# A formal framework for multi-view modeling and the multi-view consistency problem


Maria Pittou
(joint work with Prof. Stavros Tripakis)

Aristotle University, School of Sciences, Department of Mathematics

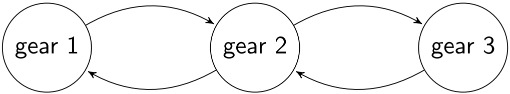

Seminar on TCS, 19/12/2018

- Powerful technique for reasoning about systems
- Provides abstractions of the system under development
- Detects errors and improves performance

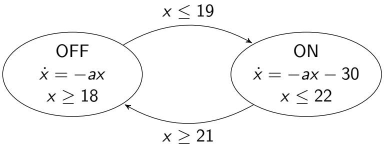
# Motivation

## System modeling formalisms

- State machines and automata

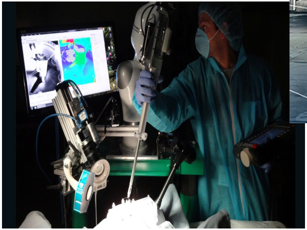



- Differential equations $\rightarrow$ physical plant of CPSs
- Timed and Hybrid Automata




Figures from: Viewpoints, Formalisms, Languages, and Tools for Cyber-Physical Systems, 2012, D. Broman et al.

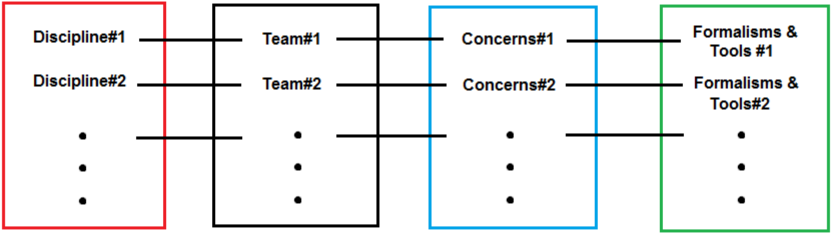
# Motivation
## Complex systems

# Motivation

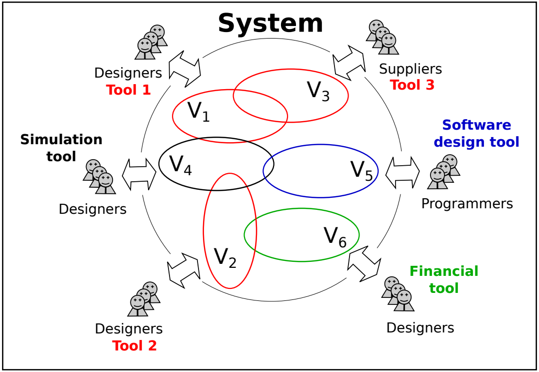
## Modeling of large and heterogeneous systems

The construction of any large and complex system involves multiple design teams with their own perspectives of the system.



# Motivation
## The multiple views of a system

The construction of any large and complex system involves multiple design teams with their own view of the system.

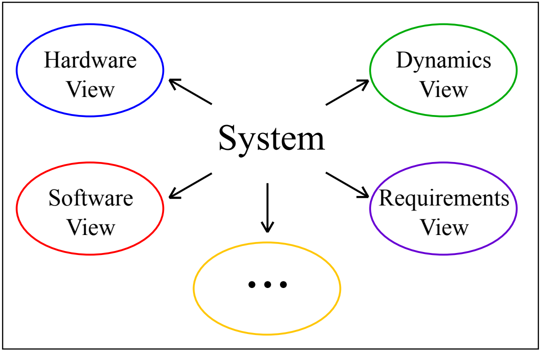



Modified figure from: Multi-view Modeling to Support Embedded Systems Engineering in SysML, A. A. Shah et al, 2010.

# Motivation

## Multi-view modeling (MVM)

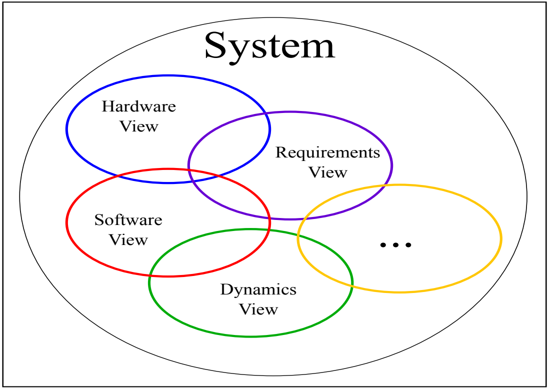
In multi-view modeling (MVM for short) the different stakeholders derive separate but yet related models, called views, of the same system.



# Motivation

## Multi-view consistency

One of the main challenges in multi-view modeling is to ensure consistency among the different views.



# Outline

# Related work

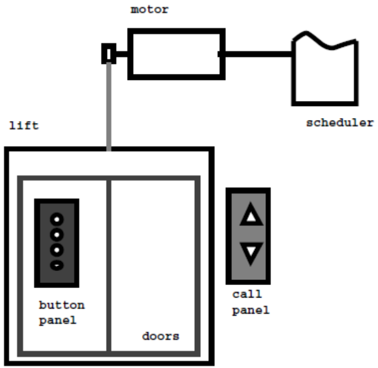
- Early work on multi-view modeling
- Multi-modeling languages
- Multi-view modeling for embedded and cyber-physical systems
- Other approaches to multi-view modeling
- A formal framework for multi-view modeling

# Related work

## Early work on MVM

- Viewpoints: A framework for integrating multiple perspectives in system development, 1992, A. Finkelstein et al.

- One of the first papers that studies the problem
- Informal framework illustrated by a lift system
- Tool support discussion



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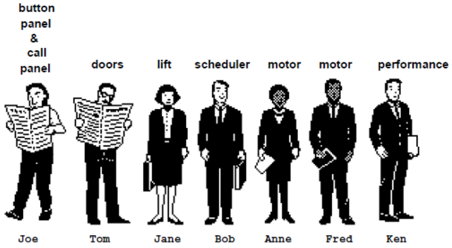
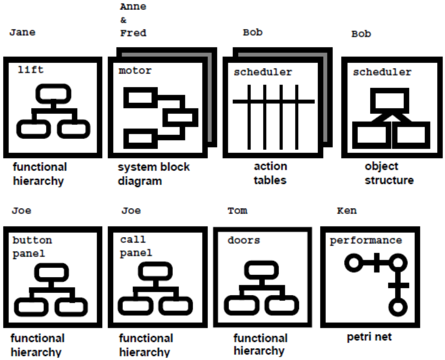


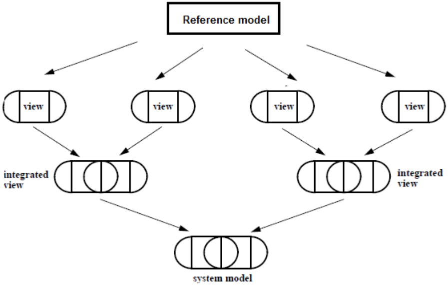



# Related work

## Early work on MVM

- Viewpoints: A combined reference model- and view- based approach to system specification, 1997, G. Engels et al.

- A reference model is used to generate the views




- View inconsistencies and integration
- Specification by graph transformations and illustration by a banking system

# Related work

## Early work on MVM

- Living with inconsistency in large systems, 1988, R. W. Schwanke and G. E. Kaiser

- Consistency with respect to type safety in programming languages
- Inconsistency is sometimes unavoidable and more effective
- CONMAN programming environment

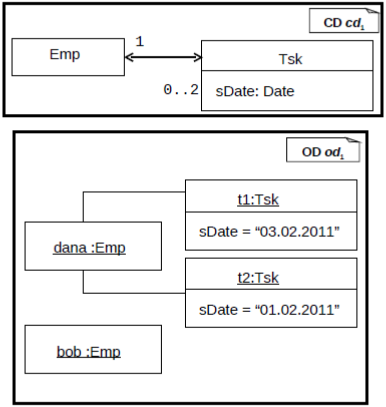
- Multi-view modeling is supported by multi-modeling languages
- Multi-modeling languages provide diagrams to specify abstractions of software and hardware systems
- UML and SysML are multi-modeling languages

# Related work

## Multi-modeling languages

- Semantically configurable consistency analysis for class and object diagrams, 2011, S. Maoz et al.

- Views of a system are described by class and object diagrams



# Related work

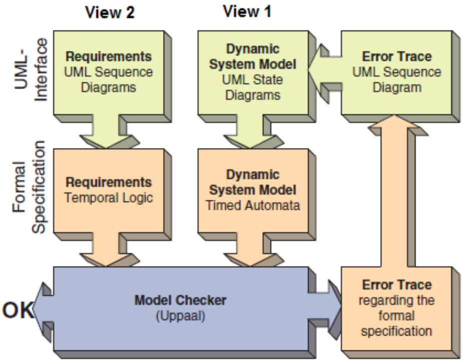
## Multi-modeling languages

- Semantically configurable consistency analysis for class and object diagrams, 2011, S. Maoz et al.

- Views of a system are described by class and object diagrams
- Semantic consistencies are investigated
- Automated consistency checking

- Vooduu: Verification of Object-Oriented Designs Using UPPAAL, 2004, K. Diethers and M. Huhn

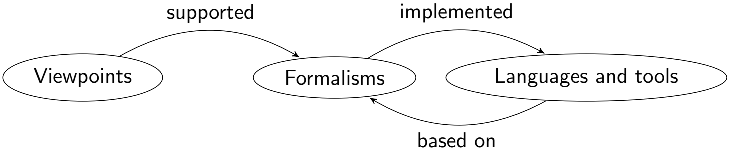
- Views are state or sequence diagrams with timing constraints
- Multi-view consistency is reduced to model checking
- Tool that enables verification of UML diagrams



# Related work

## Multi-view modeling for embedded and cyber-physical systems

- Viewpoints, Formalisms, Languages, and Tools for Cyber-Physical Systems, 2012, D. Broman et al.



- A Characterization of Integrated Multi-View Modeling in the Context of Embedded and Cyber-Physical Systems, 2013, M. Persson et al.

- View relations for describing multi-view systems
- Main characteristics of views and basic challenges in multi-view modelling
- A nice survey on different approaches to MVM

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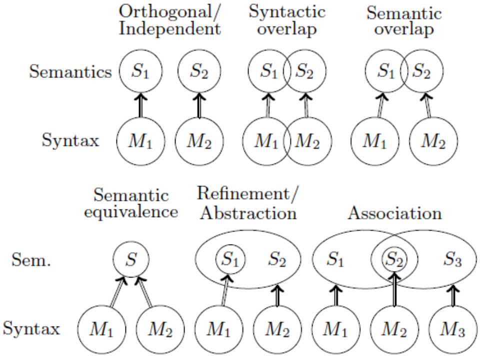



Content relationships between views.

- A Characterization of Integrated Multi-View Modeling in the Context of Embedded and Cyber-Physical Systems, 2013, M. Persson et al.

- View relations for describing multi-view systems
- Main characteristics of views and basic challenges in multi-view modelling
- A nice survey on different approaches to MVM

# Related work

## Other approaches to multi-view modeling

- Metamodeling
- Aspect-Oriented Modeling
- Interface Theories

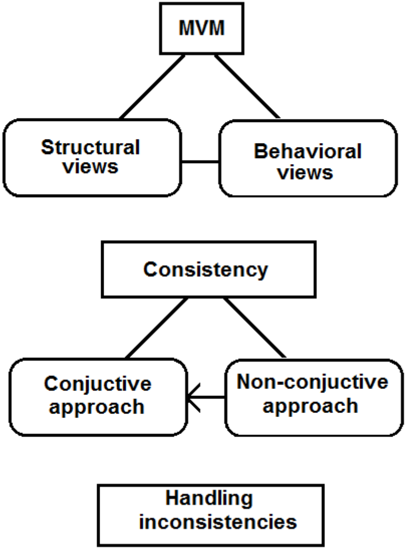
## A formal framework for multi-view modeling

- Basic problems in multi-view modeling, 2014, J. Reineke and S. Tripakis.
- Basic problems in multi-view modeling, 2016 (journal version), J. Reineke, C. Stergiou and S. Tripakis.

- Checking multi-view consistency of discrete systems with respect to periodic sampling abstractions, 2018, M. Pittou, P. Manolios, J. Reineke and S. Tripakis.

# Related work

## Methods on MVM



# Related work

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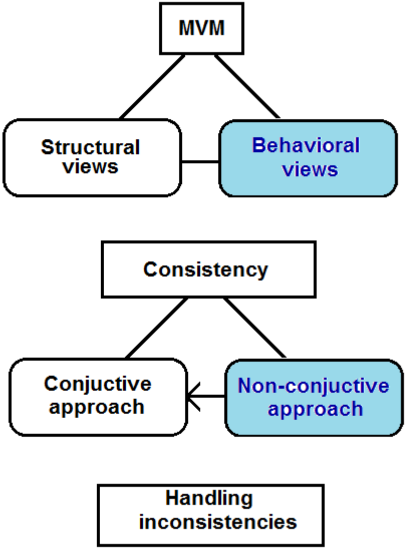


# Outline

## Problem to be solved

Given a (finite) set of views, are they consistent?

↓

1) How are the views (and the system) defined?

2) How are the views derived from the system?

3) What does view consistency mean?

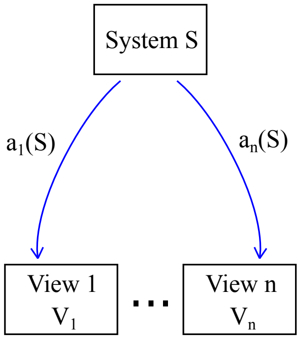
4) How do we synthesize a system from its views?

# Formal framework for multi-view modeling

## System, views and abstraction functions

Systems and views are defined semantically.

- System $S$: set of behaviors
- View $V$: set of behaviors
- Abstraction function $V = a(S)$



Views are intuitively an incomplete picture of a system.

- Some behaviors may be missing from the view
- Some parts of a behavior itself may be missing in the view.
- A view may be obtained by some other kind of transformation

Examples from: Basic problems in multi-view modeling, 2014, J. Reineke and S. Tripakis.

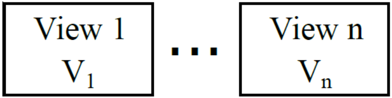
# Formal framework for multi-view modeling

## System, views, and abstraction functions notations

- $U$ is the set of all possible system behaviors
- $S \subseteq U$ is a system
- $D_i$ denotes the set of view behaviors
- $V_i \subseteq D_i$ is a view
- $a_i : U \rightarrow D_i$ is an abstraction fuction

# Formal framework for multi-view modeling

## The multi-view consistency problem



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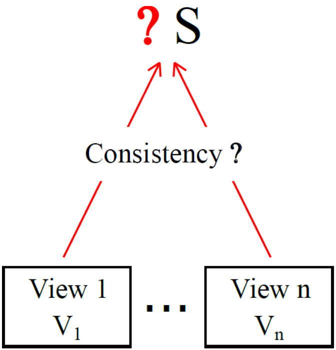

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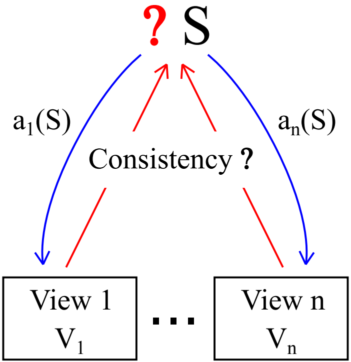
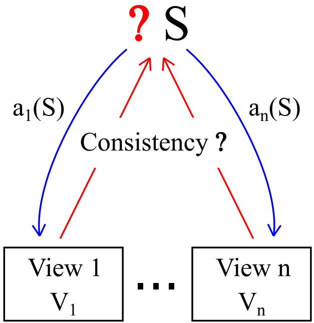
## The multi-view consistency problem



### View consistency

The views $V_1, \dots, V_n$ over view domains $D_1, \dots D_n$ are *consistent with respect to the abstraction functions* $a_1, \dots, a_n$, if there exists a system $S$ over $U$ so that

$$V_1 = a_1(S), \dots, V_n = a_n(S).$$



**View consistency**

The views $V_1, \ldots, V_n$ over view domains $D_1, \ldots D_n$ are *consistent with respect to the abstraction functions $a_1, \ldots, a_n$*, if there exists a system $S$ over $U$ so that

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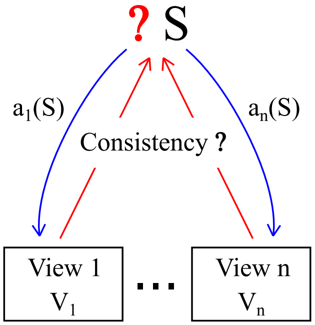



- We call such a system $S$ a *witness system* to the consistency of $V_1, \ldots, V_n$.
- If there is no such system, then we say that the views are inconsistent.

# Consistency as a special case of conformance

- Consistency is described by strict equality $V = a(S)$.
- Consistency is a special case of conformance.
- Conformance expresses how faithful is a view to a system.

# Consistency as a special case of conformance

- Conformance expresses how faithful is a view to a system.
- Conformance is defined w.r.t. a partial order $\sqsubseteq$ on the powerset of a view domain $D$.
- A view conforms to a system w.r.t. $a$ iff $V \sqsupseteq a(S)$.
- Consistency $V = a(S)$ is a special case of conformance.

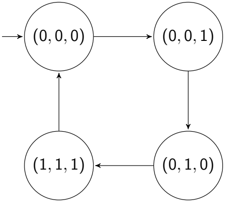
# Outline

# Contributions to the formal framework

- Basic problems in multi-view modeling, 2014.

  → **System, Views**: symbolic discrete systems (transition systems).

  → **Abstraction functions:** variable hidings.



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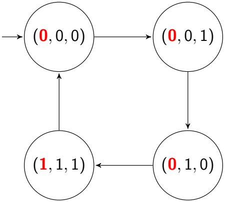

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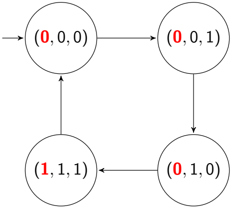
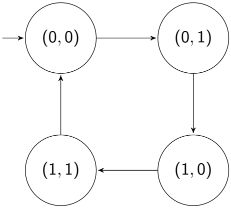


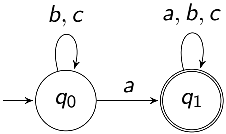



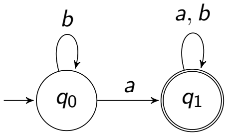
# Contributions to the formal framework

- Basic problems in multi-view modeling (journal version), 2017.

  → **System, Views**: either finite automata or $\omega$-finite automata

  → **Abstraction functions:** projections of an alphabet of events onto a subalphabet.



# Contributions to the formal framework

- Checking multi-view consistency of discrete systems with respect to periodic sampling abstractions, 2018.

  → **System, Views**: symbolic transition systems or Buchi automata

  → **Abstraction functions:** timing abstractions (periodic samplings)

↬ A **necessary and sufficient** condition for **view consistency independent** of the particular **instantiation** of systems, views, and abstraction functions

# Contributions to the formal framework

## Motivation for the instantiations of formal MVM framework

- Buchi automata and symbolic transition systems are prominent modeling structures
- Both are used by widespread verification tools such as SMV or Spin
- Sampling (time-driven/periodic, or event-driven) is a widely used mechanism in observation, control, embedded software etc

  $\rightarrow$ example: drive-by-wire system in a modern car (sensors are periodically sampling some physical values)

# Outline

1. Motivation for multi-view modeling
2. Related work
3. Formal framework for multi-view modeling
4. Contributions to the formal framework
5. Generic algorithm for checking view consistency
6. Challenges in MVM and future work

# Canonical witness system candidate

## Canonical witness system candidate

- $V_1, \ldots, V_n$ are views
- $a_1, \ldots, a_n$ respective abstraction functions

$$S = \bigcap_{i=1}^{n} a_i^{-1}(V_i)$$

**Theorem**

$V_1, \ldots, V_n$ are consistent iff for all $i = 1, \ldots, n$ it holds that $a_i(S) = V_i$.

$\looparrowright$ The canonical witness $S$ is the most general witness.

# Generic algorithm for checking view consistency

### Canonical witness system candidate

- $V_1, \ldots, V_n$ are views
- $a_1, \ldots, a_n$ respective abstraction functions

$$S = \bigcap_{i=1}^{n} a_i^{-1}(V_i)$$

### Algorithm to check view consistency

1. Compute $S$, i.e., compute the inverse abstractions $a_i^{-1}(V_i)$ and their intersection.
2. Compute $a_i(S)$ and check whether $a_i(S) = V_i$.

# *Instantiating the generic algorithm

### Algorithm to check view consistency

1. Compute $S = \bigcap_{i=1}^{n} a_i^{-1}(V_i)$
2. Compute $a_i(S)$ and check whether $a_i(S) = V_i$.

### Checking consistency of two Büchi automata views

- $V_1$ and $V_2$ are nondeterministic Büchi automata (NBA).
- $a_1^{-1}$ and $a_2^{-1}$ are inverse periodic samplings.
- $S = a_1^{-1}(V_1) \cap a_2^{-1}(V_2)$ is NBA intersection.
- $a_1(S)$ and $a_2(S)$ are periodic samplings.
- $a_1(S) = V_1$ and $a_2(S) = V_2$ is an NBA language equivalence problem.

# *Checking consistency of discrete systems w.r.t. periodic sampling

## Overview of results

- Checking multi-view consistency of discrete systems with respect to periodic sampling abstractions, 2018

- A necessary and sufficient condition for checking view consistency.
- Solution for the multi-view consistency problem for views described by NBA.
- Solution for the multi-view consistency problem for views described by symbolic transition systems.
- Complexity analyses for the various algorithms.

# Outline

1. Motivation for multi-view modeling
2. Related work
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6. Challenges in MVM and future work

# Main challenges in MVM

- View consistency
- Conformance checking
- View reduction
- Orthogonality of views
- Extendability of views
- Automation, view reuse, change propagation...

# Future work

## For the formal framework of MVM

- Heterogeneous instantiations of the formal MVM framework.
- Real case study for the formal MVM framework.

*Thank you!*