integration - Outline

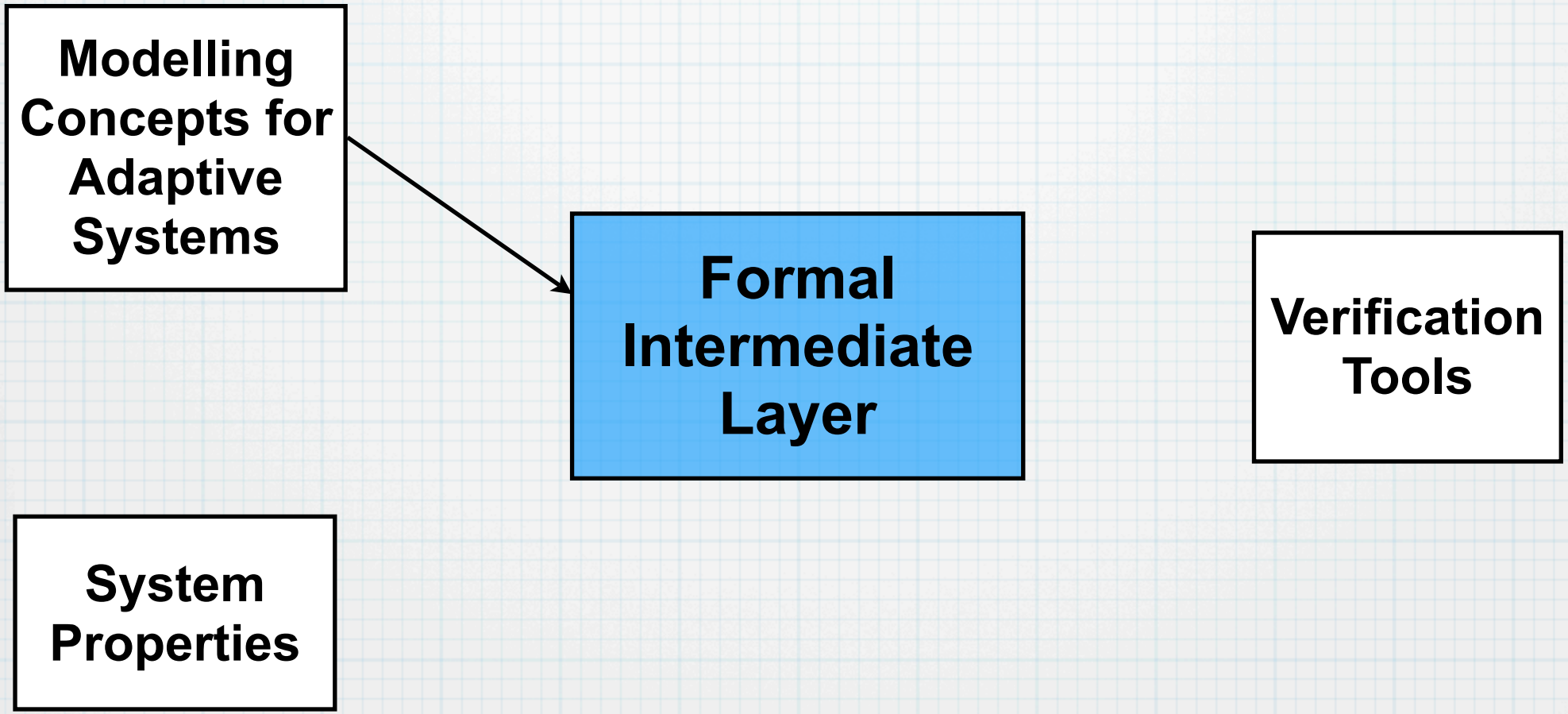
Modelling Concepts for Adaptive Systems

Formal Intermediate Layer

Verification Tools

System Properties

Integration - Outline



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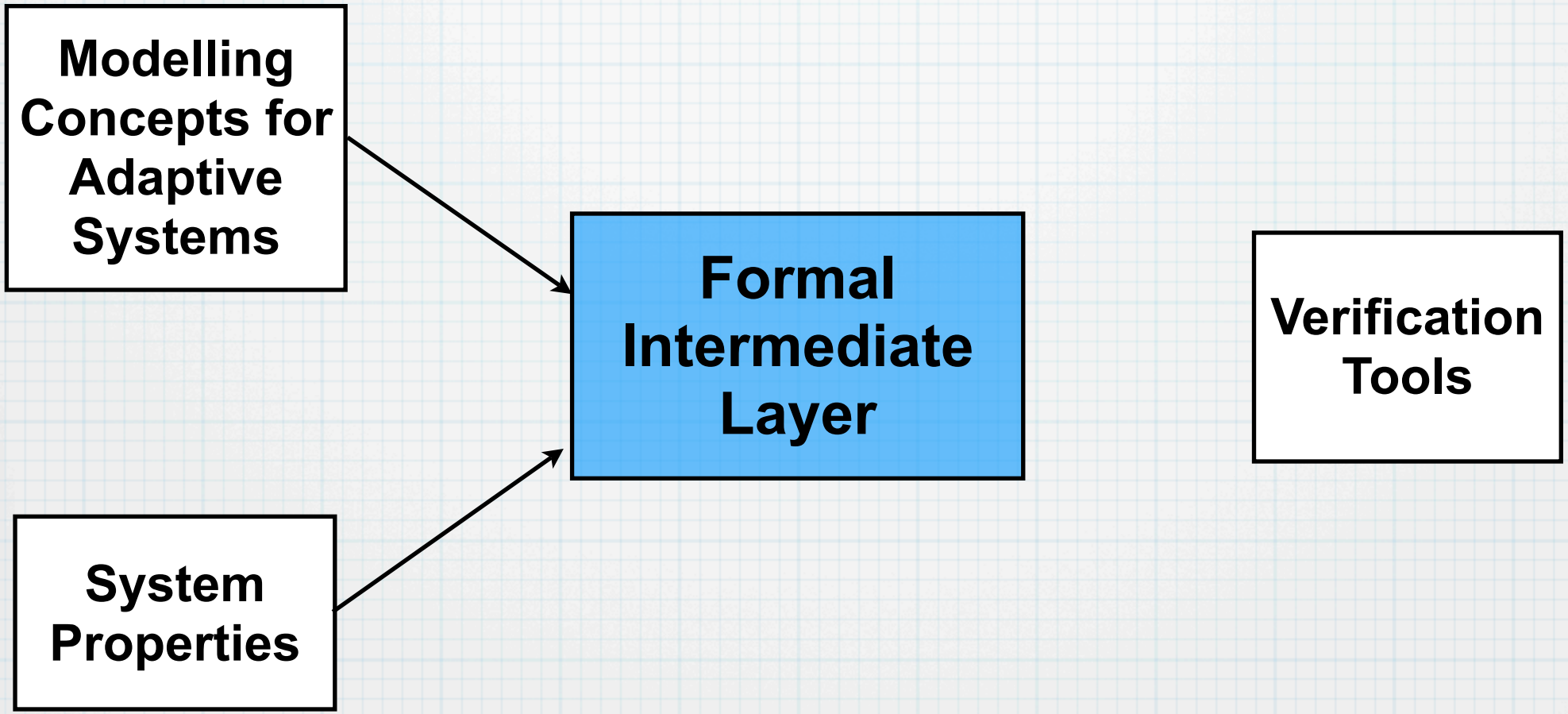

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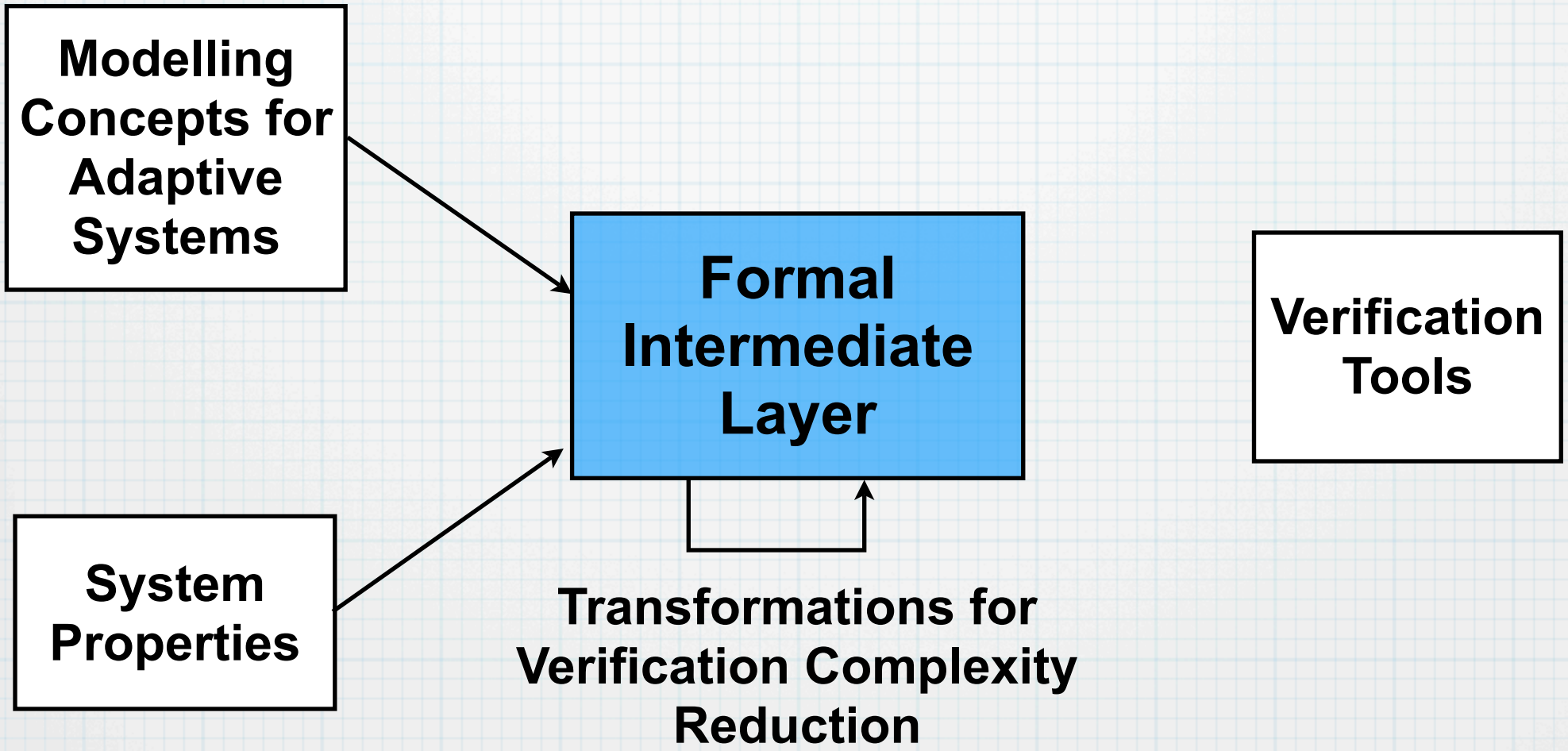

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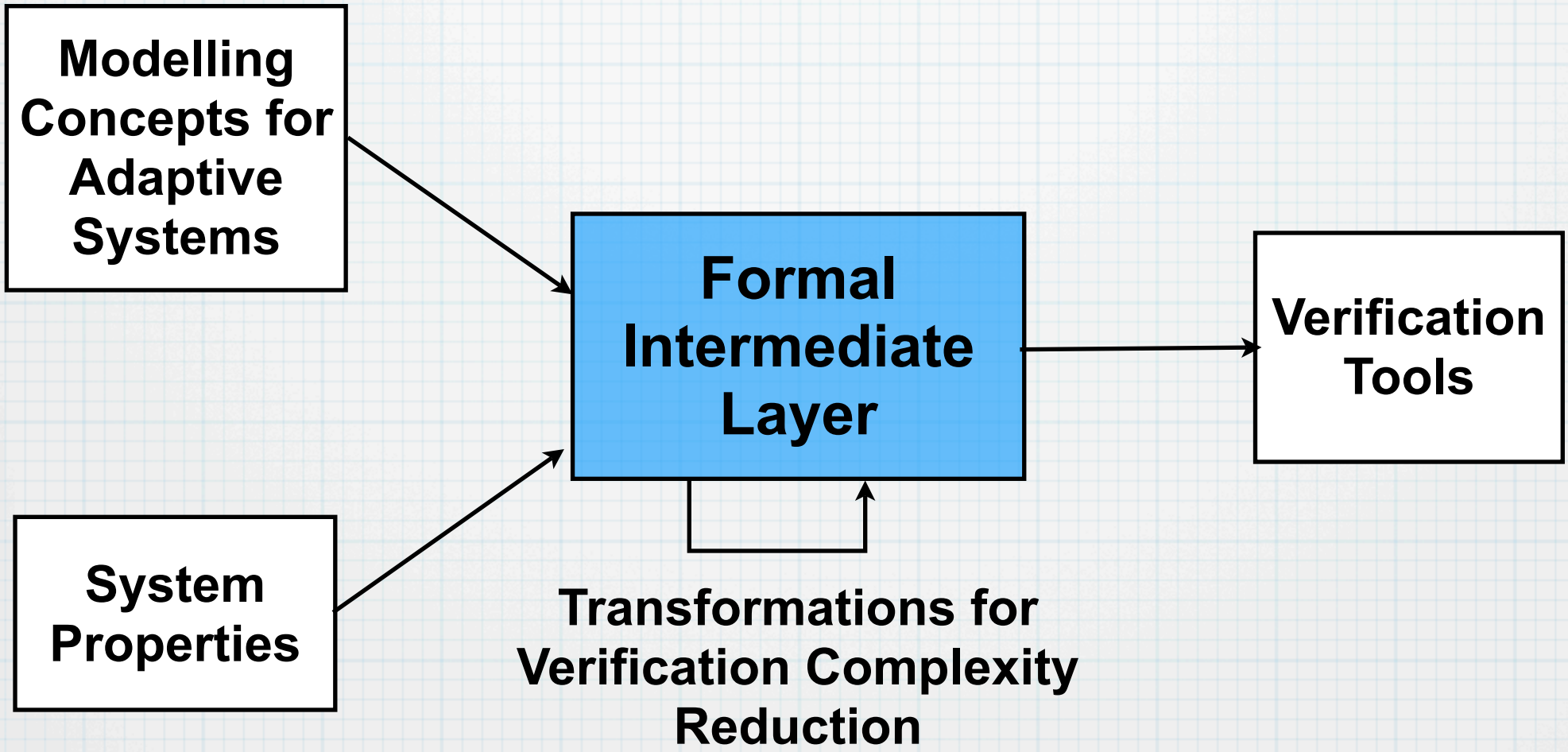

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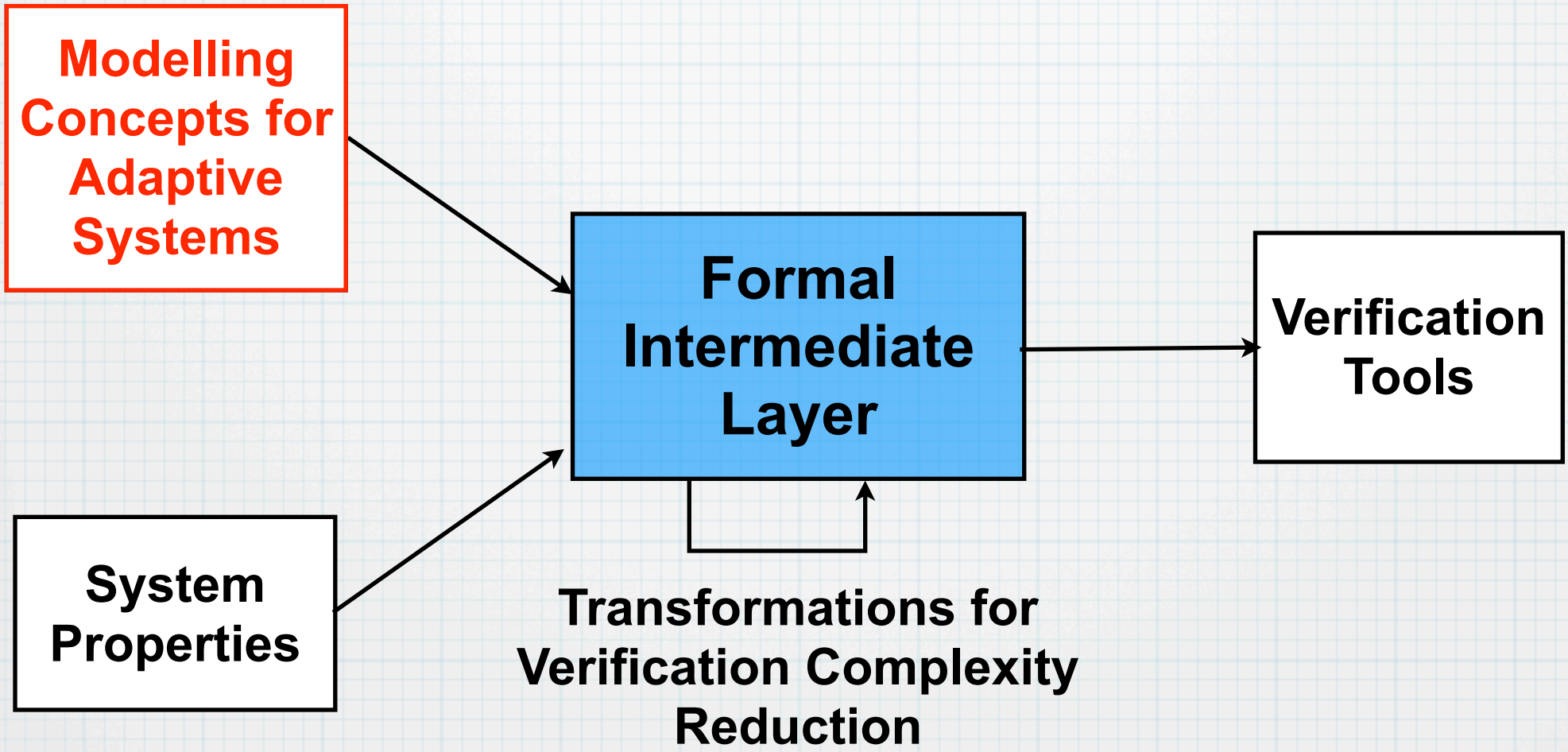
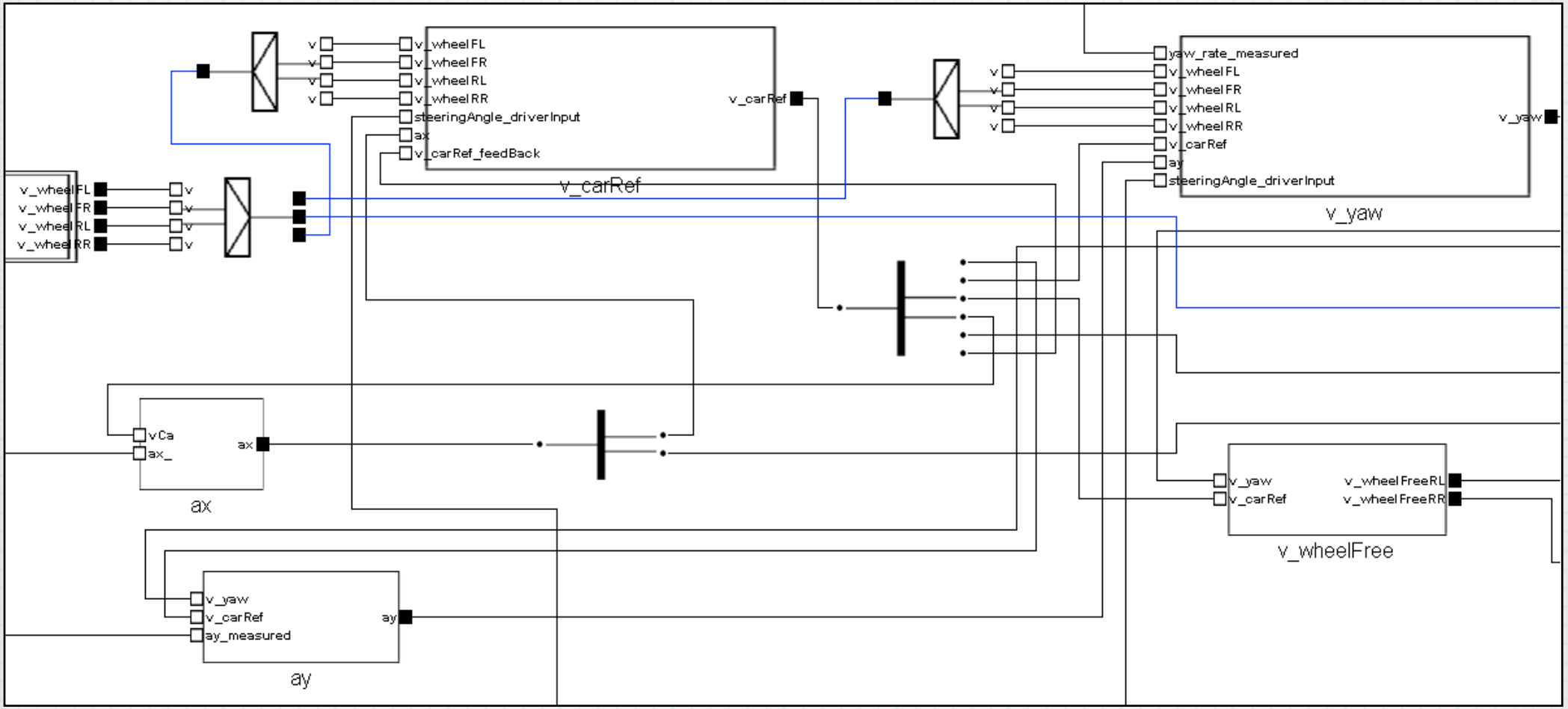


Adaptive System Modelling (MARS)

Main Concepts reducing Design Complexity:

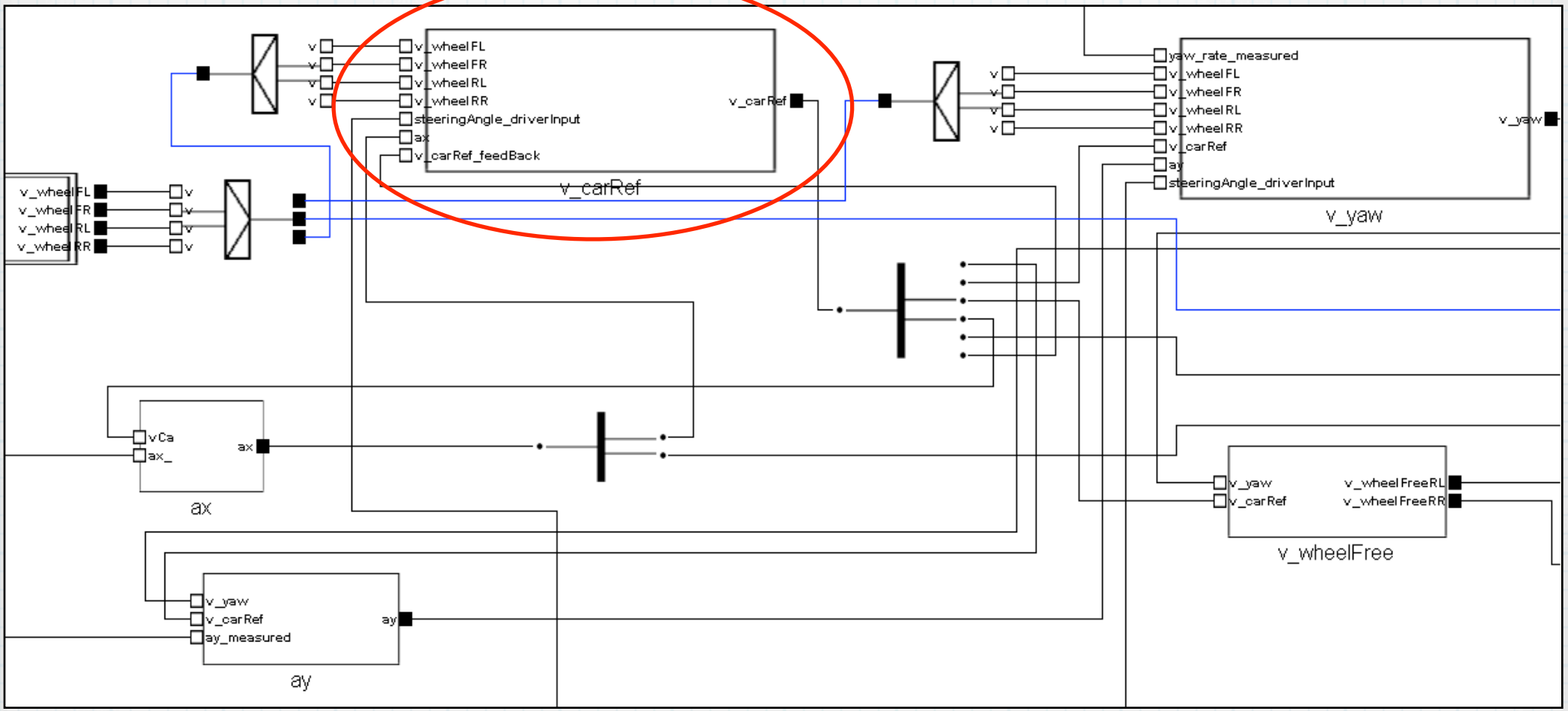
- **Modular System Structure**
- **Separation of Adaptation and Functionality in Modules**
- **Propagation of Adaptation by Qualities attached to Data**

Modular System Structure



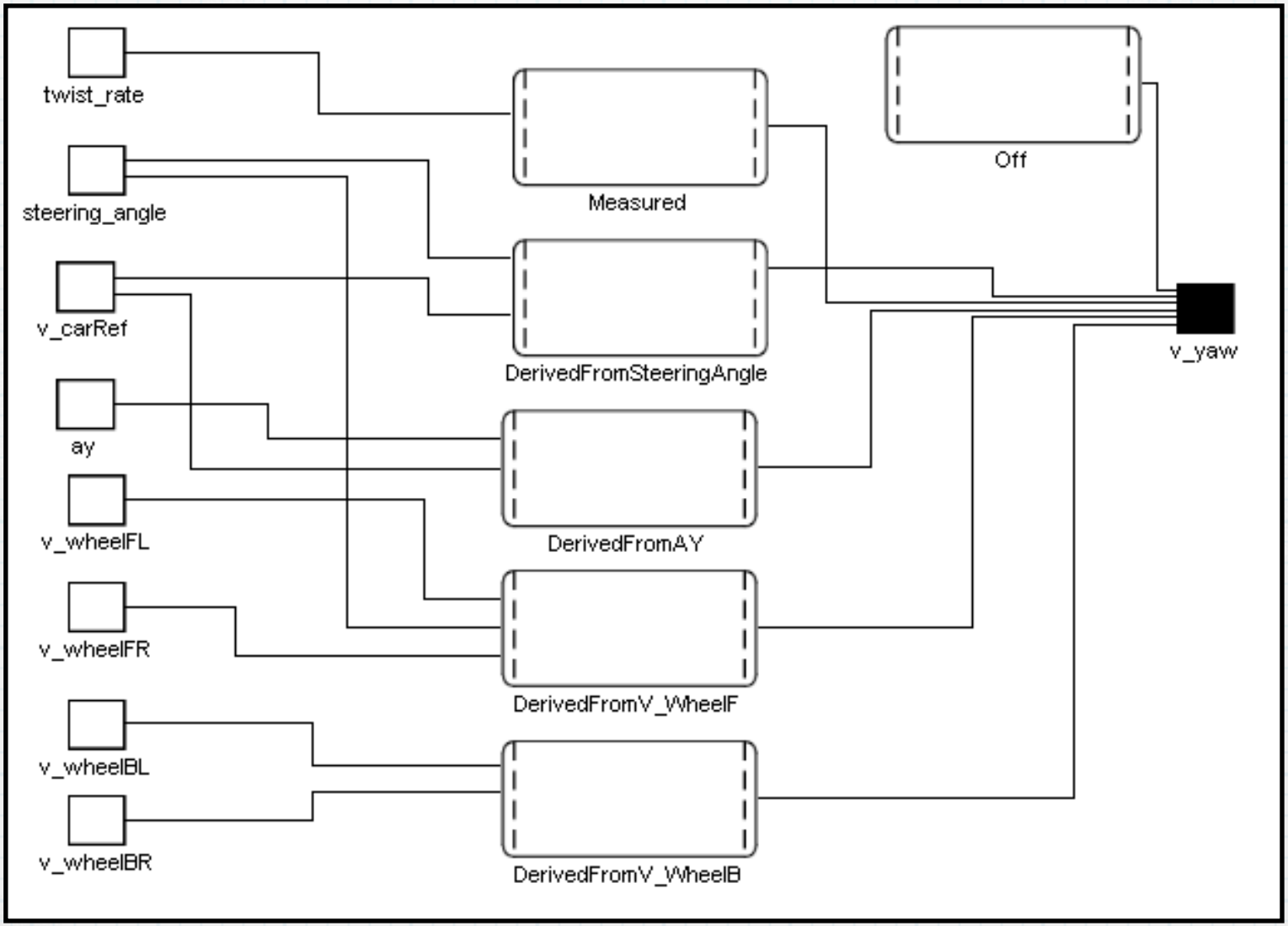
Modular System Structure

Module



Adaptive MARS Modules

Example: Yaw Rate Module



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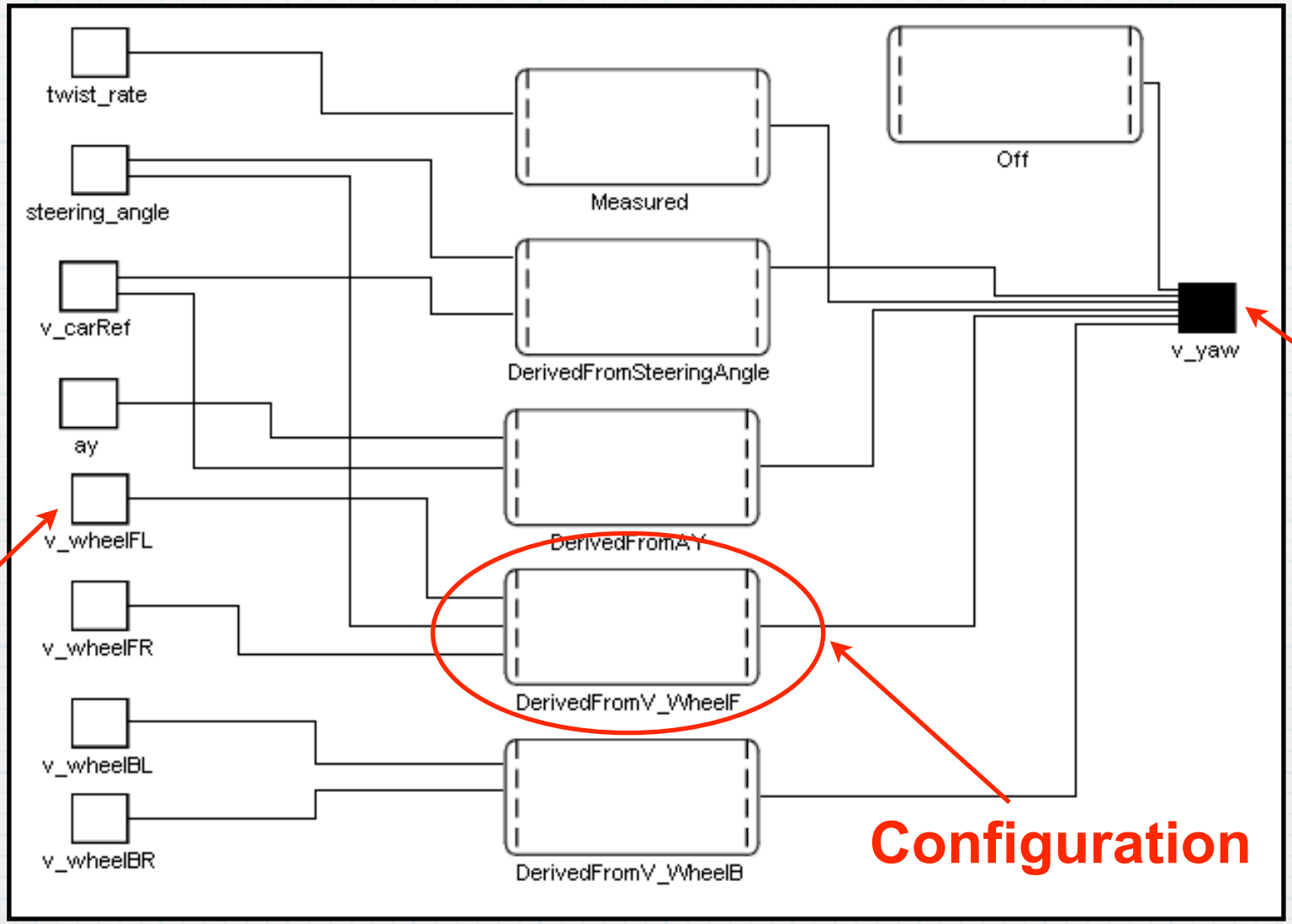
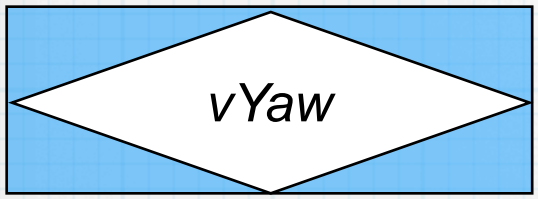
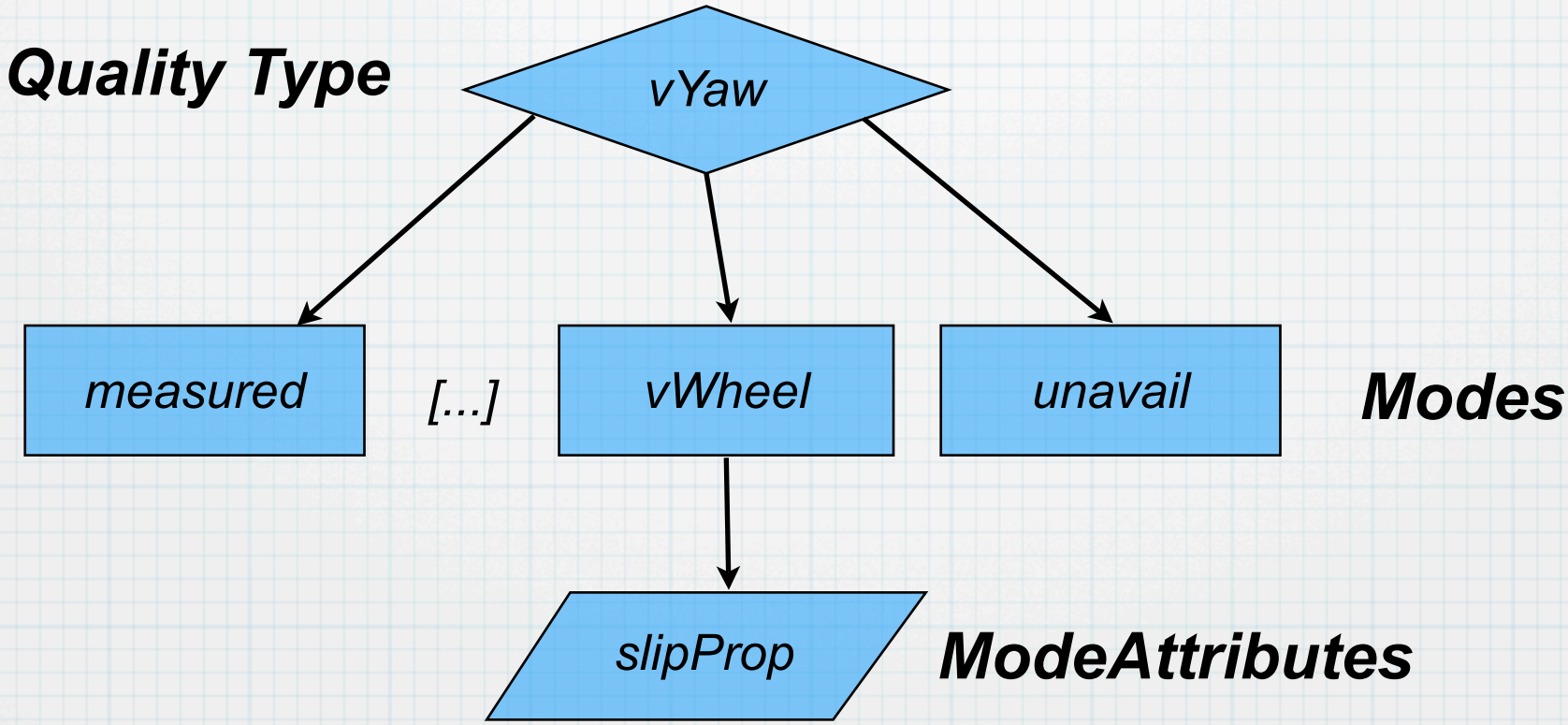


Adaptation Behaviour - Qualities



Quality-Extended Datatypes for Adaptive Systems

Dative = [data type, quality type]



Modelling Adaptation

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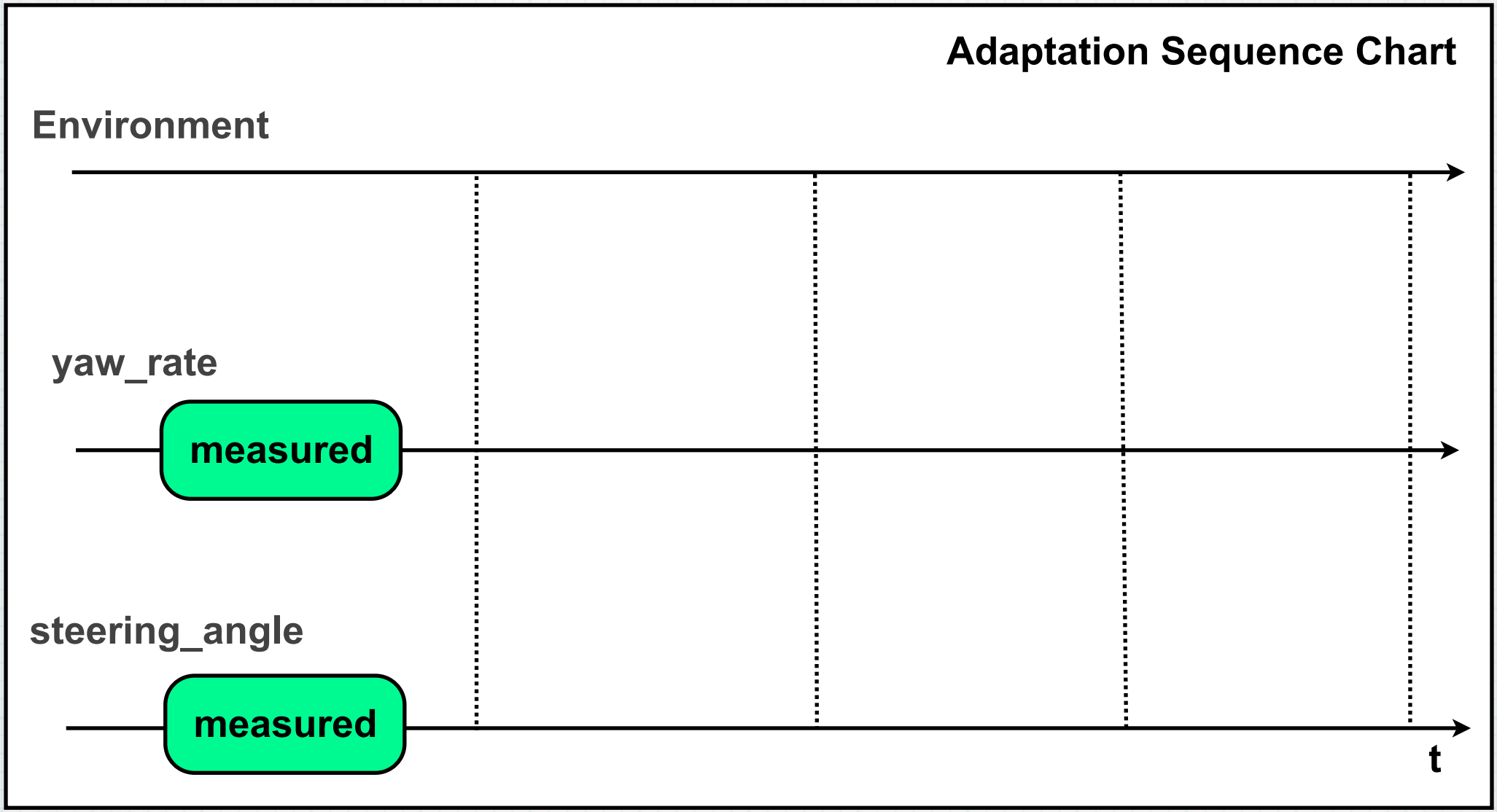

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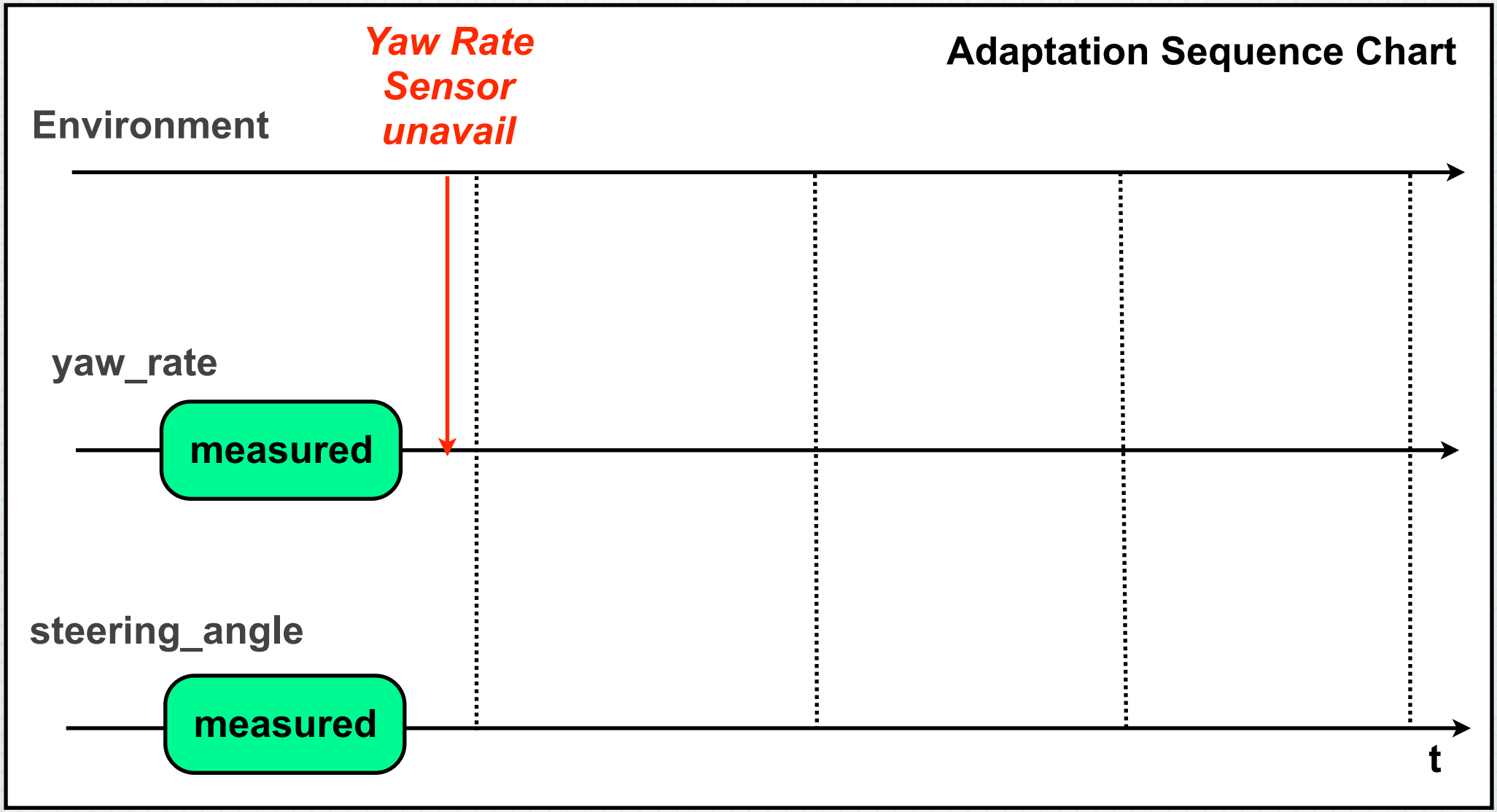

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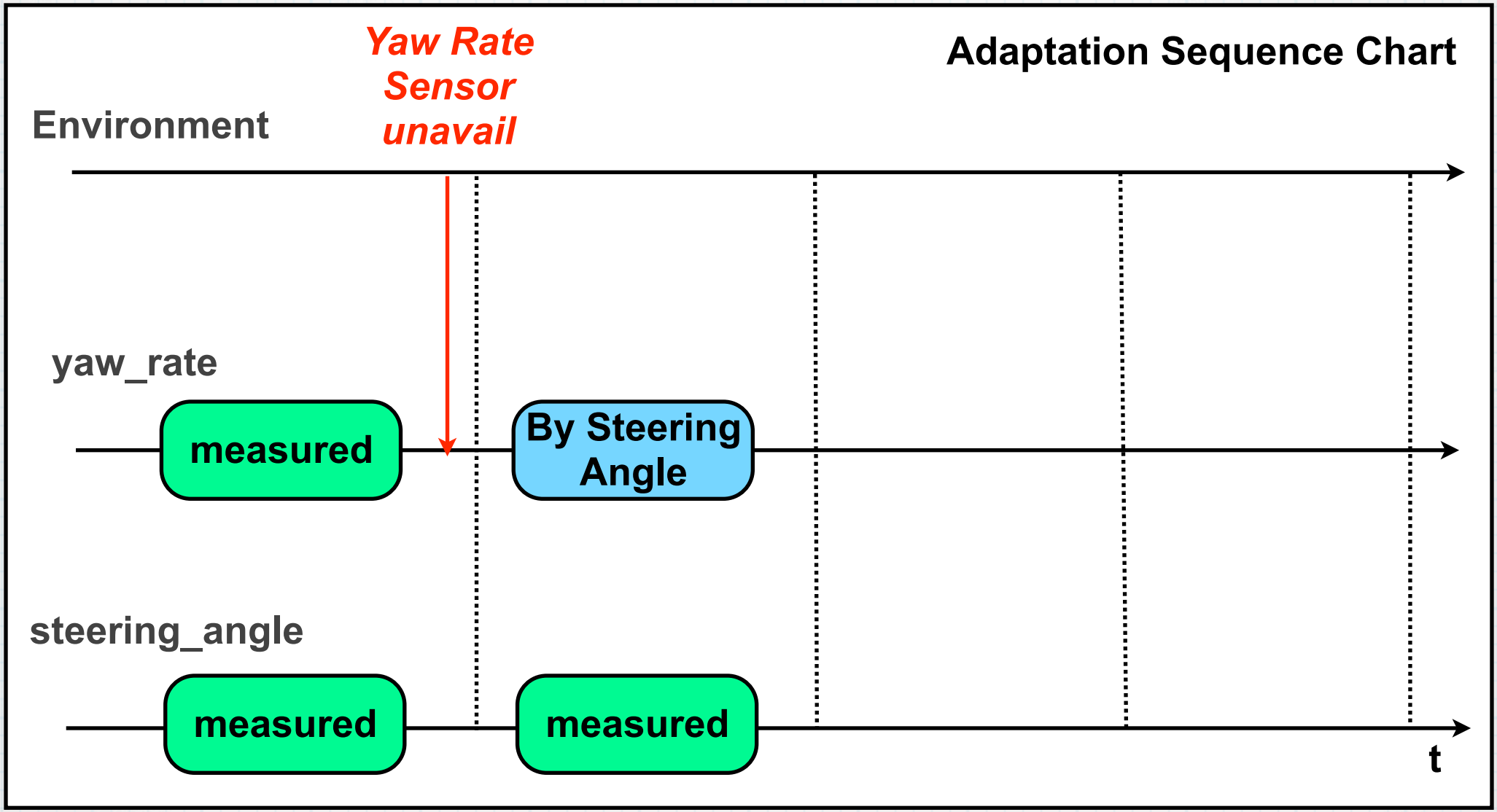

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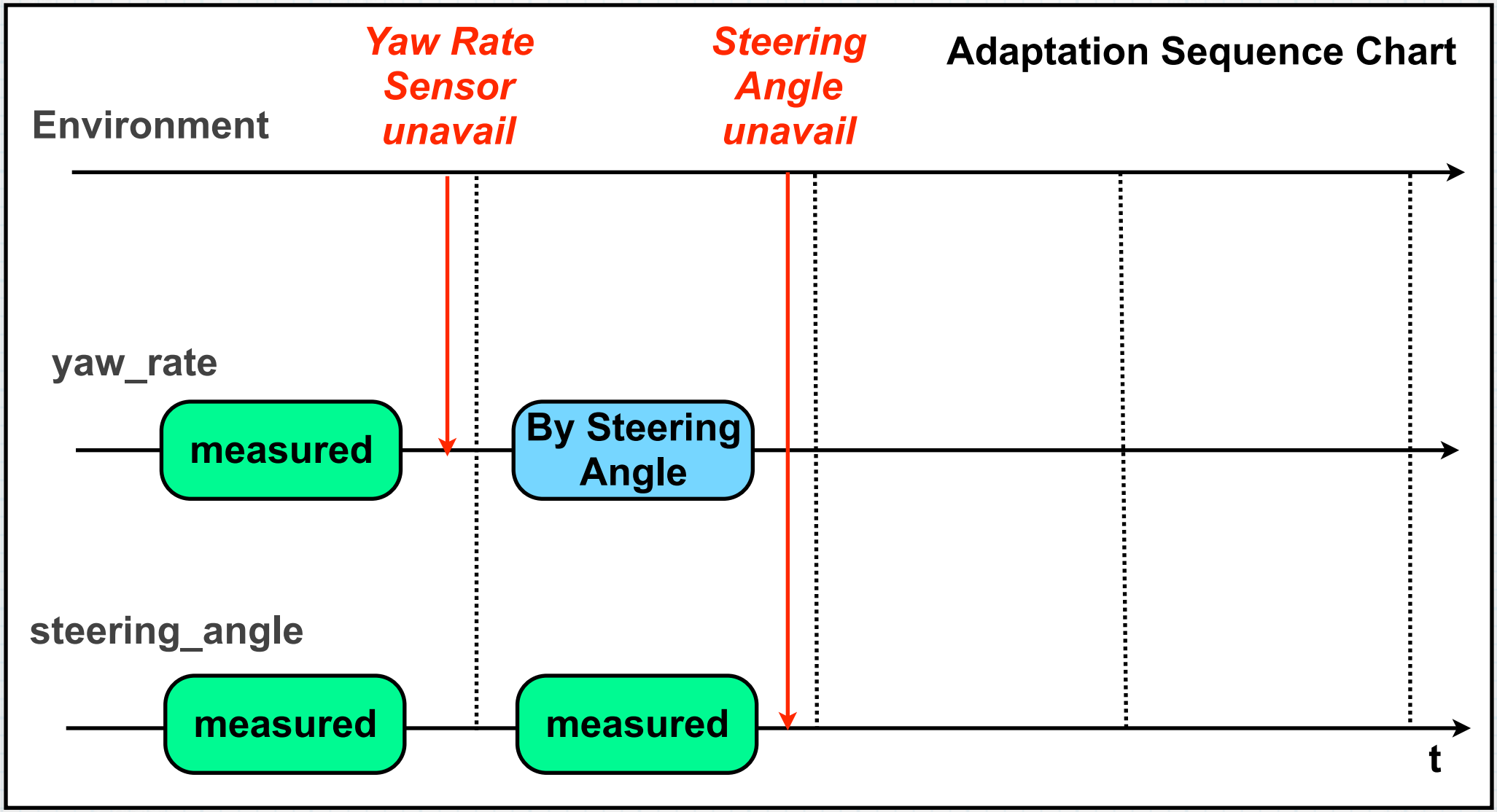

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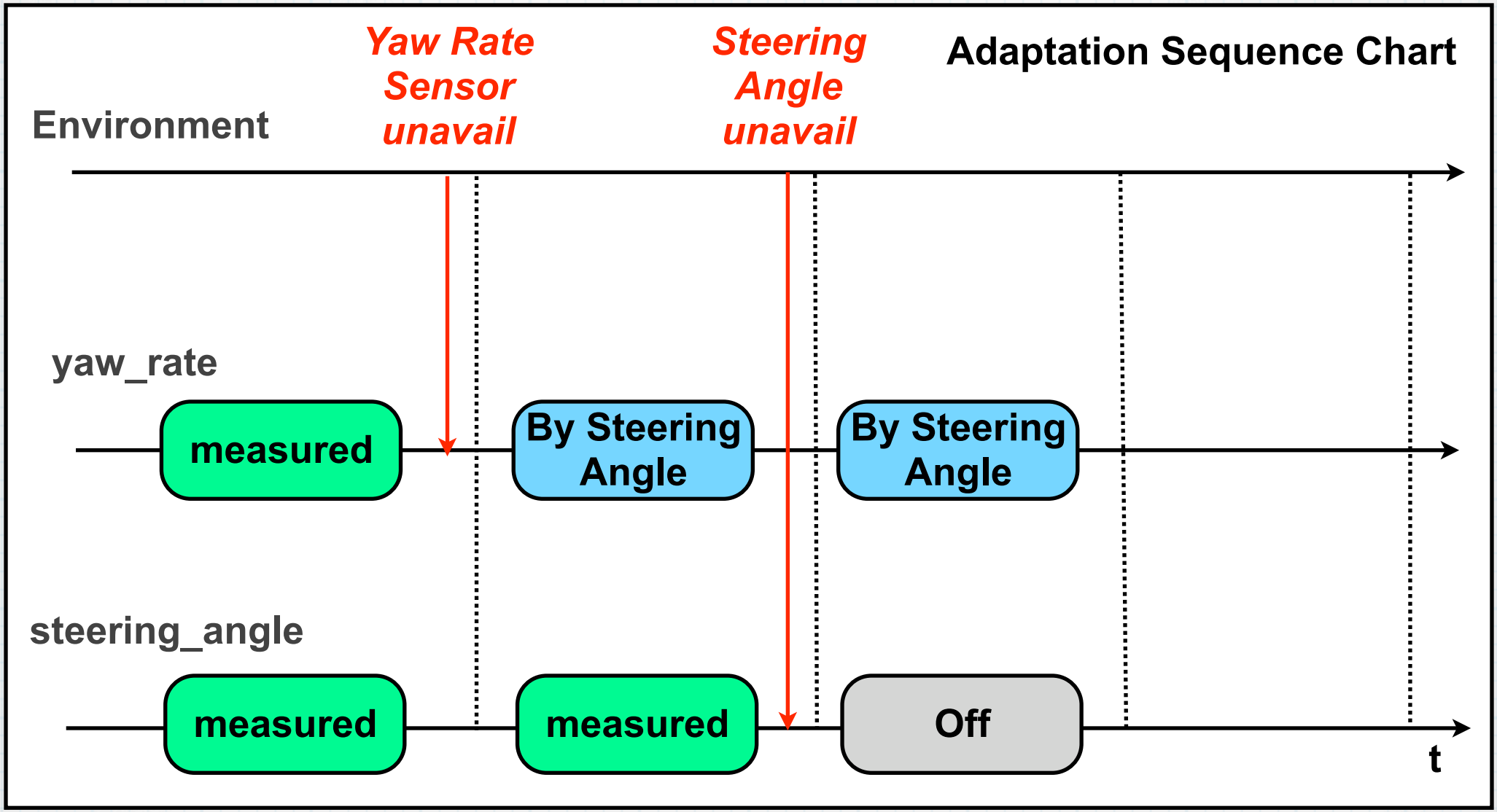

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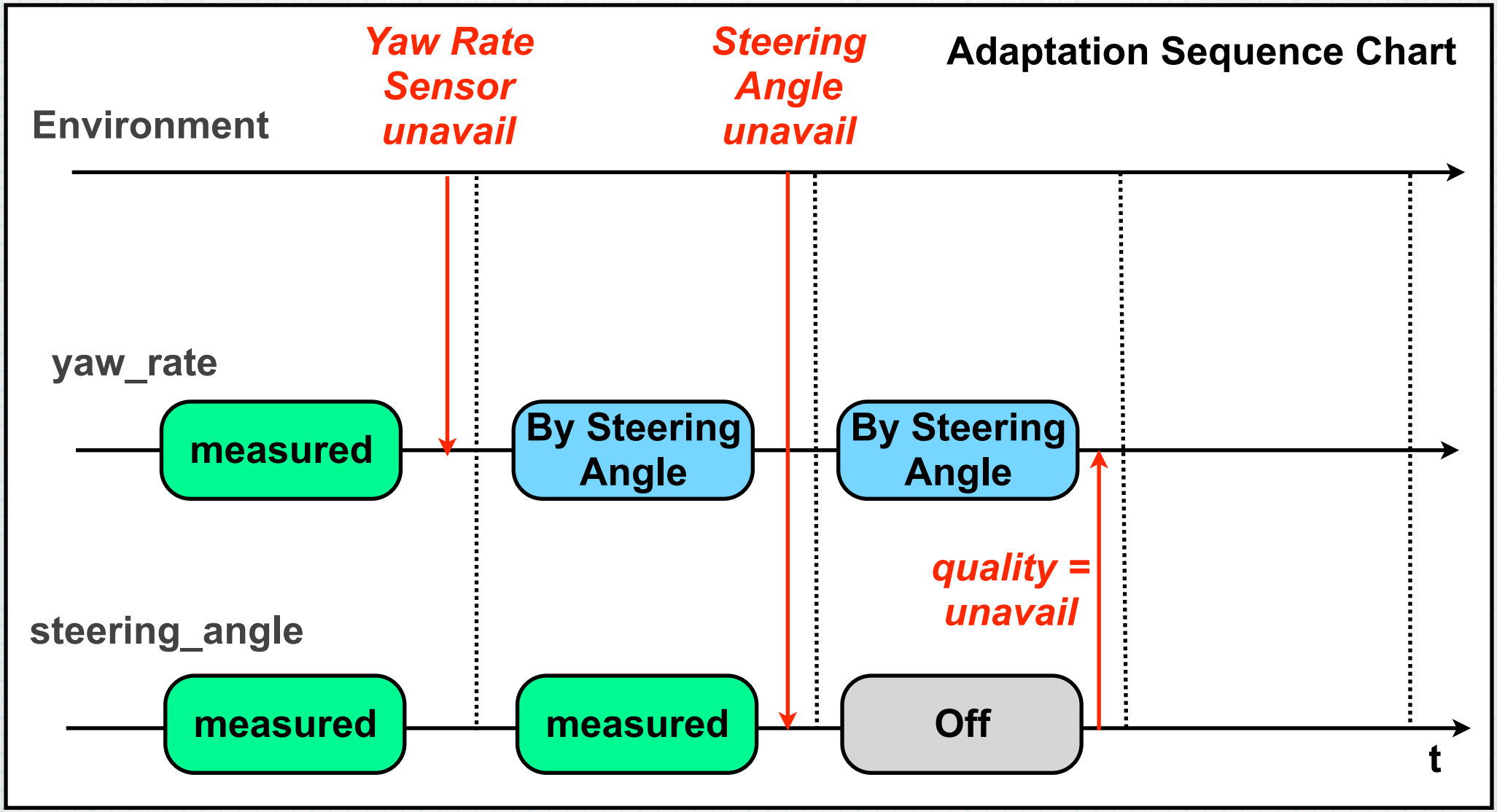

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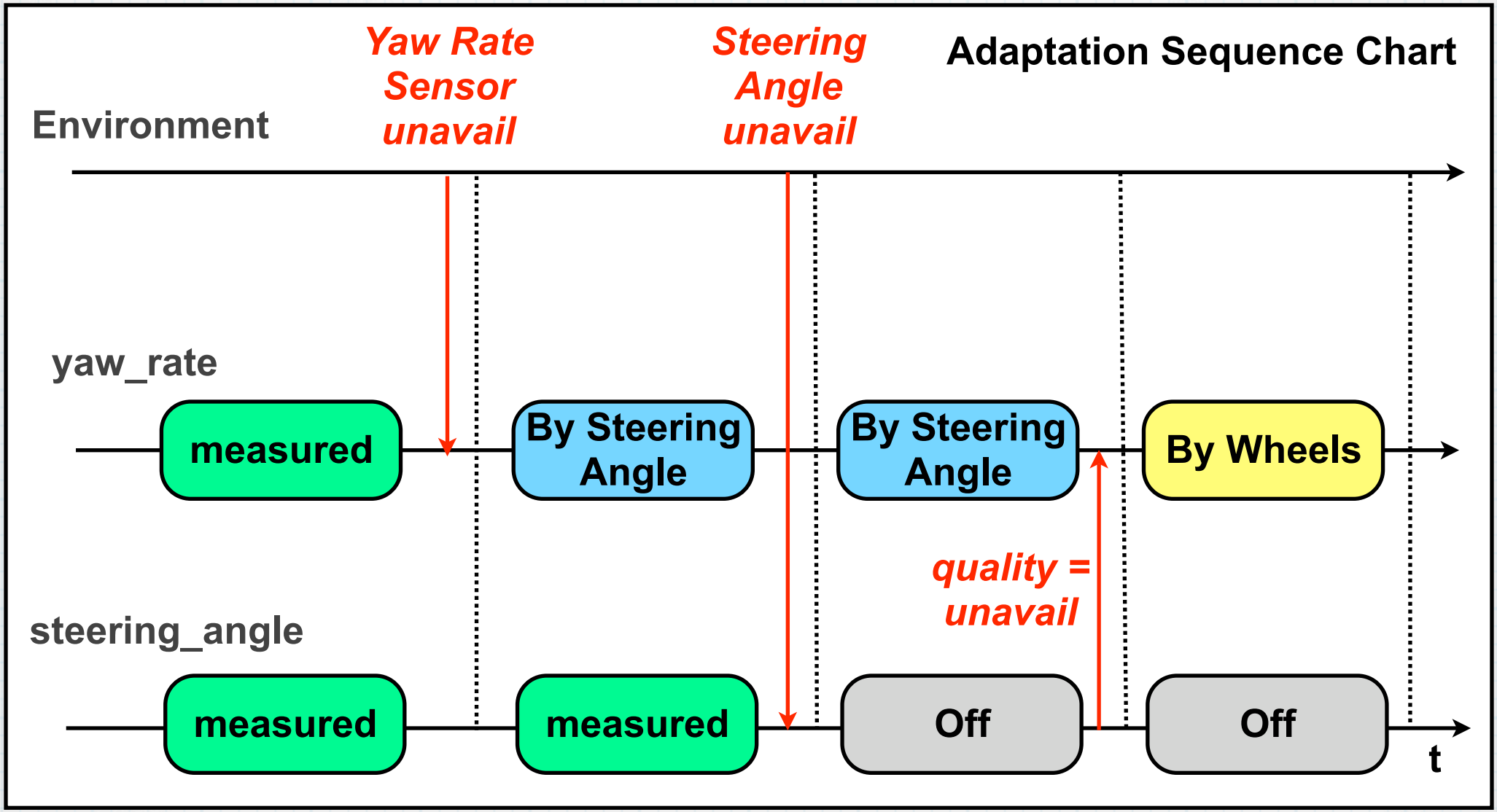
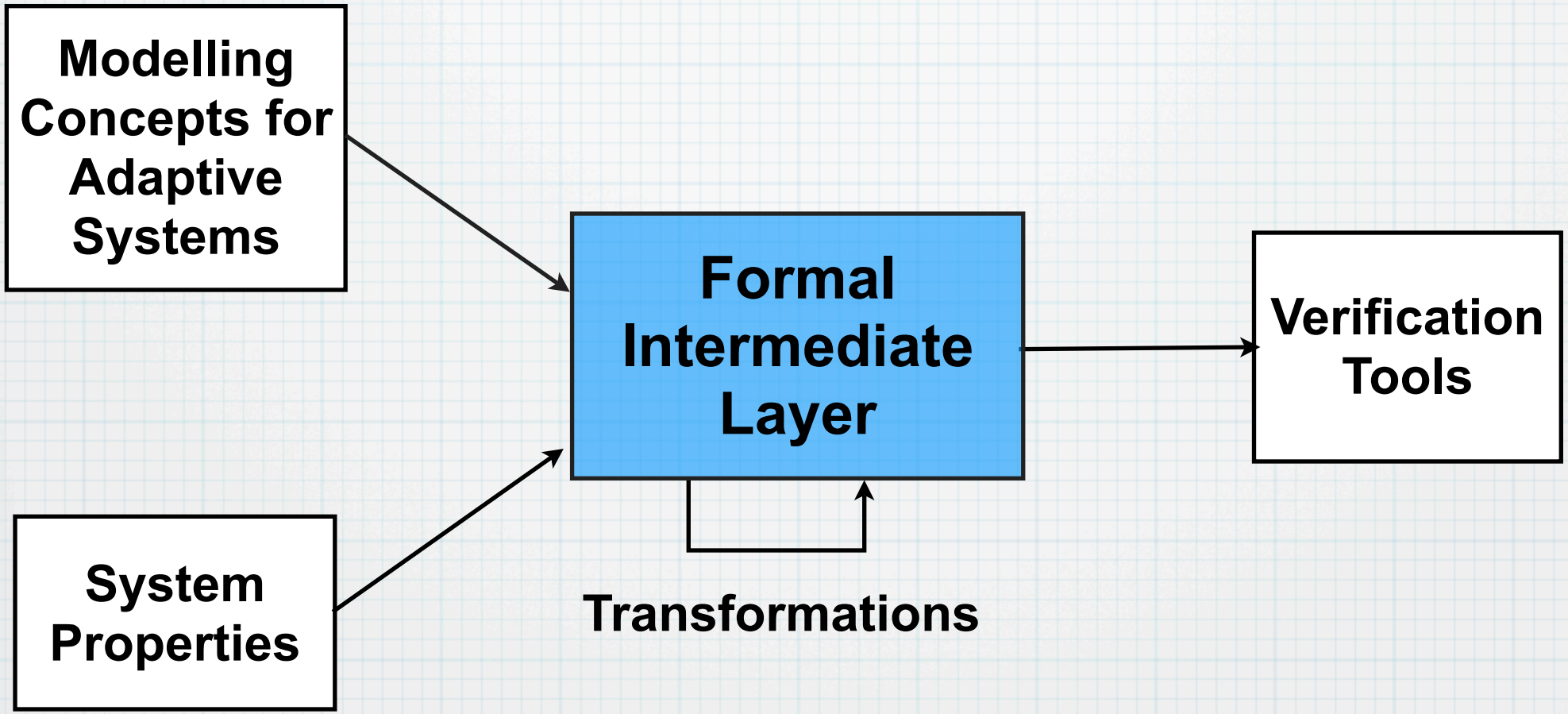


Integration - Outline



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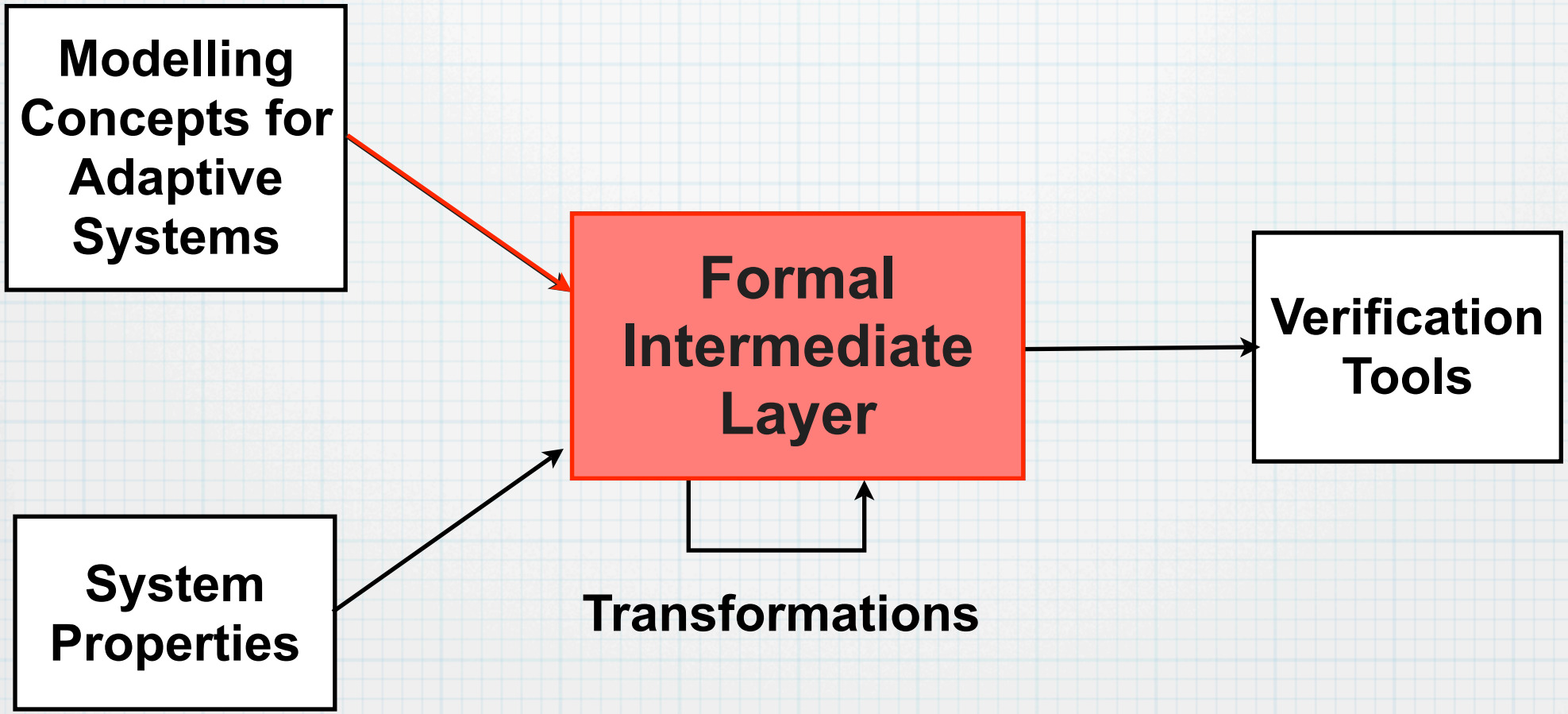


Synchronous Adaptive Systems

Design Goals:

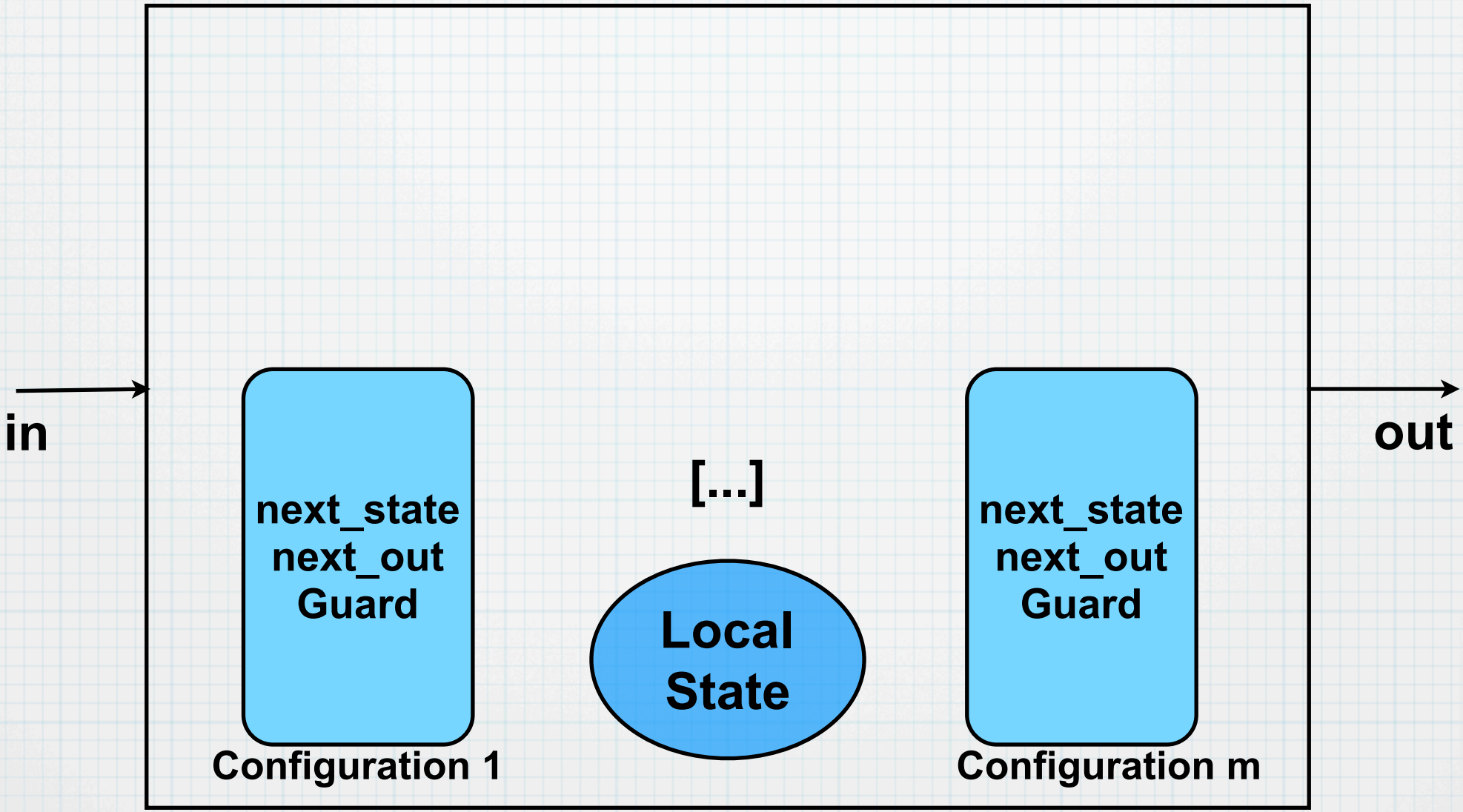
- Modular System Structure
- Explicit and Separated Modelling of Adaptation and Functionality
- Formal Mathematical Model

Main Concepts:

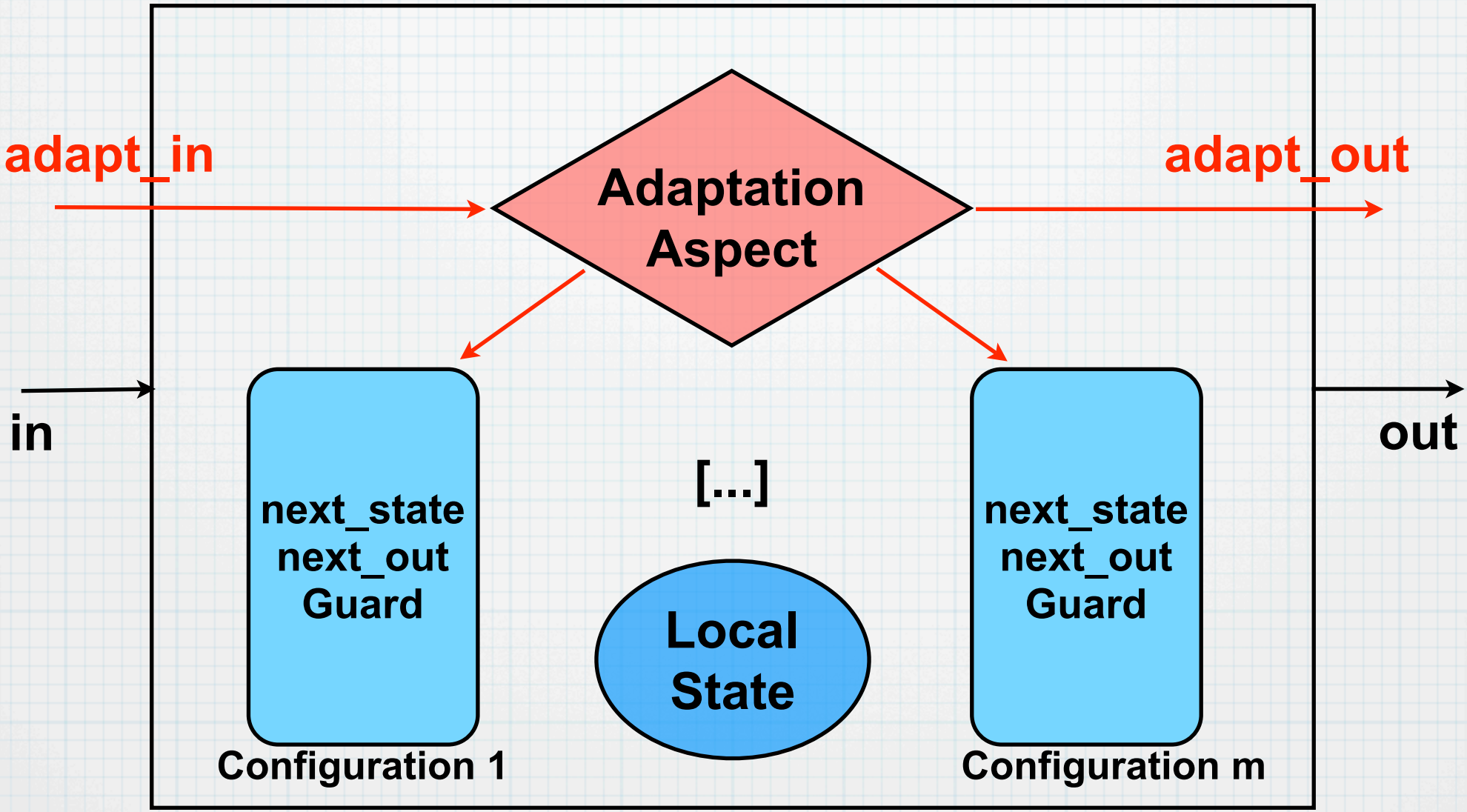
- Based on State-Transition Systems
- Uses Adaptation Aspect

SAS Module

SAS Module

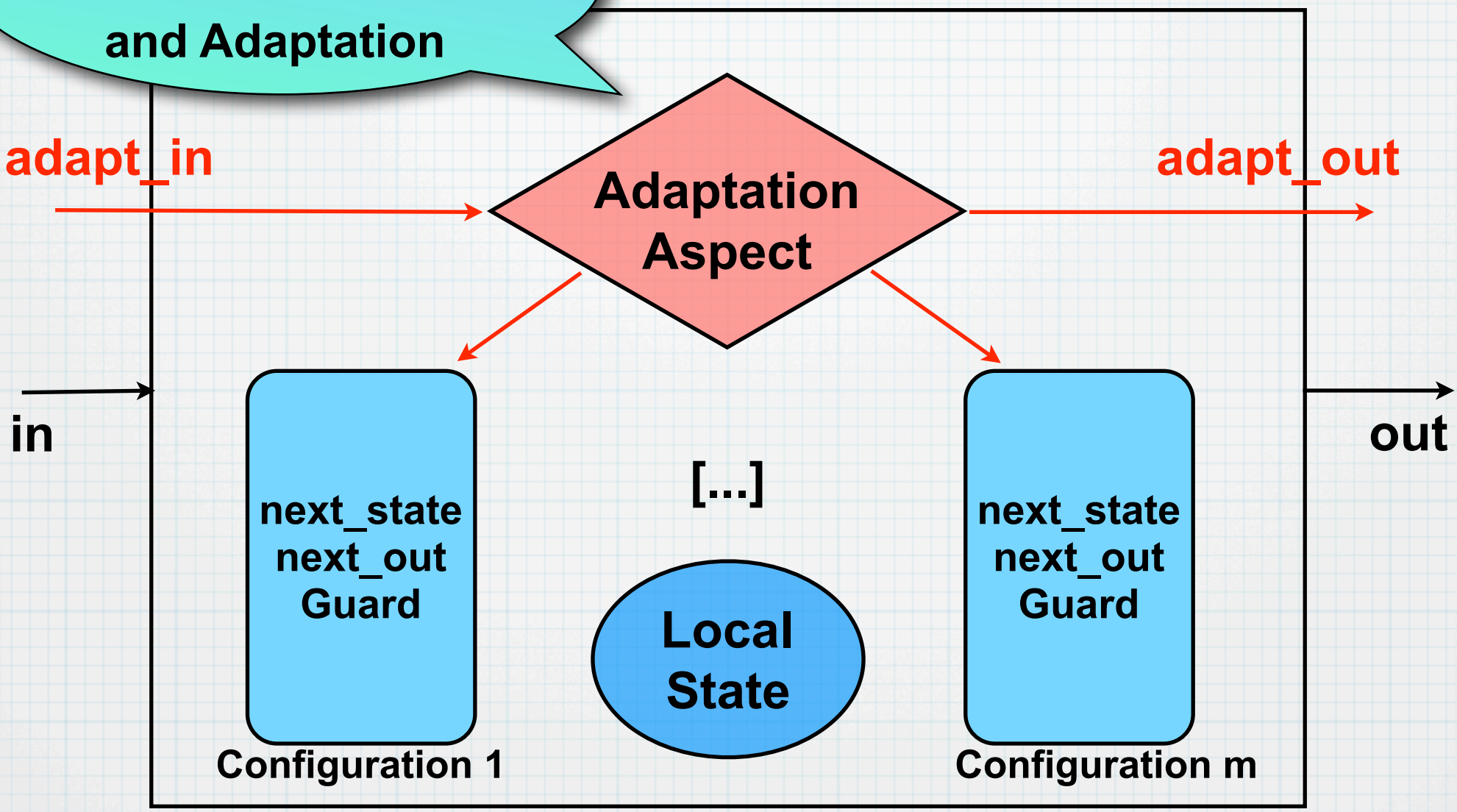

in
next_state
next_out
Guard
Configuration 1
[...]
Local
State
next_state
next_out
Guard
Configuration m
out

SAS Module


adapt_in
Adaptation Aspect
adapt_out
in
out
next_state
next_out
Guard
[...]
Local State
next_state
next_out
Guard
Configuration 1
Configuration m

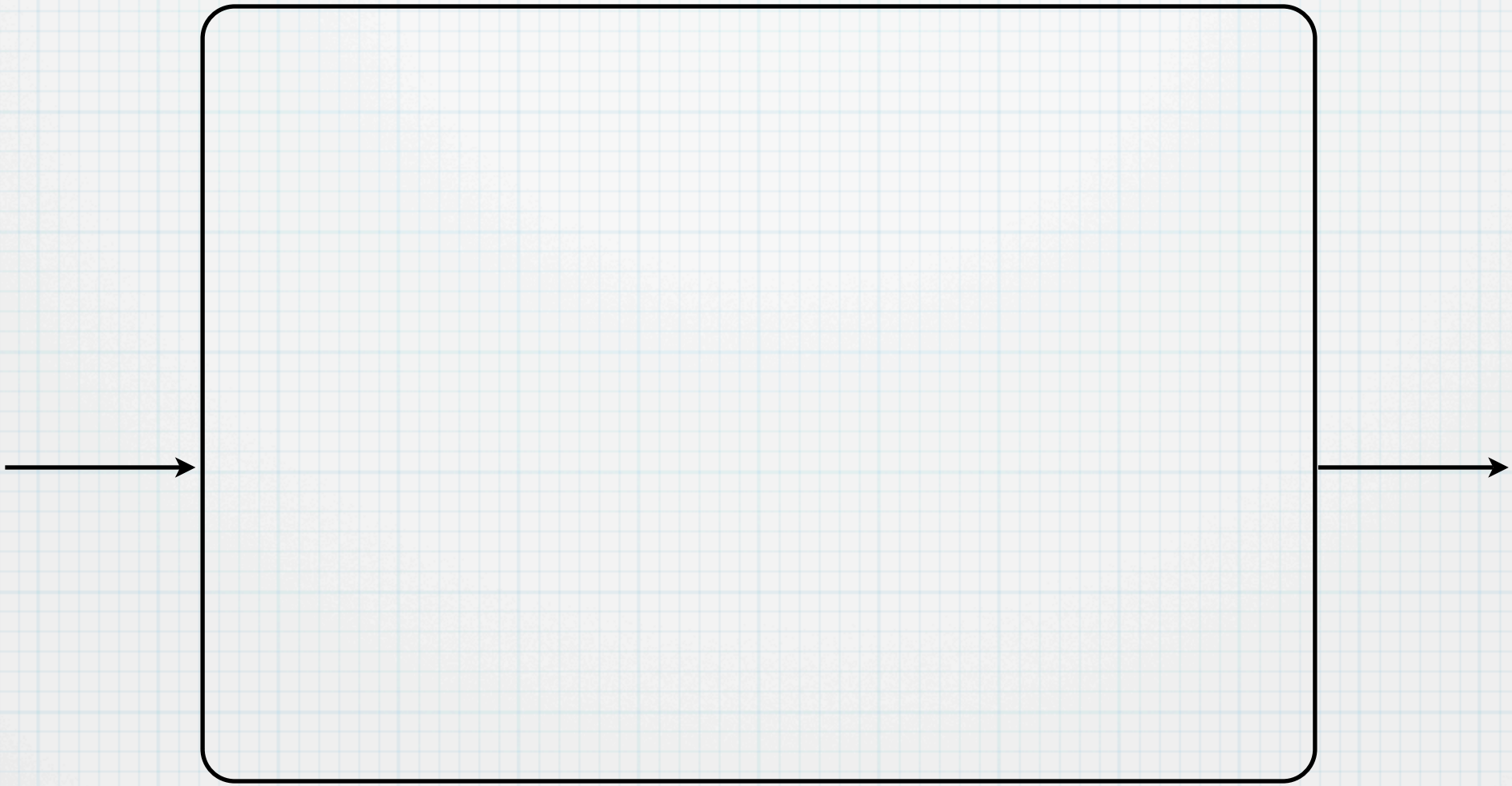
AS Module

Independent Modelling of Functionality and Adaptation



Traction Control System

Example: Yaw Rate Module



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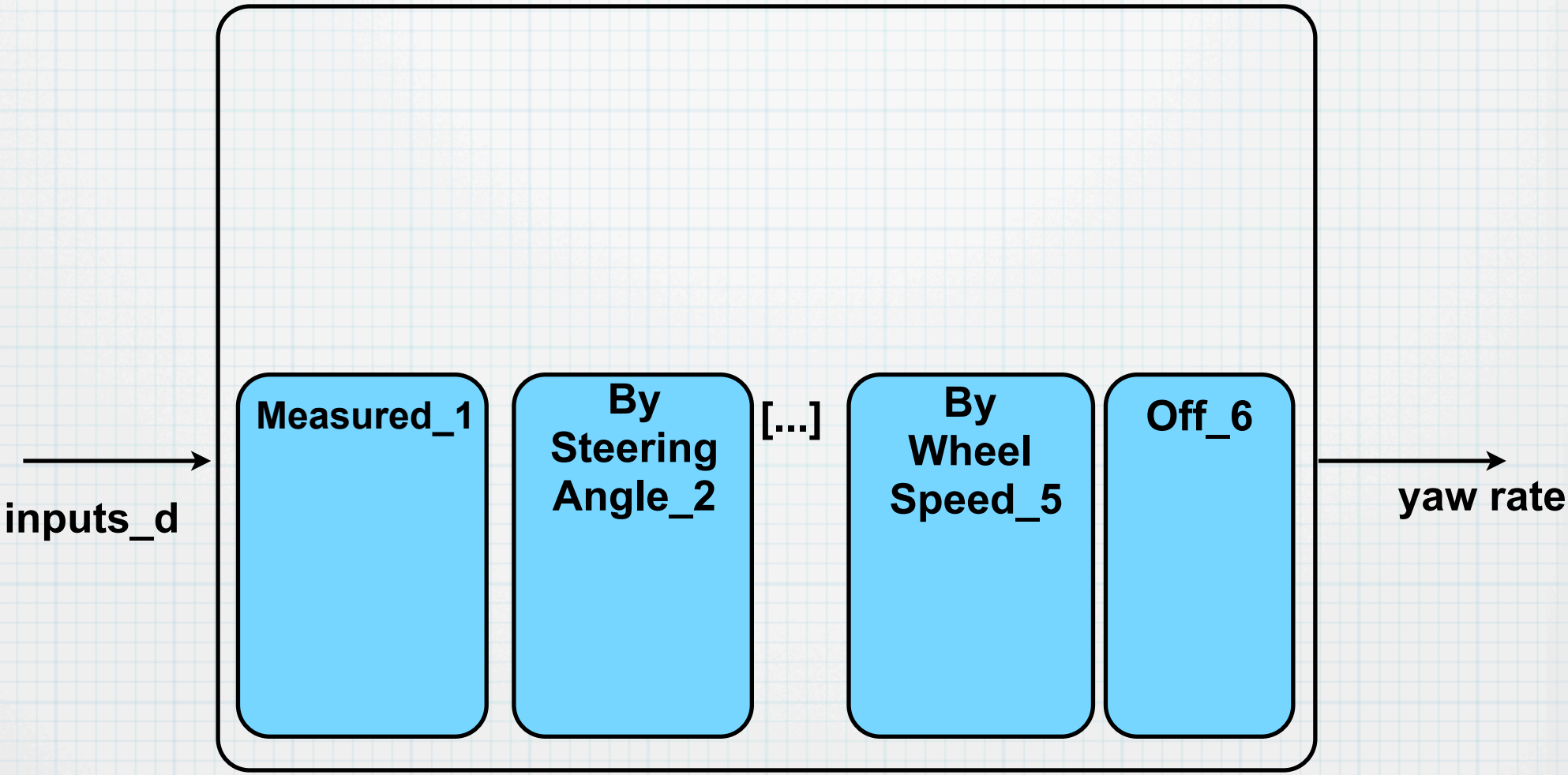

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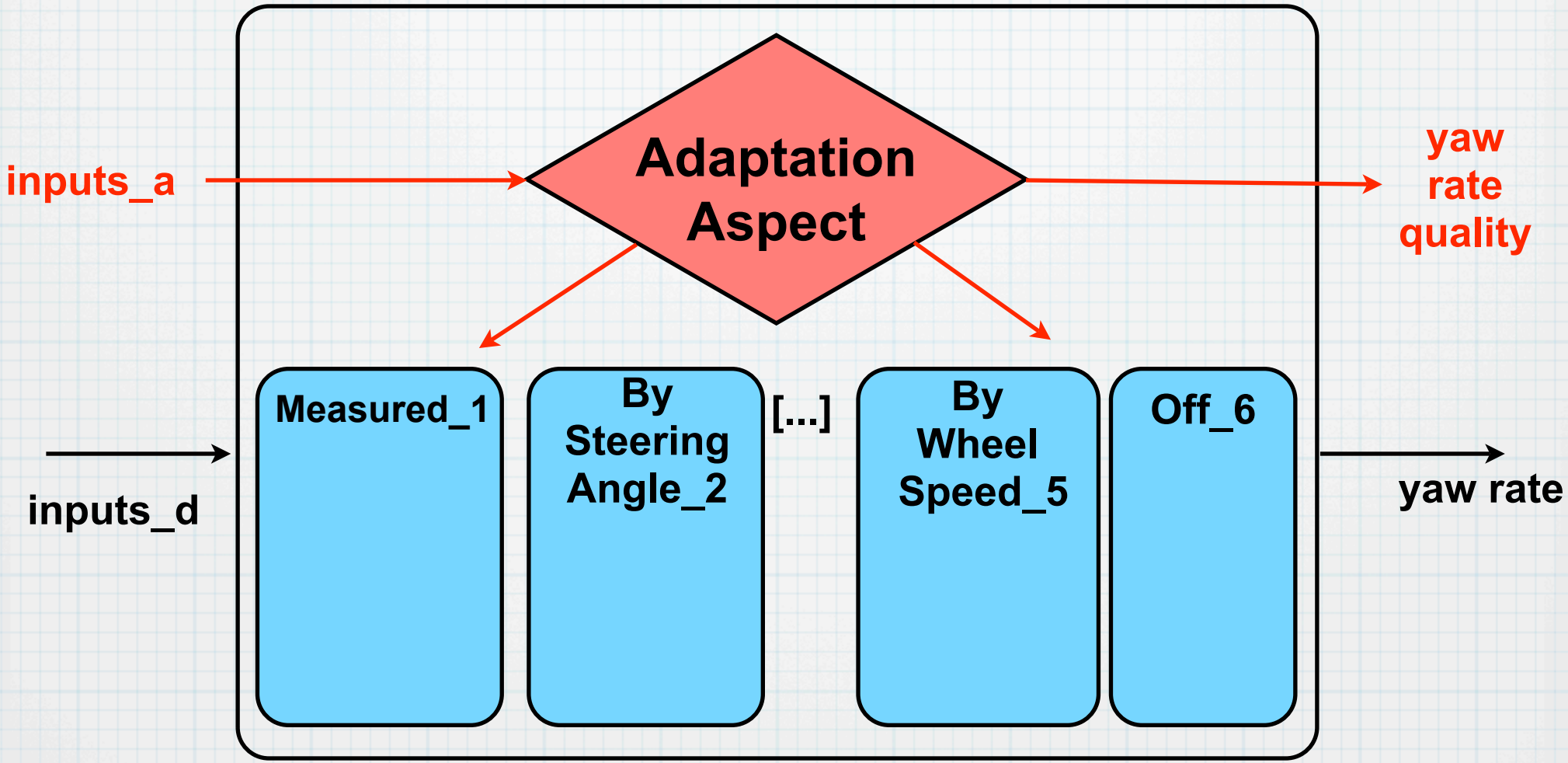

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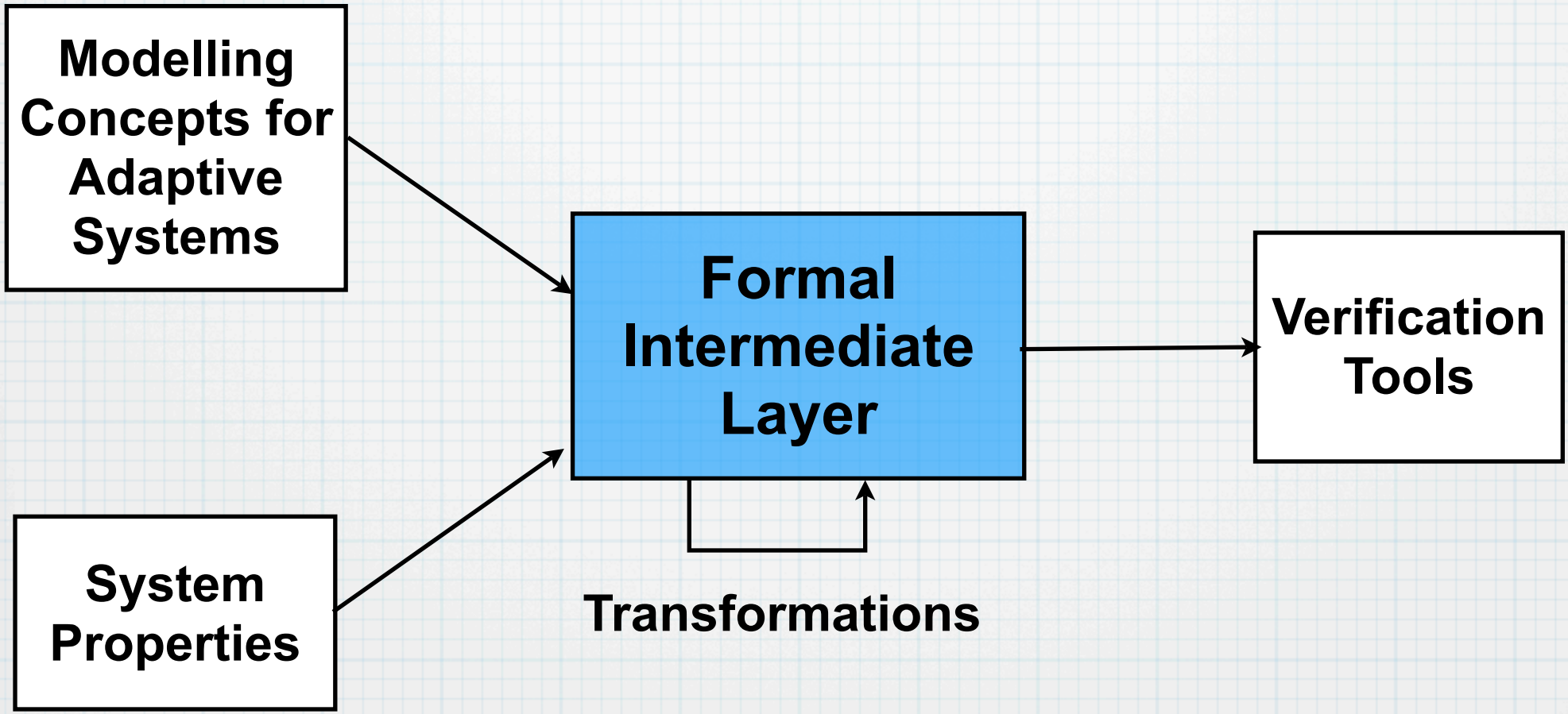

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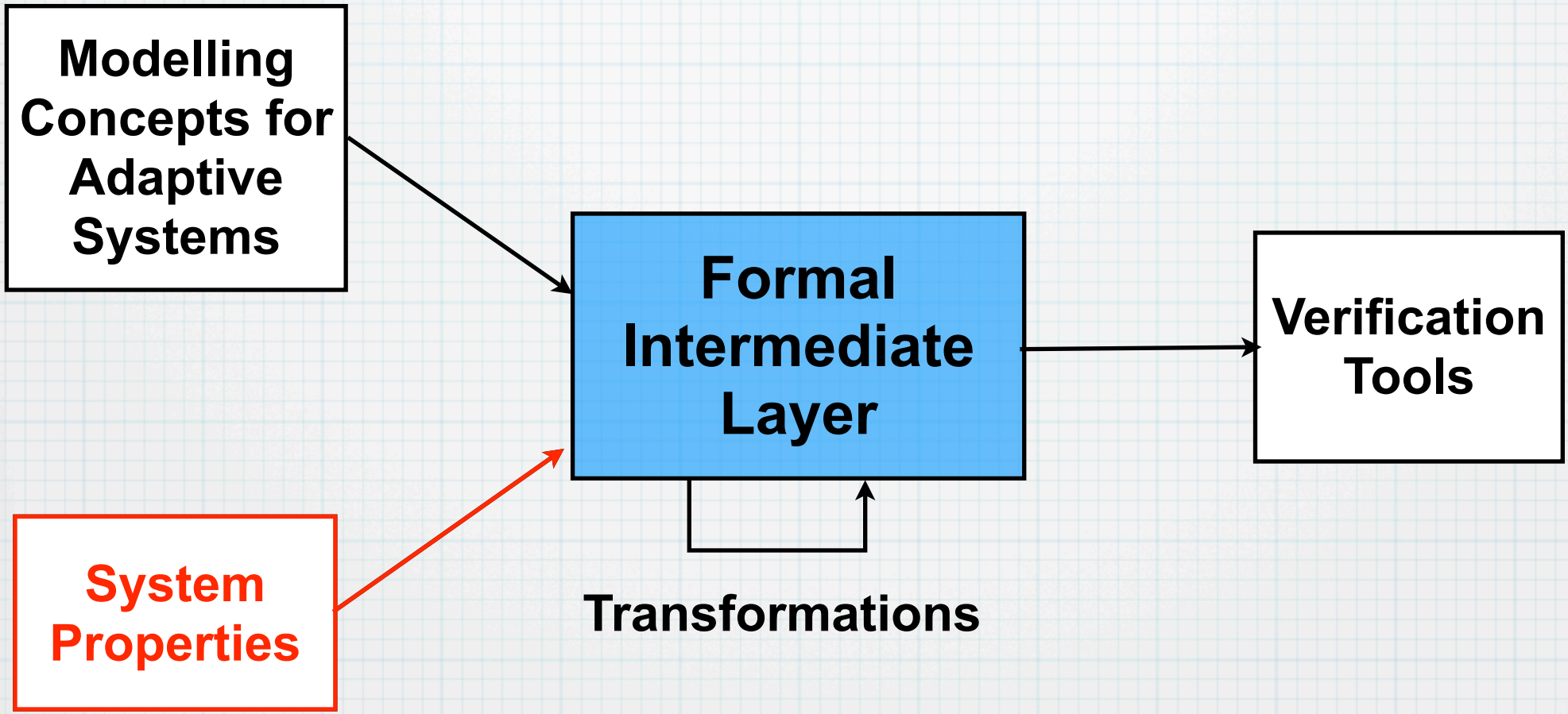
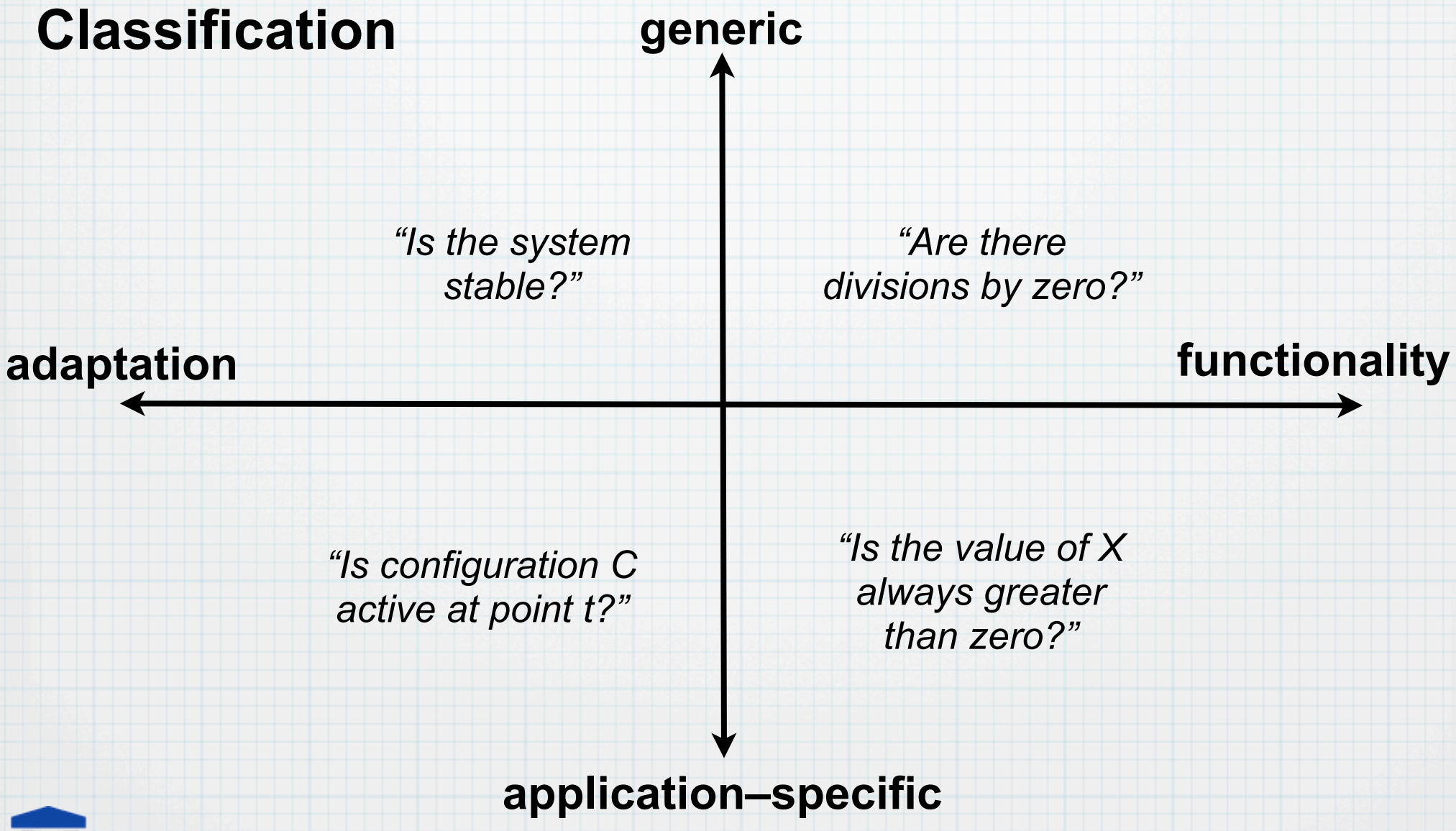


System Properties



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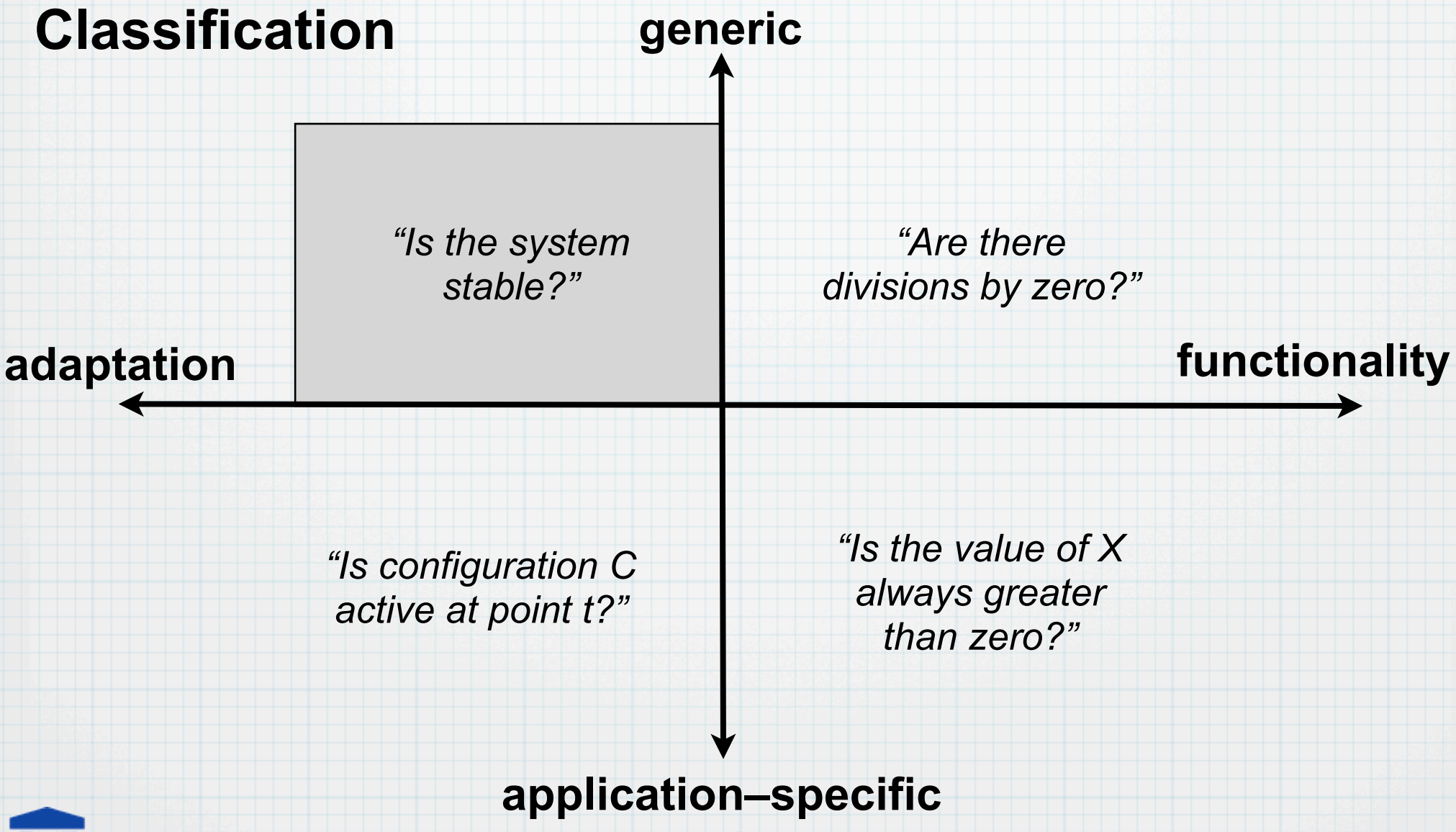


Adaptive Generic Properties

- **No module gets stuck in the default configuration ‘off ’:**

$$\mathsf{AG}(c = \text{off} \rightarrow \mathsf{EF} c \neq \text{off})$$

- **Every module can reach all configurations at all times:**

$$\mathsf{AG}(\bigwedge_{i=1}^{n} \mathsf{EF}\ c = \text{config}_i)$$

- **No inconsistent states can be reached:**

$$\mathsf{AG}(\bigvee_{i=1}^{n} c = \text{config}_i)$$

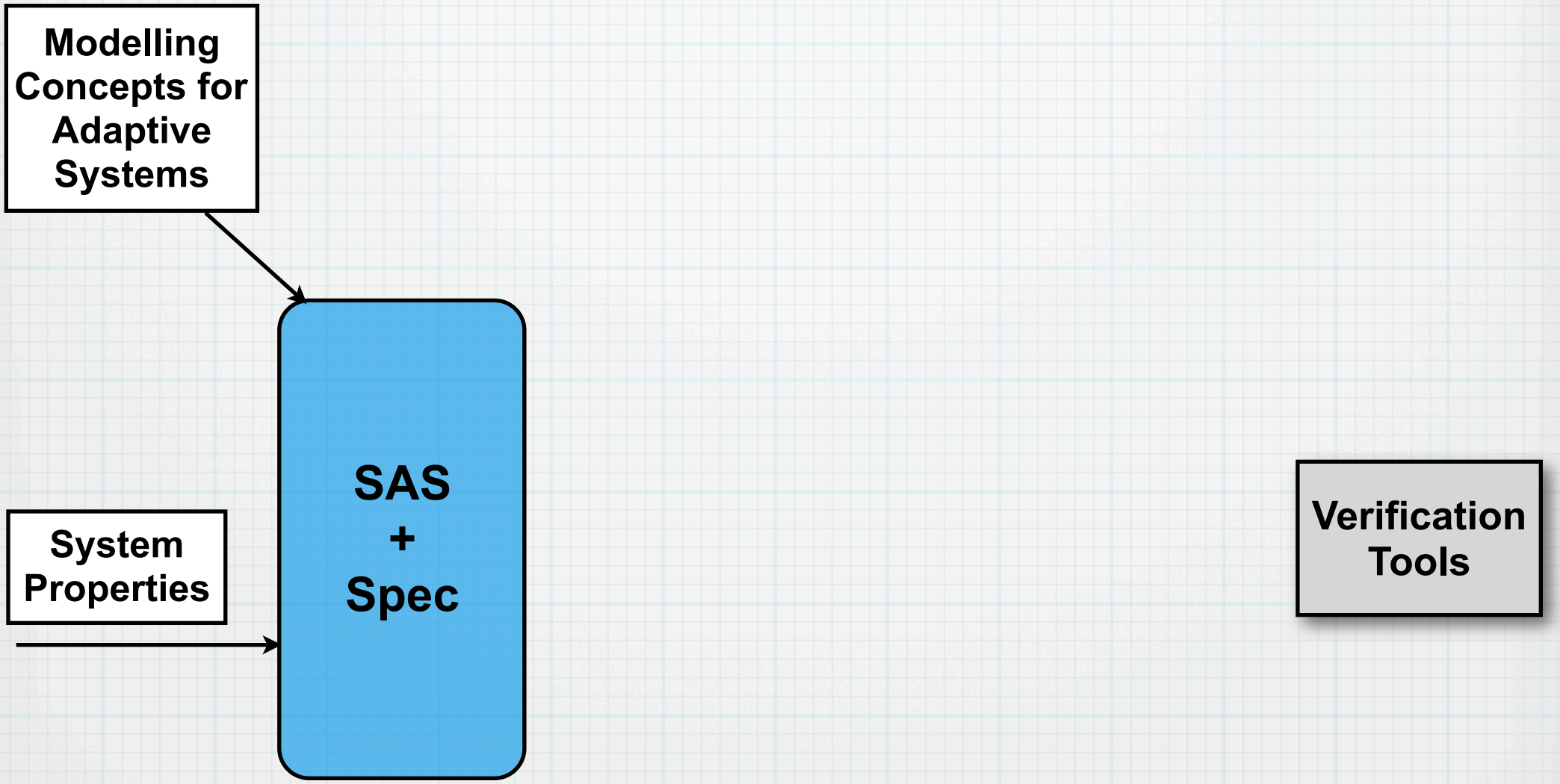
- **No configuration is always only transient:**

$$\bigwedge_{i=1}^{n} \mathsf{EFEG}\ c = \text{config}_i$$

Integration Framework

Modelling Concepts for Adaptive Systems

Integration Framework



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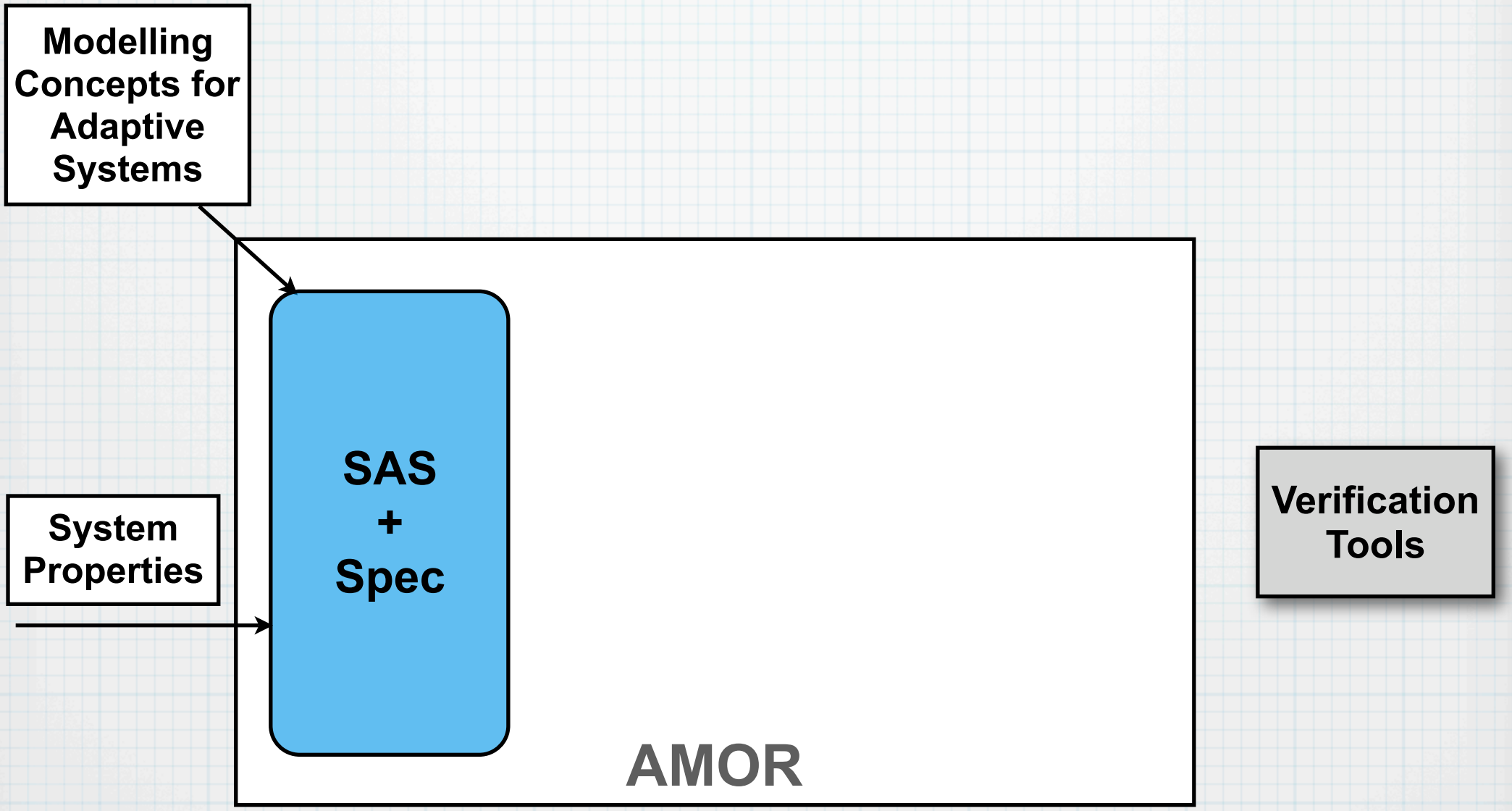

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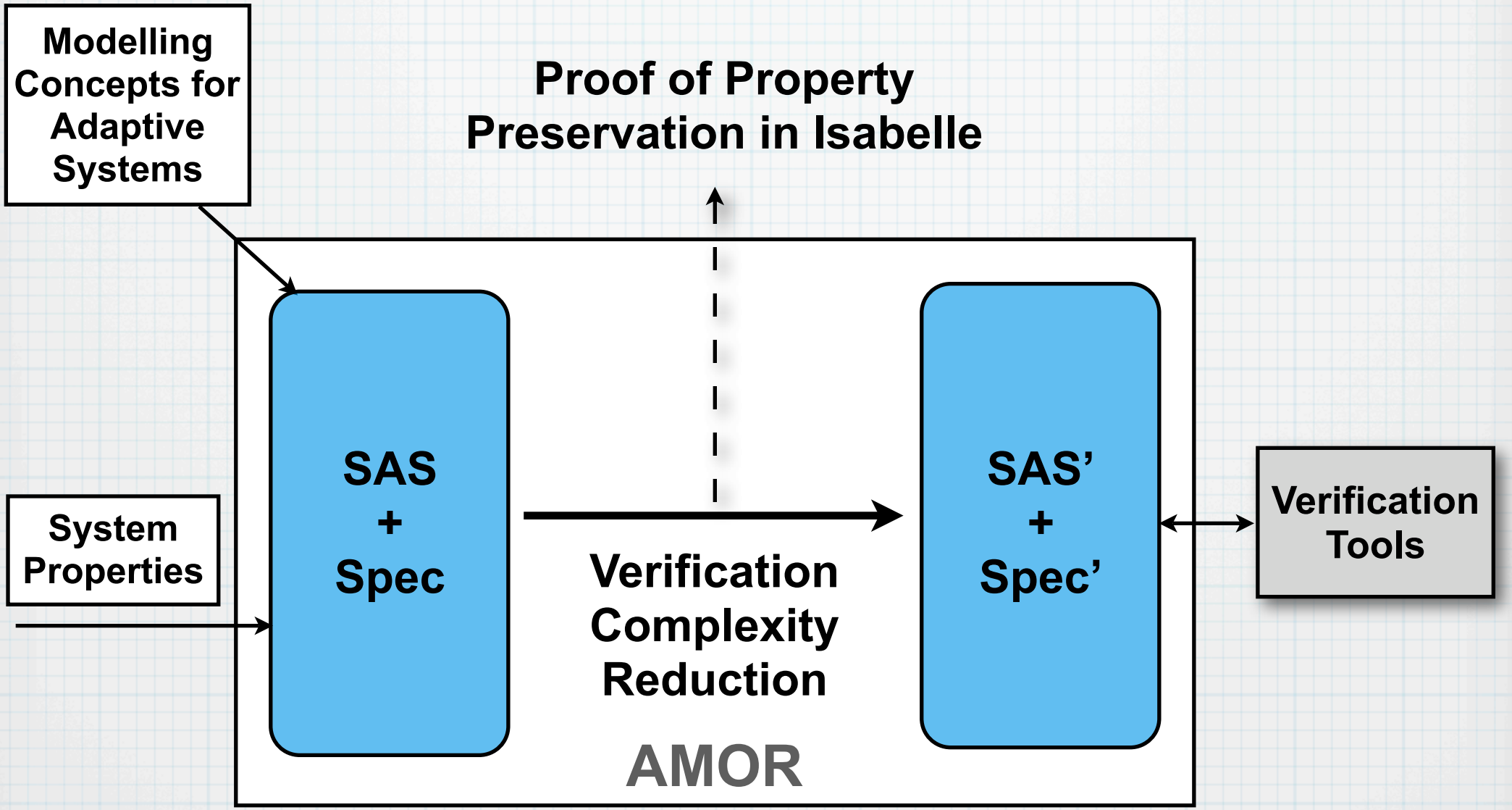

Verification Complexity Reductions

- Reductions by Slicing
- Data Domain Abstractions
- Compositional Reasoning

Stabilisation of Adaptation

If input is unchanged, configurations will stabilise.

AG(**G** same_inputs => **F G** same_configurations)

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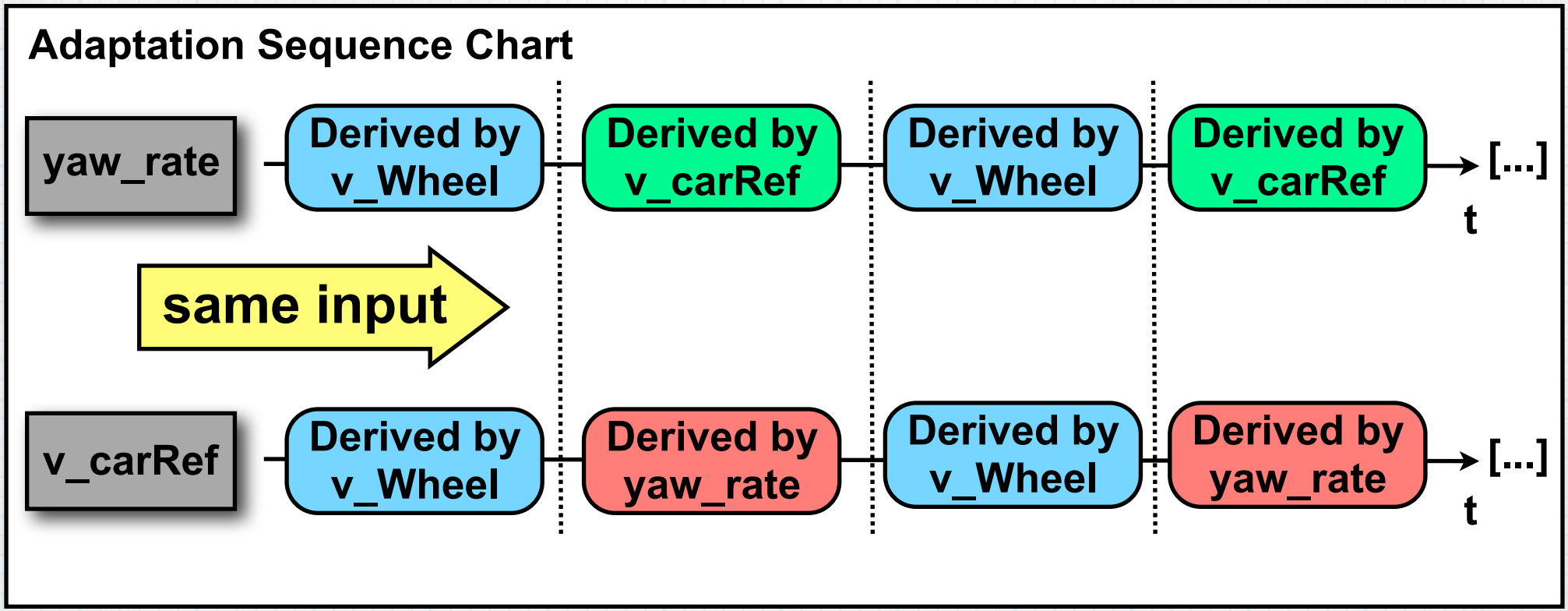

Verification of Stability

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- **can be checked by standard LTL model checking**
- **involves two alternating fixpoints ⇒ not very efficient**

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- **Alternative Procedure:**

  Analyse two systems with one independent fixpoint each

  1. **Original System ➢ set of reachable states**
  2. **System restricted to input steady paths without self-loops ➢ set of states with an infinite path (outputs not steady)**

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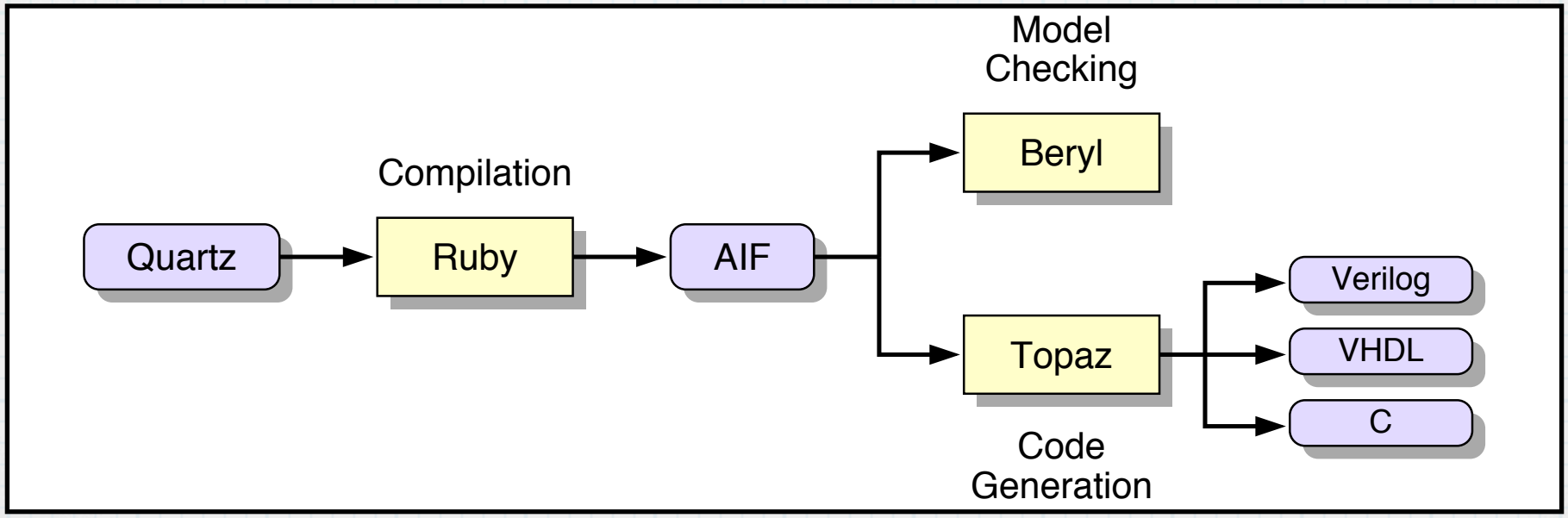
  2. **System restricted to input steady paths without self-loops**

     ➢ set of states with an infinite path (outputs not steady)

Theorem: Original system is stable iff intersection is empty!

Verification with AVEREST

- Framework for the development of reactive systems
- Quartz: synchronous language for describing parallel, deterministic systems
- Process communication and synchronisation part of the language



Experimental Results

Traction Control System:

28 modules, 70 configurations, > 2000 lines of Quartz code
151 generic adaptation properties

Generic specifications of adaptation behaviour

event variables	min. [s]	avg. [s]	max. [s]	total [s]
no	< 1	5	222	782

Stability of adaptation behaviour

LTL model checking: > 1h	**Specialised procedure: ~0.48h**

Related Work

Modelling and Verification of Adaptive Systems

- [Bradbury et al.; 2004]:
  Survey on Self-Managed Software Architectures

- [Zhang, Cheng; 2005/06]:
  Modelling and Verification of Adaptation Behaviour based on Petri Nets

- [Schneider, Schüle, Trapp; 2006]:
  Direct Translation of Modelling Concepts to Verification Tools

Conclusion

Main Results:

- **Modelling Concepts for Adaptive Systems**
- **Framework for Integration of Model-based Design and Formal Verification using with High-Level Formal Model and Automatic Transformations for Complexity Reduction**
- **Standard and Specialised Verification Techniques for Adaptive Systems**

Future Work

- Extension of Modelling Concepts with Intuitive Property Specification at Modelling Level
- Further Development of Reduction and Verification Techniques
- Propagation of Verification Results to Modelling Level