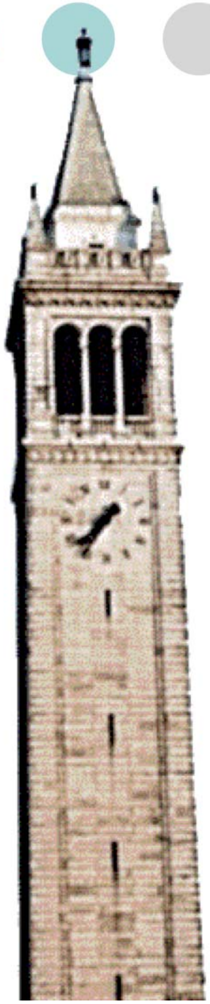

Correctly Composing Components: *Ontologies and Modal Behaviors*

Edward A. Lee

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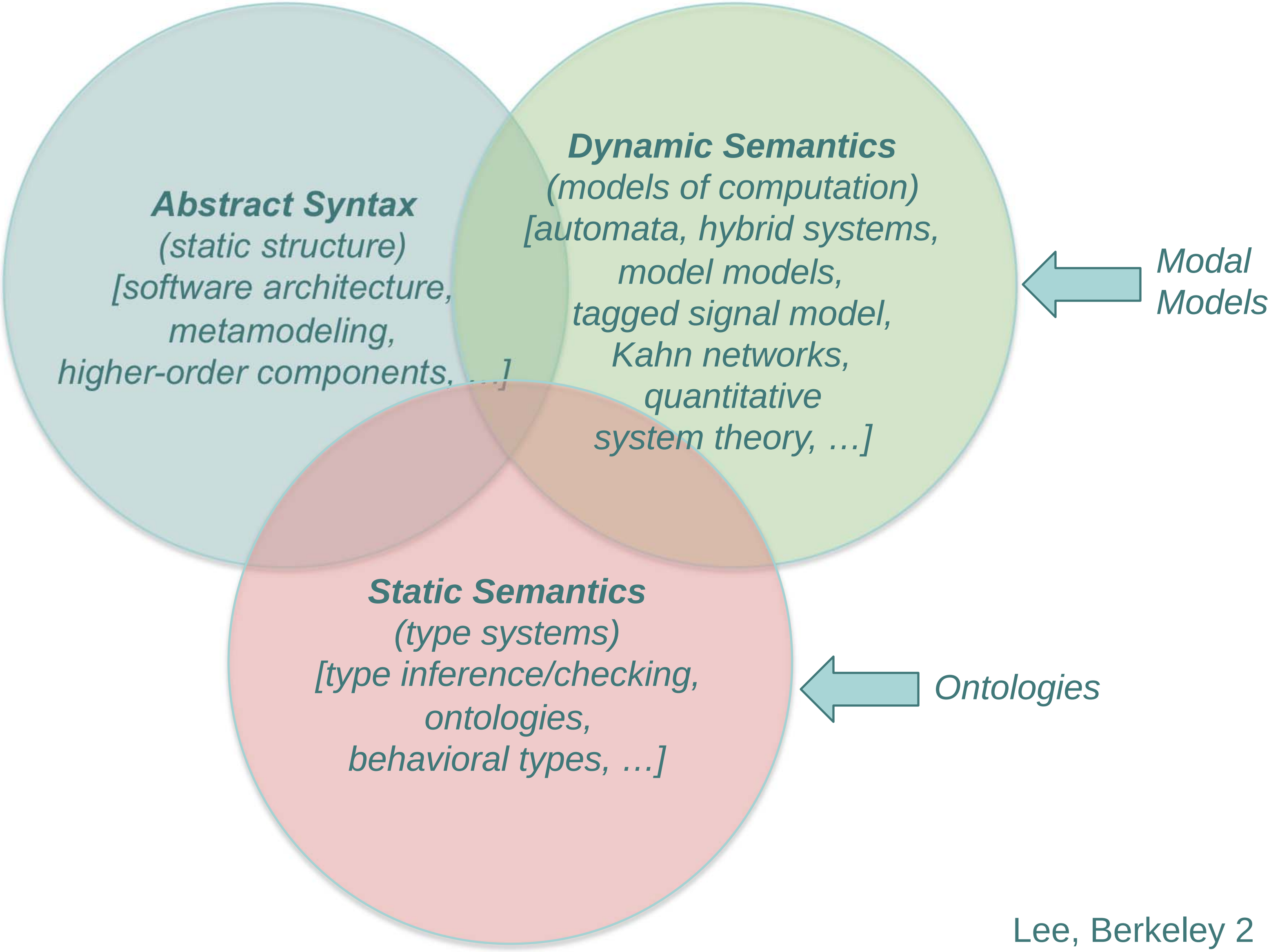
UC Berkeley

With: Ben Lickly, Man-Kit Leung, Thomas Mandl,
Elizabeth Latronico (Bosch), Charles Shelton (Bosch), Stavros Tripakis

MURI Review

December 2, 2009
Berkeley, CA

A Taxonomy of Modeling Issues



Abstract Syntax
(static structure)
[software architecture,
metamodeling,
higher-order components, …]

Dynamic Semantics
(models of computation)
[automata, hybrid systems,
model models,
tagged signal model,
Kahn networks,
quantitative
system theory, …]

Static Semantics
(type systems)
[type inference/checking,
ontologies,
behavioral types, …]

Modal
Models

Ontologies

Reporting Progress in Two Dimensions of Model Engineering

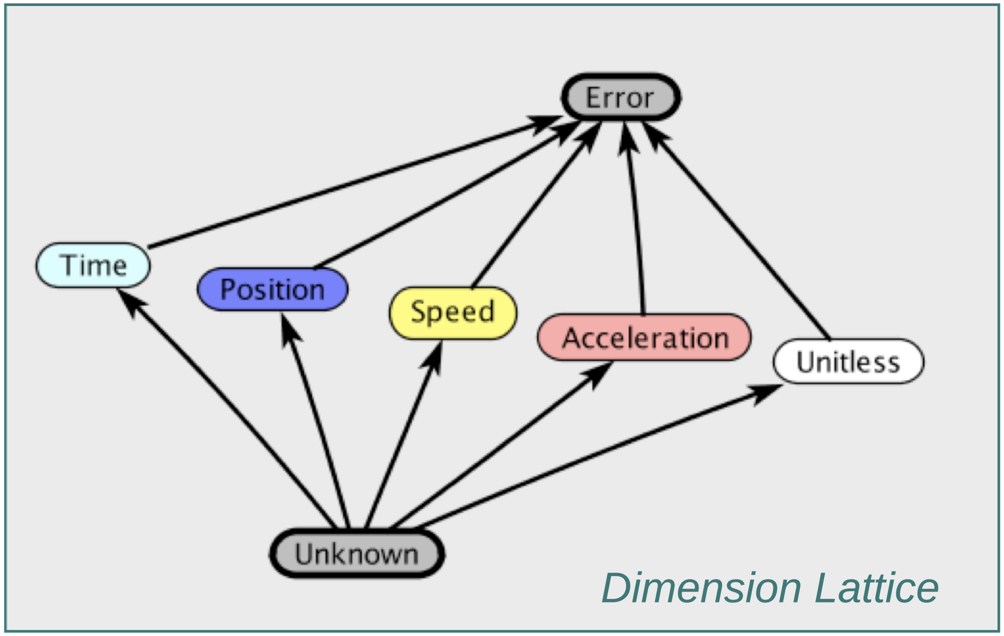
"Model engineering" is the "software engineering" of models. How to build, maintain, and analyze large models.

I will talk about two specific accomplishments:

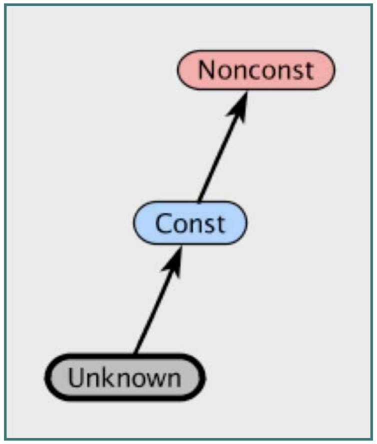
- Model ontologies (static semantics)
  - Check for compatible static semantics in pieces of models
  - Using semantic property annotations and inference
  - Based on sound foundations (type theories)
  - Scalable to large models
- Modal models (dynamic semantics, a form of multimodeling)
  - Components of a model with distinct modes of operation
  - Switching between modes is governed by a state machine
  - State machines composable with many concurrency models
  - Hybrid systems are a special case

Static Semantics

First: capture domain-specific semantic information



Example of a simple domain-specific semantic lattice (an ontology) for vehicle motion models.

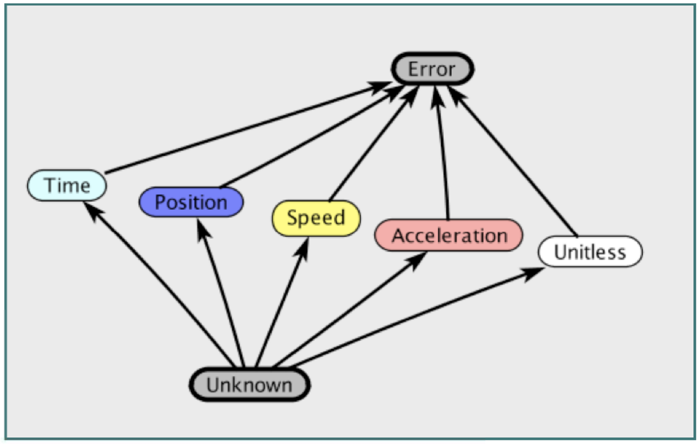


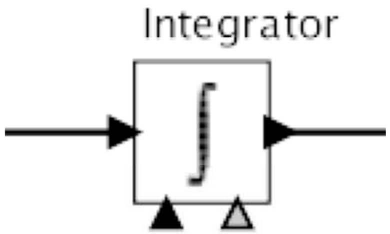
Another example of a an ontology for model optimization.

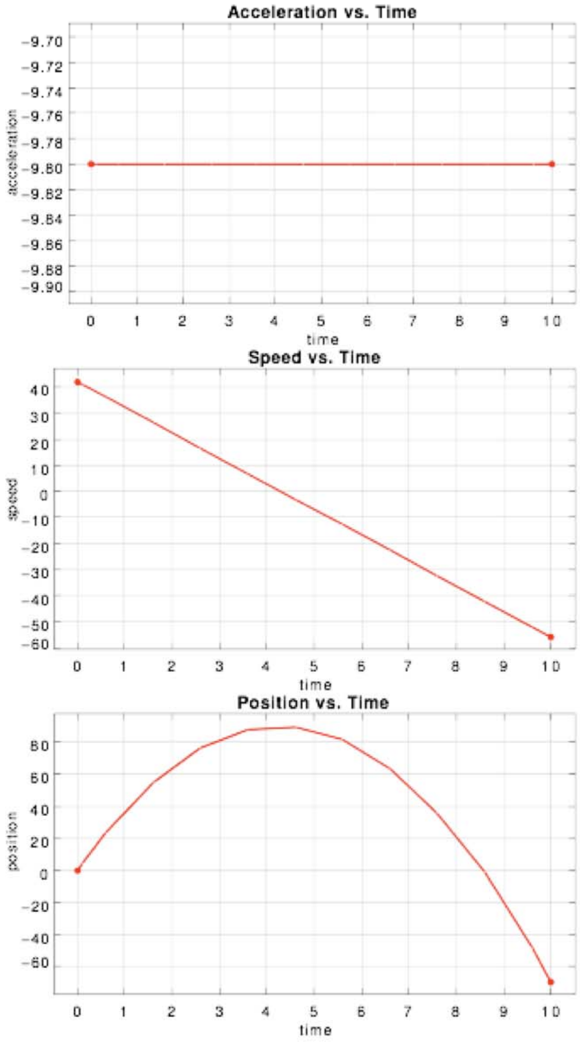
Const-Nonconst Lattice

- Components in a model (e.g. parameters, ports) can have properties drawn from a lattice.
- Components in a model (e.g. actors) can impose constraints on property relationships.
- The type system infrastructure can infer properties and detect errors.

Static Semantics
Second: Define constraints across components





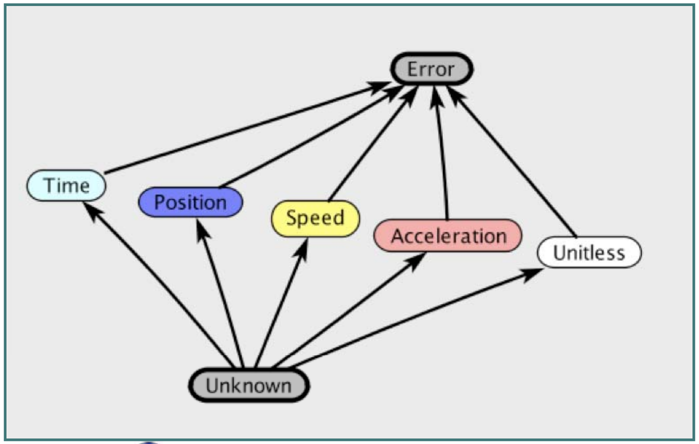


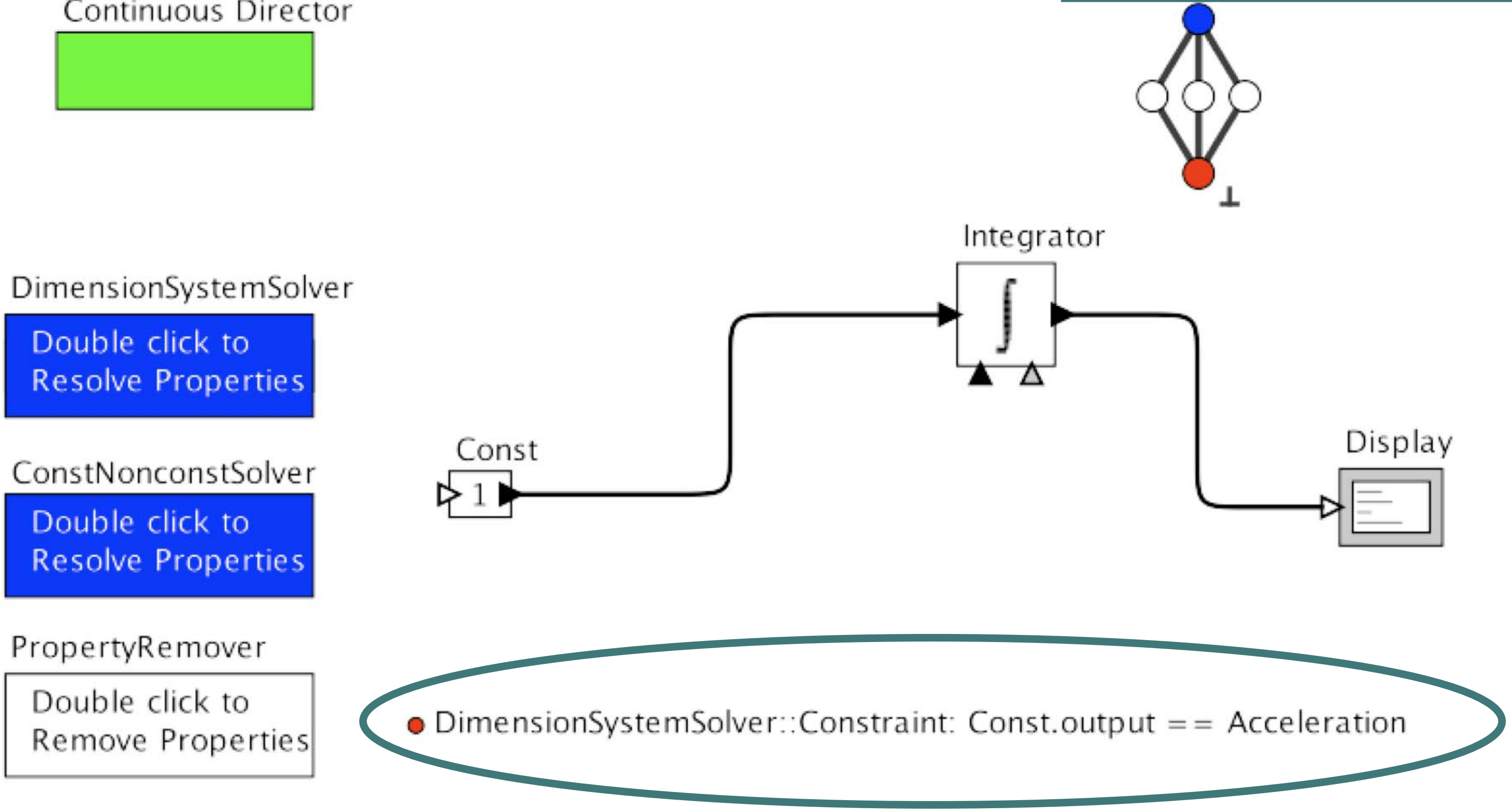
$$\int \mathit{acceleration}(t)\,dt = \mathit{speed}(t)$$

$$\int \mathit{speed}(t)\,dt = \mathit{position}(t)$$

Static Semantics

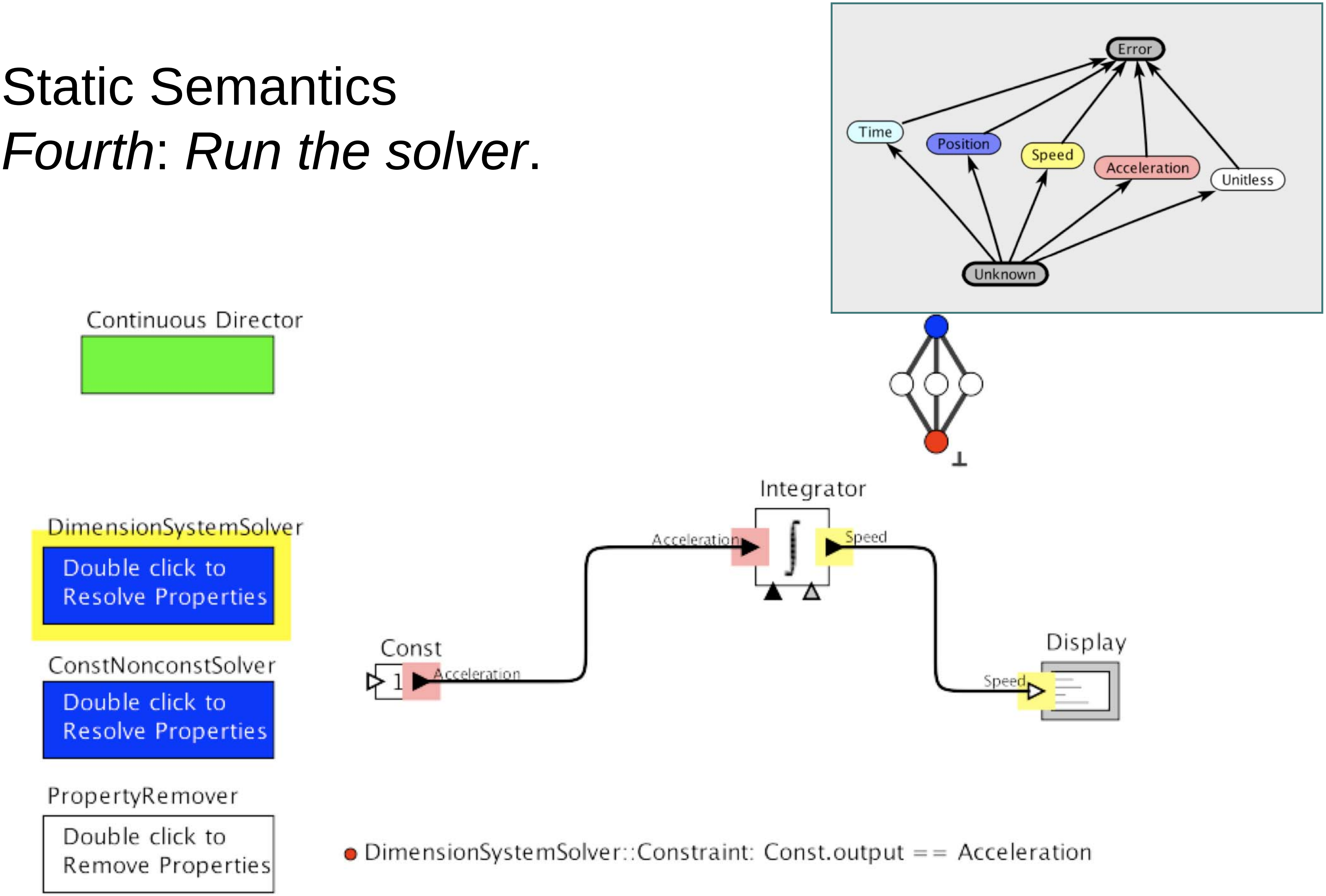
Third: annotate the model





● DimensionSystemSolver::Constraint: Const.output == Acceleration

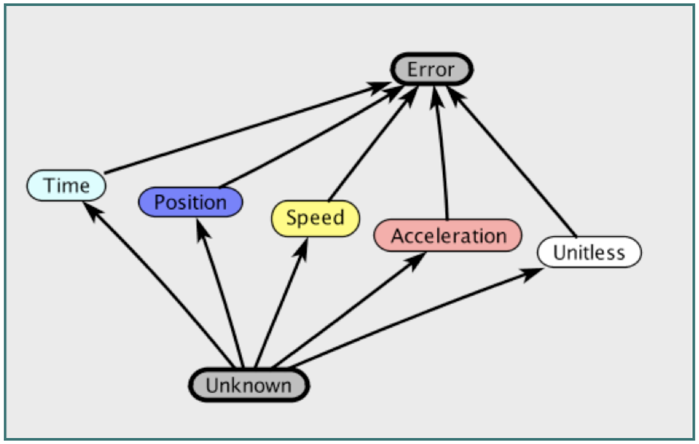
Static Semantics
Fourth: *Run the solver*.

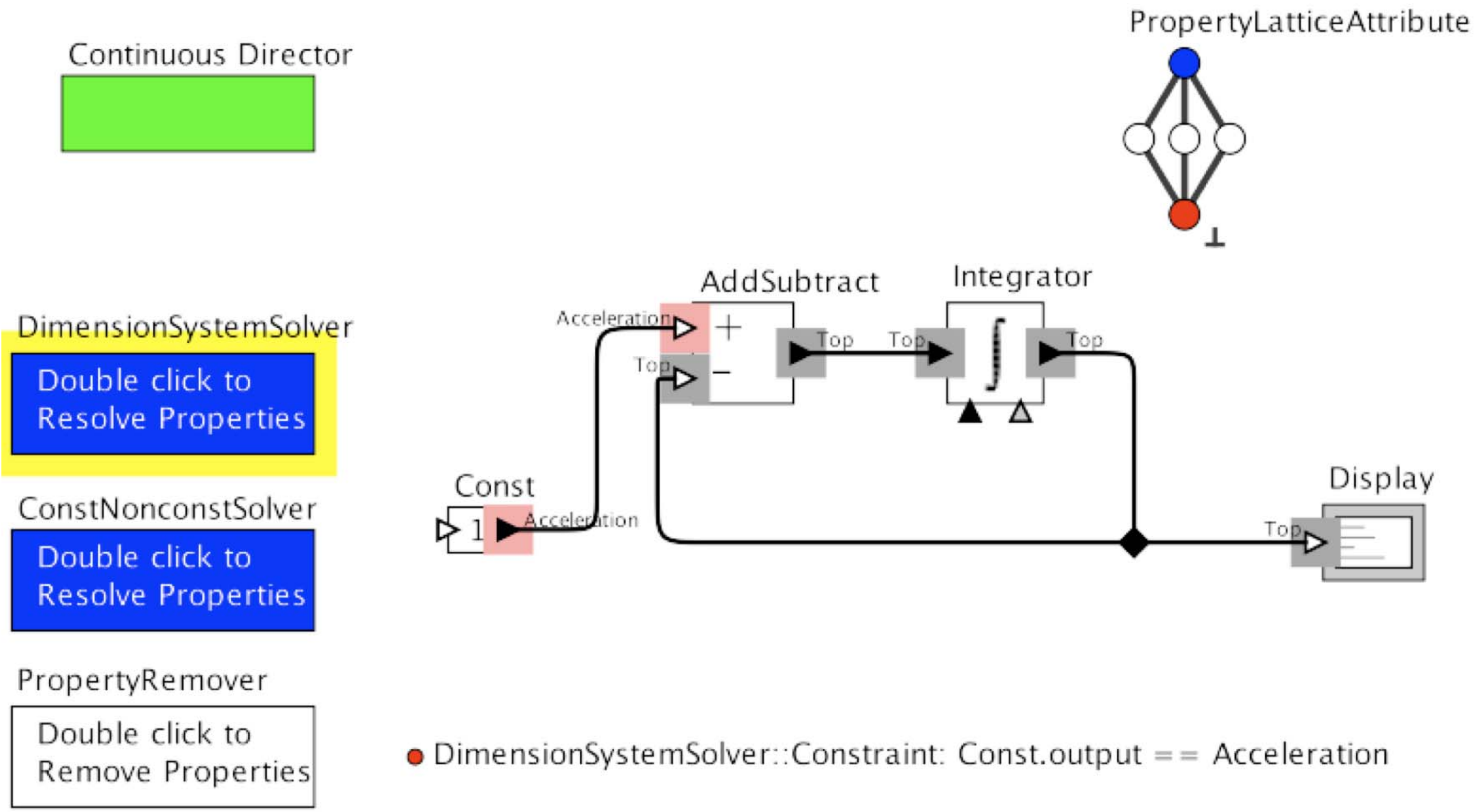


● DimensionSystemSolver::Constraint: Const.output == Acceleration

Static Semantics

Fifth: Resolve inconsistencies exposed by the solver.





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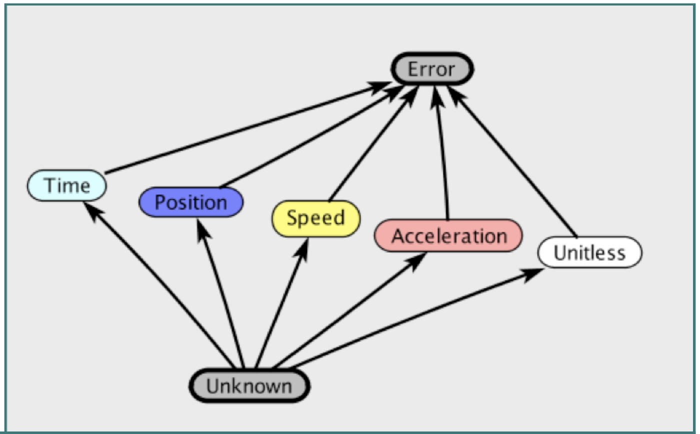
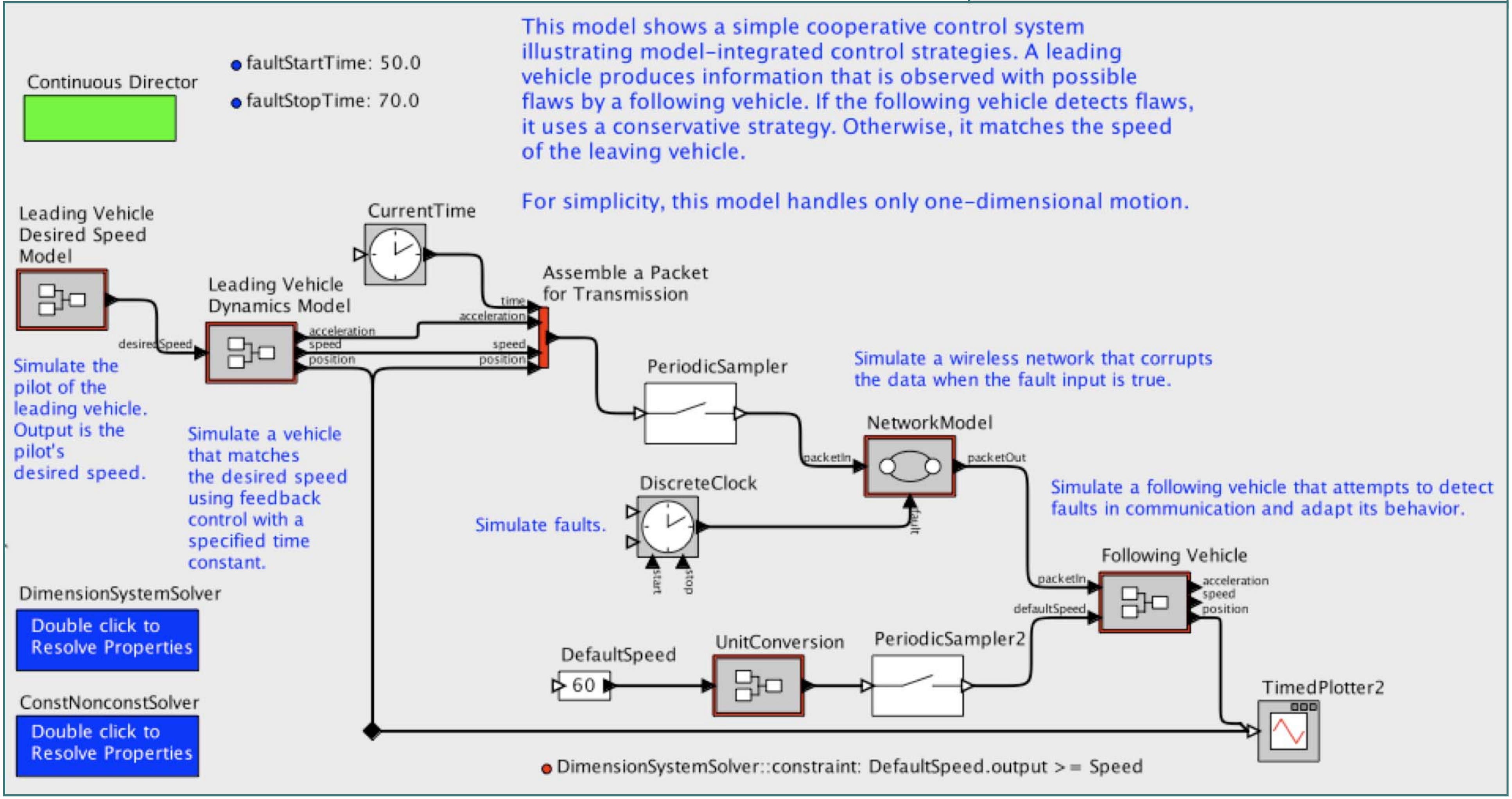
Applying this ontology to a model: Cooperative control system





This model shows a simple cooperative control system illustrating model-integrated control strategies. A leading vehicle produces information that is observed with possible flaws by a following vehicle. If the following vehicle detects flaws, it uses a conservative strategy. Otherwise, it matches the speed of the leaving vehicle.

For simplicity, this model handles only one-dimensional motion.

● faultStartTime: 50.0

● faultStopTime: 70.0

Simulate the pilot of the leading vehicle. Output is the pilot's desired speed.

Simulate a vehicle that matches the desired speed using feedback control with a specified time constant.

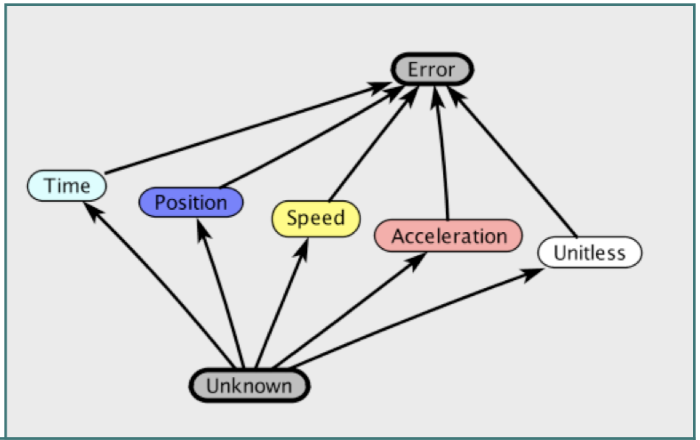
Simulate faults.

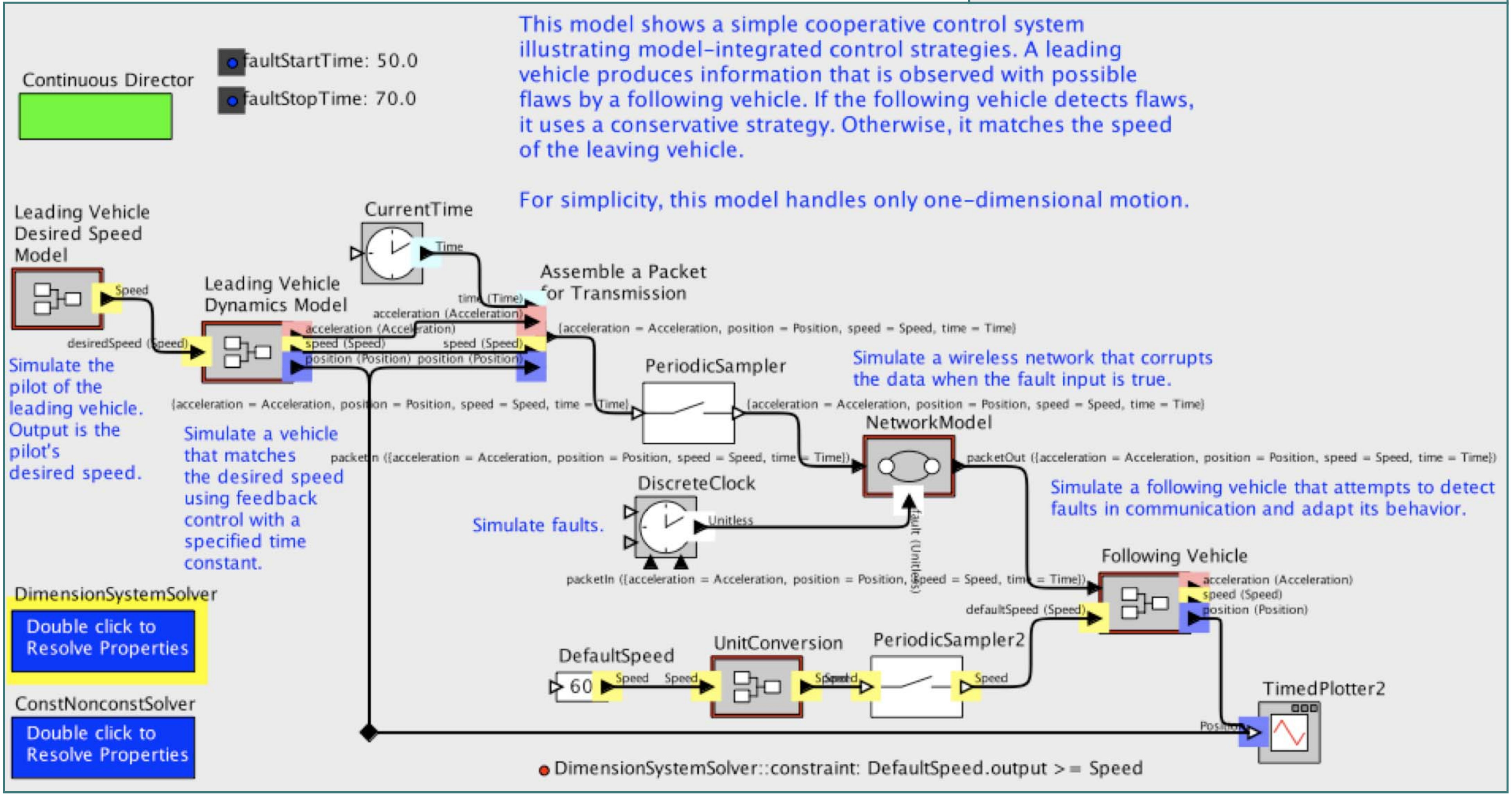
Simulate a wireless network that corrupts the data when the fault input is true.

Simulate a following vehicle that attempts to detect faults in communication and adapt its behavior.

● DimensionSystemSolver::constraint: DefaultSpeed.output >= Speed

Applying this ontology to a model:
Cooperative control system

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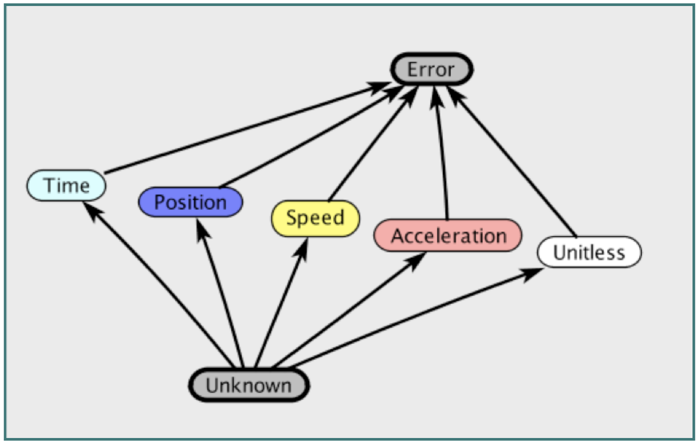
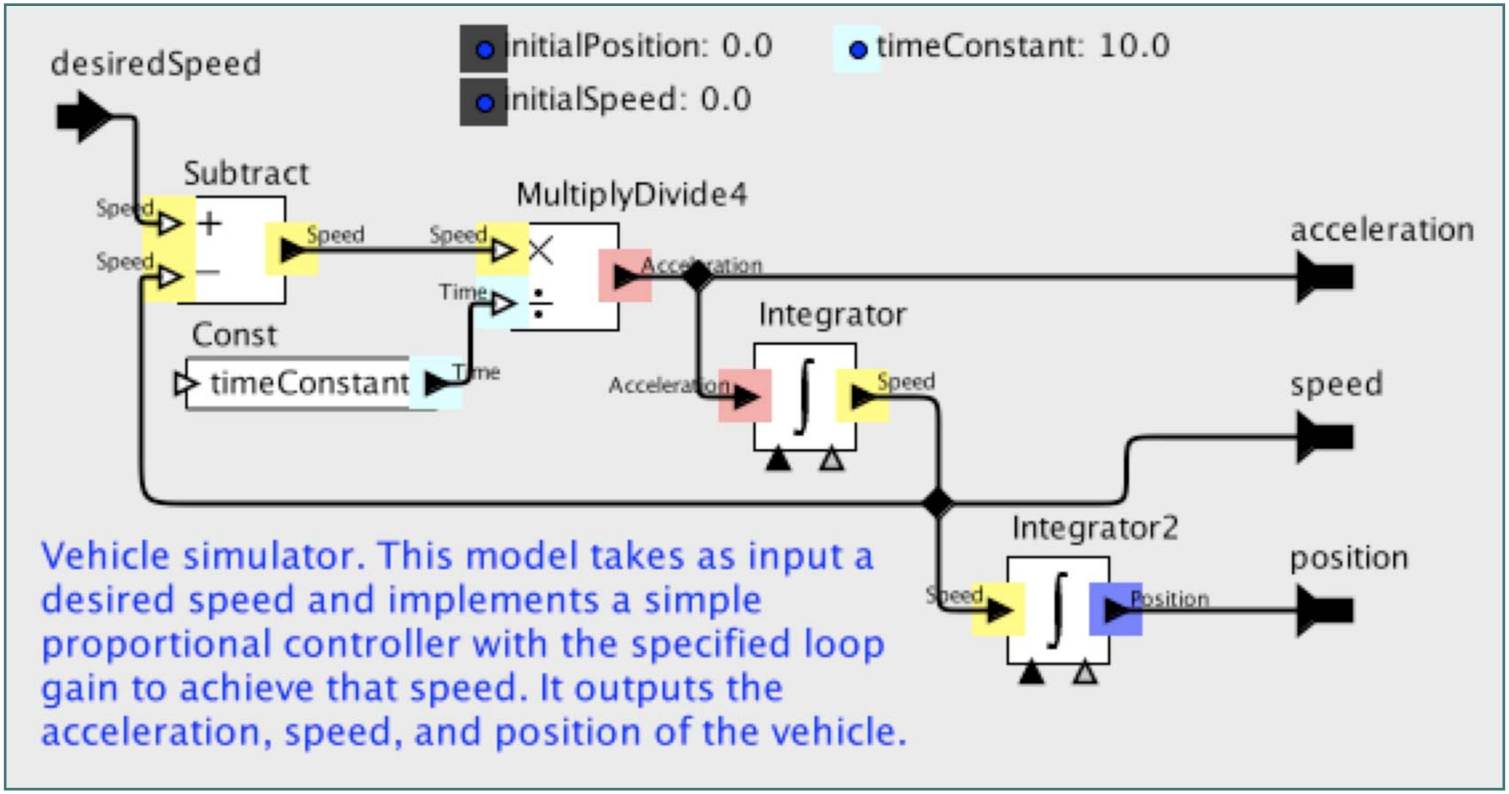
DimensionSystemSolver::constraint: DefaultSpeed.output >= Speed

Solver infers ontology information throughout the model and checks for consistent usage.

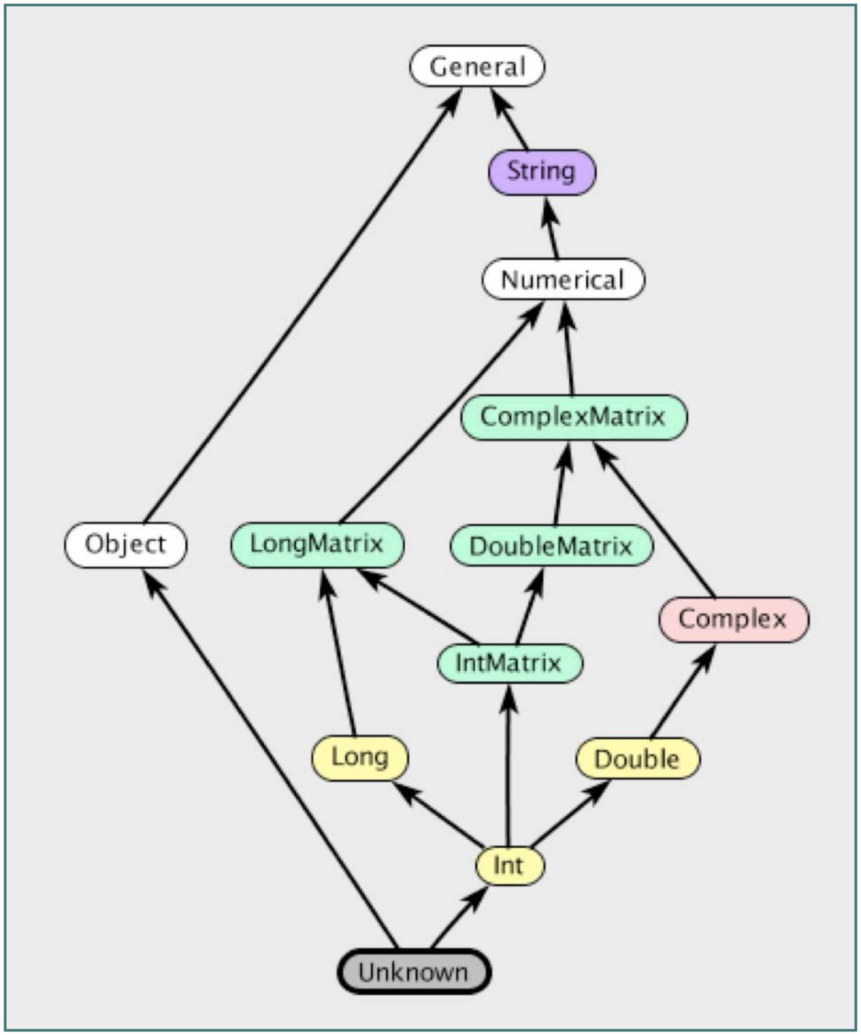




initialPosition: 0.0
initialSpeed: 0.0
timeConstant: 10.0

Vehicle simulator. This model takes as input a desired speed and implements a simple proportional controller with the specified loop gain to achieve that speed. It outputs the acceleration, speed, and position of the vehicle.

Background for Model Ontologies: Hindley-Milner Type Theories



- A *lattice* is a partially ordered set (poset) where every subset has a least upper bound (LUB) and a greatest lower bound (GLB).
- Modern type systems (including the Ptolemy II type system, created by Yuhong Xiong) are based on efficient algorithms for solving inequality constraints on lattices.

Relational Constraint Problem (RCP)

$$RCP : (P, C)$$

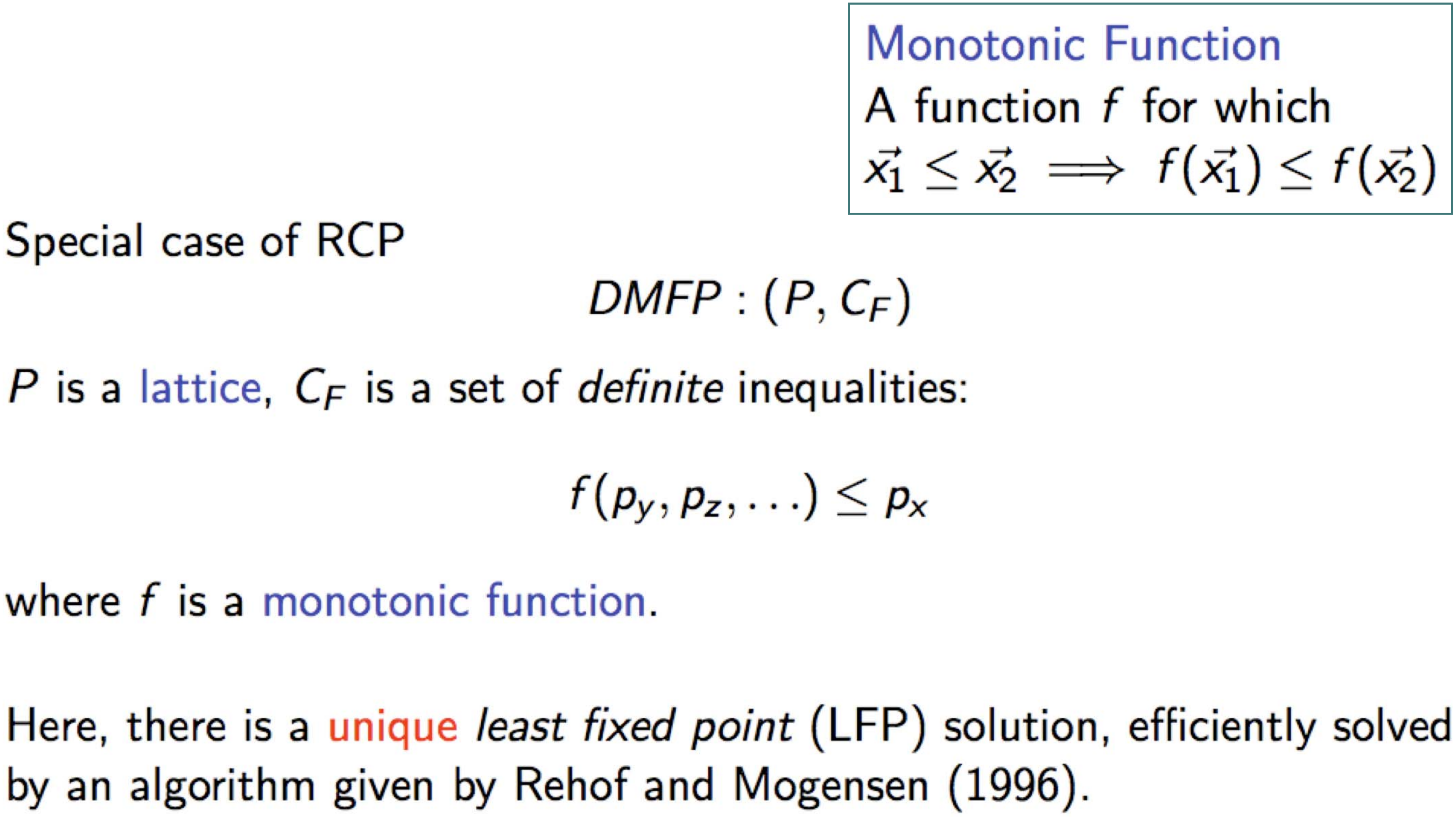
P is a partially ordered set, C is a set constraints of the form:

$$r(p_x, p_y, \ldots)$$

where r is a relation (e.g. $=, \leq$).

A *solution* is a satisfying assignment to property variables p_x, p_y, $\cdots$.

Definite Monotone Function Problem (DMFP)



Monotonic Function

A function f for which

$\vec{x_1} \leq \vec{x_2} \implies f(\vec{x_1}) \leq f(\vec{x_2})$

Special case of RCP

$$DMFP : (P, C_F)$$

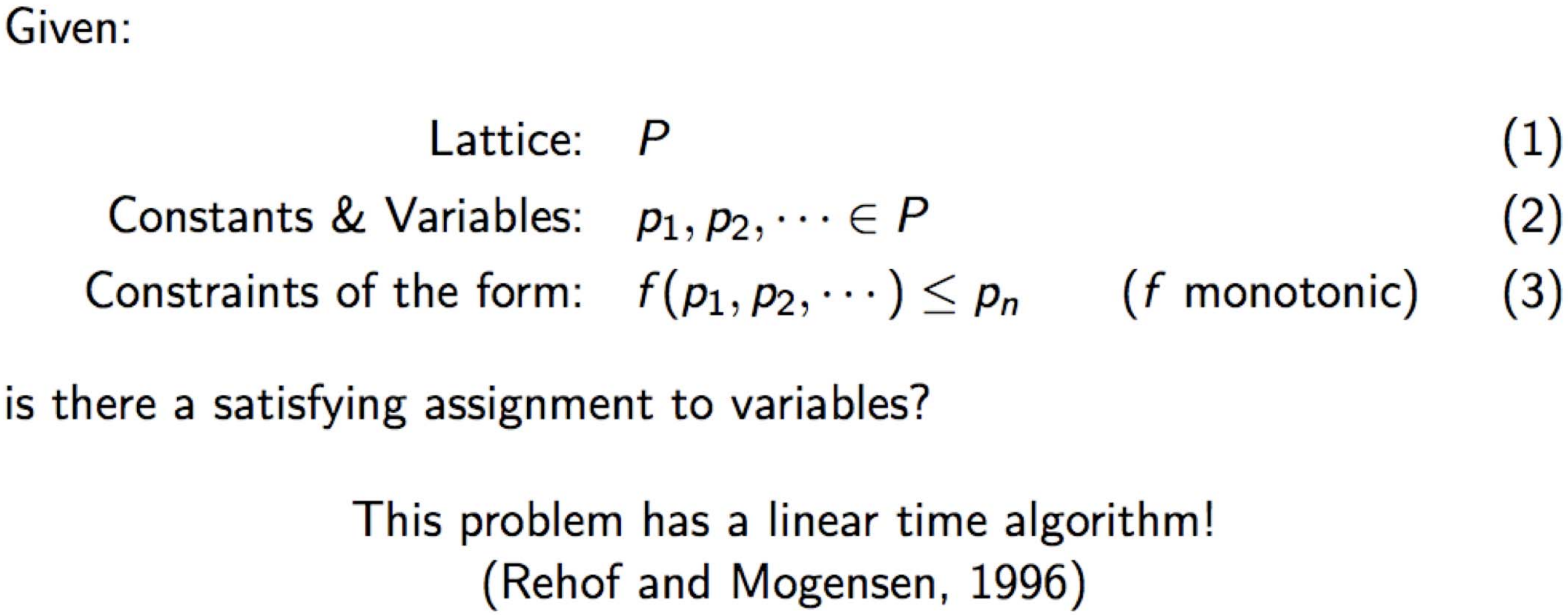
P is a lattice, C_F is a set of *definite* inequalities:

$$f(p_y, p_z, \ldots) \leq p_x$$

where f is a monotonic function.

Here, there is a unique *least fixed point* (LFP) solution, efficiently solved by an algorithm given by Rehof and Mogensen (1996).

Problem Statement



Given:

$$\text{Lattice:} \quad P \tag{1}$$

$$\text{Constants \& Variables:} \quad p_1, p_2, \cdots \in P \tag{2}$$

$$\text{Constraints of the form:} \quad f(p_1, p_2, \cdots) \leq p_n \qquad (f \text{ monotonic}) \tag{3}$$

is there a satisfying assignment to variables?

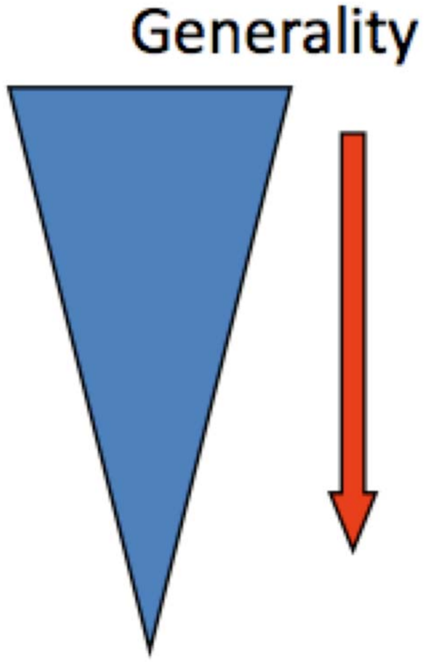
This problem has a linear time algorithm!
(Rehof and Mogensen, 1996)

How to Make this Usable in Practice?

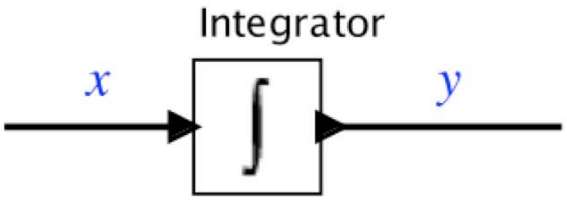
A problem is that, in general, the number of constraints is proportional to the size of the model.

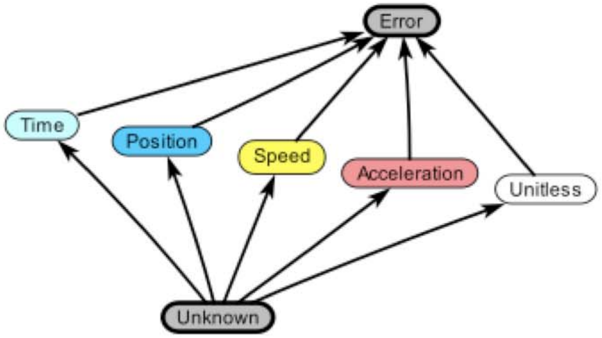
To mitigate these, organize constraints as:

- Default Constraints
  - Set globally by the property solver
  - (actors, connections, etc.)
- Actor-specific Constraints
  - Use an adapter pattern for actors
- Instance-specific Constraints
  - Specified through model annotations



Example of Actor Constraints for the Dimensions Lattice

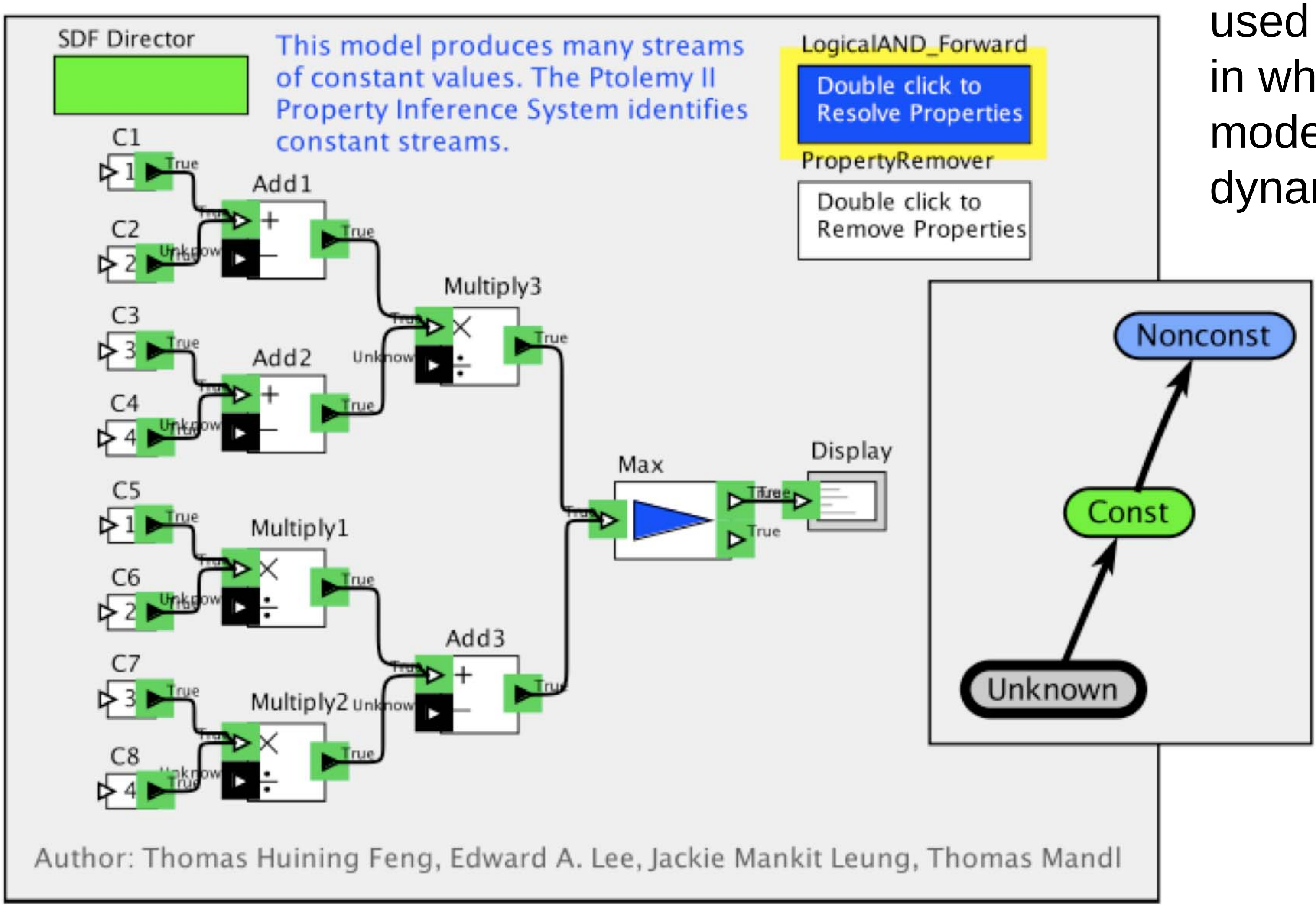




Component	Elements	Constraints
Integrator	input x, output y	$f_I(p_y) \le p_x$ $f_O(p_x) \le p_y$

$$f_I(p_y) = \begin{cases} \text{Undef.} & \text{if } p_y = \text{Undef.} \\ \text{Speed} & \text{if } p_y = \text{Pos.} \\ \text{Accel.} & \text{if } p_y = \text{Speed} \\ \text{Unitless} & \text{if } p_y = \text{Time} \\ \text{Error} & \text{otherwise} \end{cases} \qquad f_O(p_x) = \begin{cases} \text{Undef.} & \text{if } p_x = \text{Undef.} \\ \text{Pos.} & \text{if } p_x = \text{Speed} \\ \text{Speed} & \text{if } p_x = \text{Accel.} \\ \text{Time} & \text{if } p_x = \text{Unitless} \\ \text{Error} & \text{otherwise} \end{cases}$$

Another Lattice

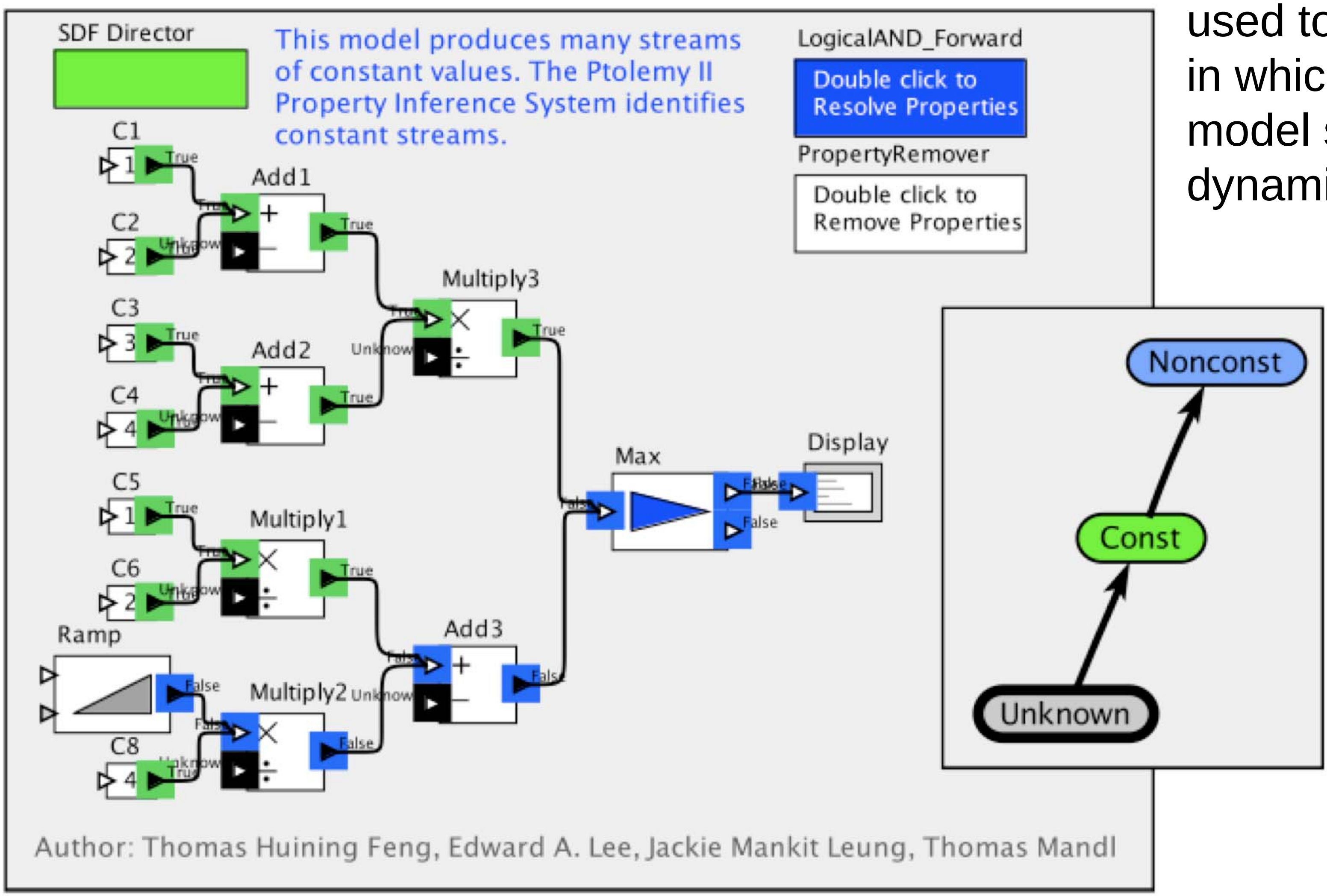


This model produces many streams of constant values. The Ptolemy II Property Inference System identifies constant streams.

Author: Thomas Huining Feng, Edward A. Lee, Jackie Mankit Leung, Thomas Mandl

This example illustrates that an ontology can be used to determine in which parts of a model signals vary dynamically.

Another Lattice



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Reporting Progress in Two Dimensions of Model Engineering

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- Modal models (dynamic semantics, a form of multimodeling)
  - Components of a model with distinct modes of operation
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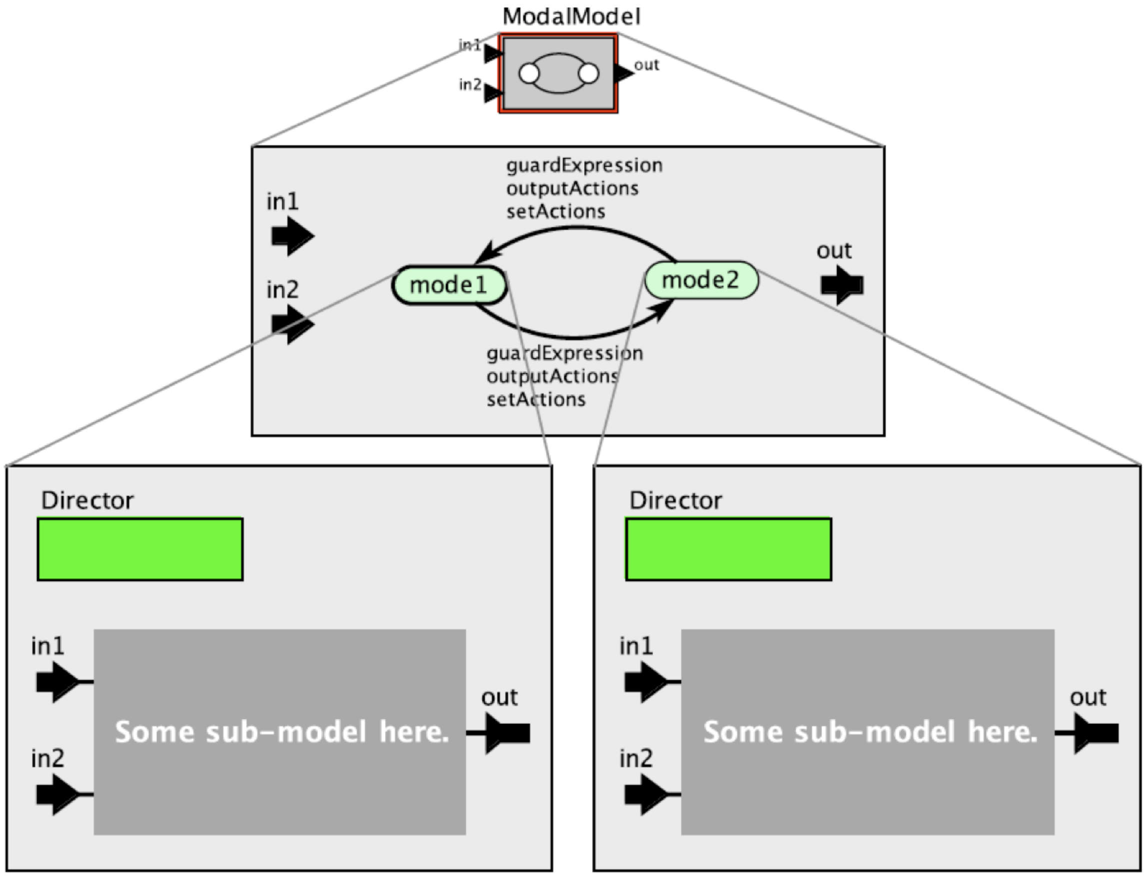
  - Hybrid systems are a special case

Dynamic Semantics
Modal Behaviors

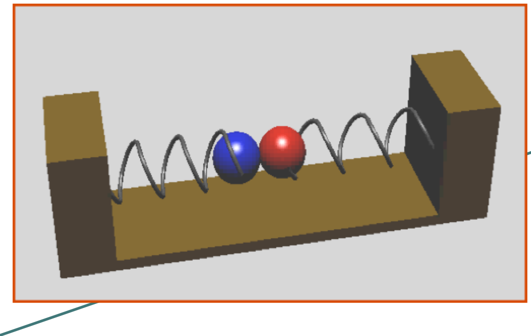
What is the meaning of modal behavior?



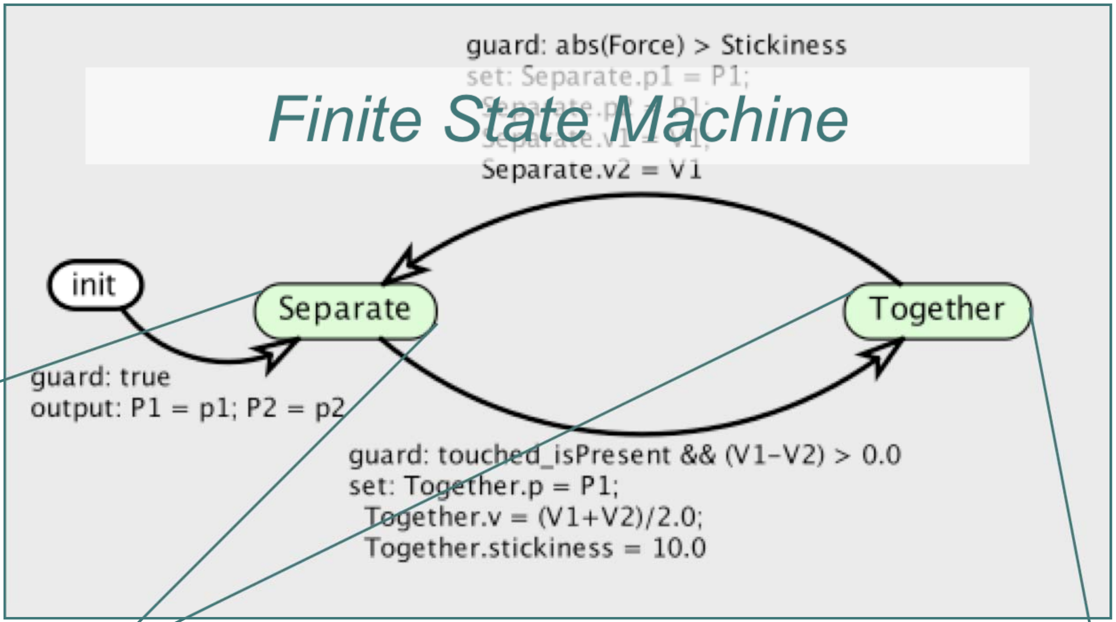
Modal models are formal representations of dynamically changing behaviors, where the changes are modeled by a state machine. They can be used to construct fault models and models of adaptive systems that react to faults.

I will describe a semantics of modal models embracing concurrent and timed models.

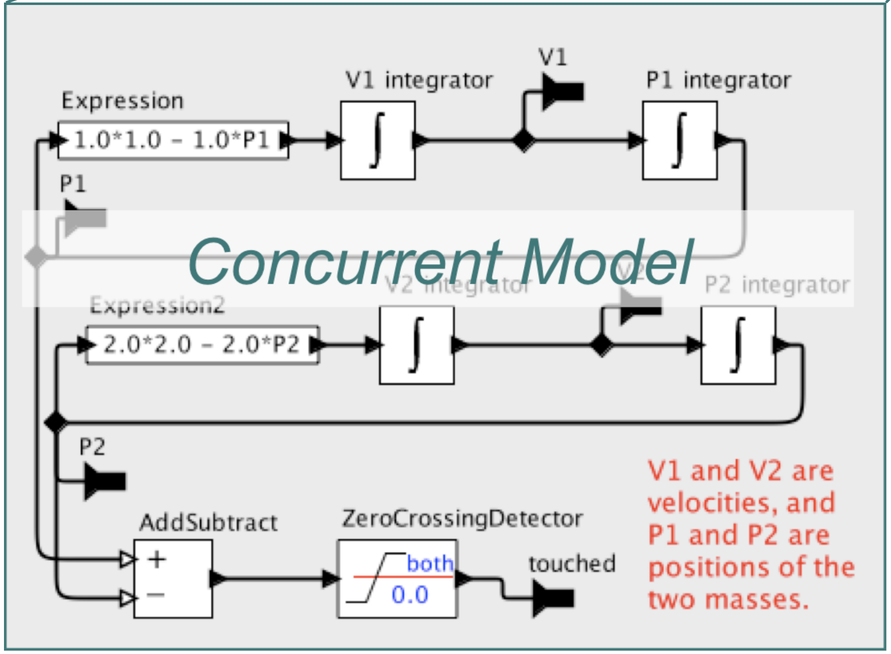
Motivating Example: Hybrid System



Finite State Machine

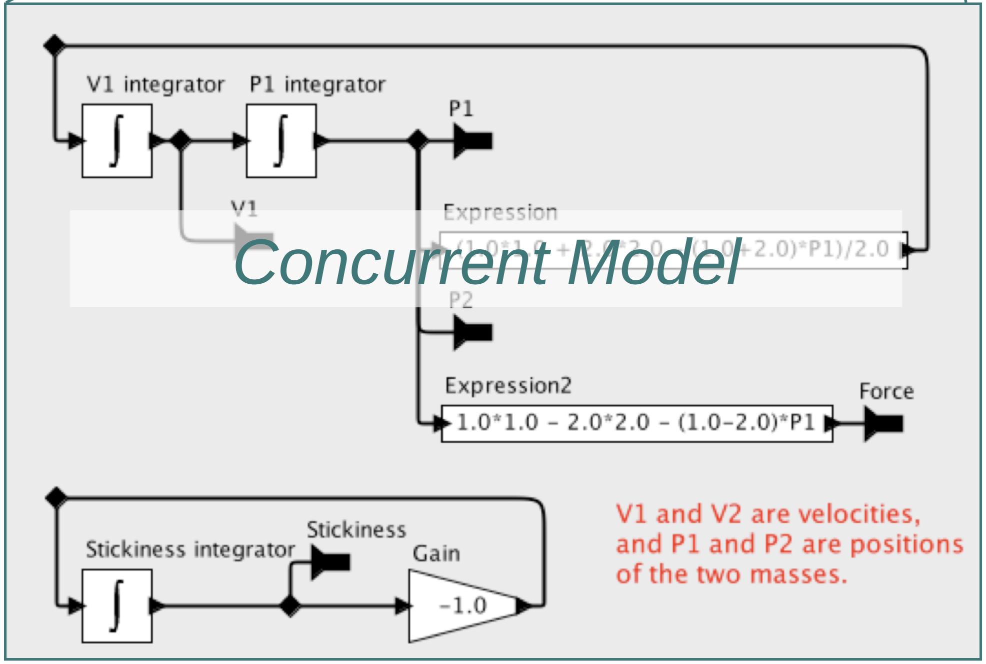


Concurrent Model



V1 and V2 are velocities, and P1 and P2 are positions of the two masses.

Concurrent Model

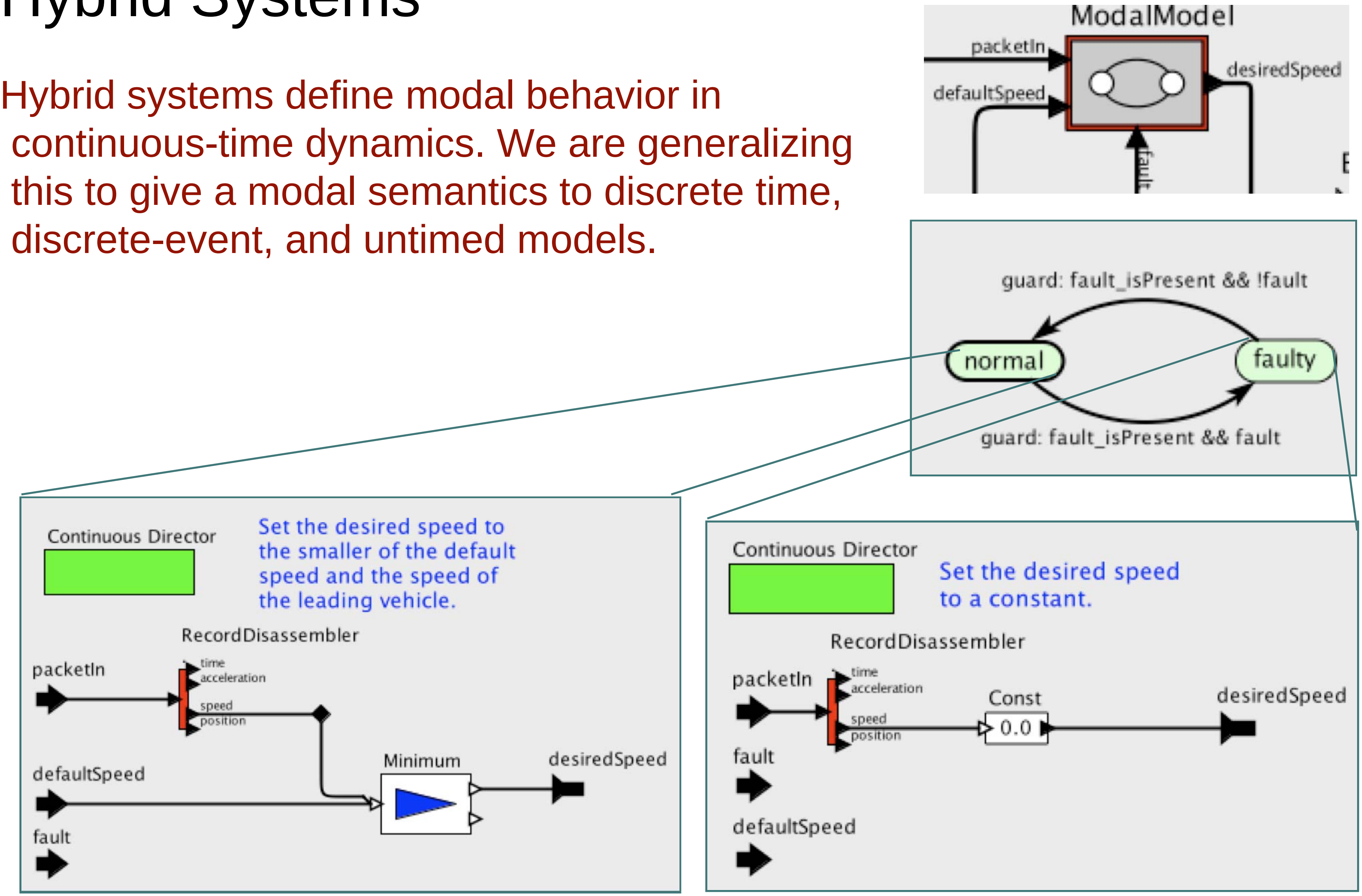


V1 and V2 are velocities, and P1 and P2 are positions of the two masses.

Generalizing Beyond Hybrid Systems

Hybrid systems define modal behavior in continuous-time dynamics. We are generalizing this to give a modal semantics to discrete time, discrete-event, and untimed models.

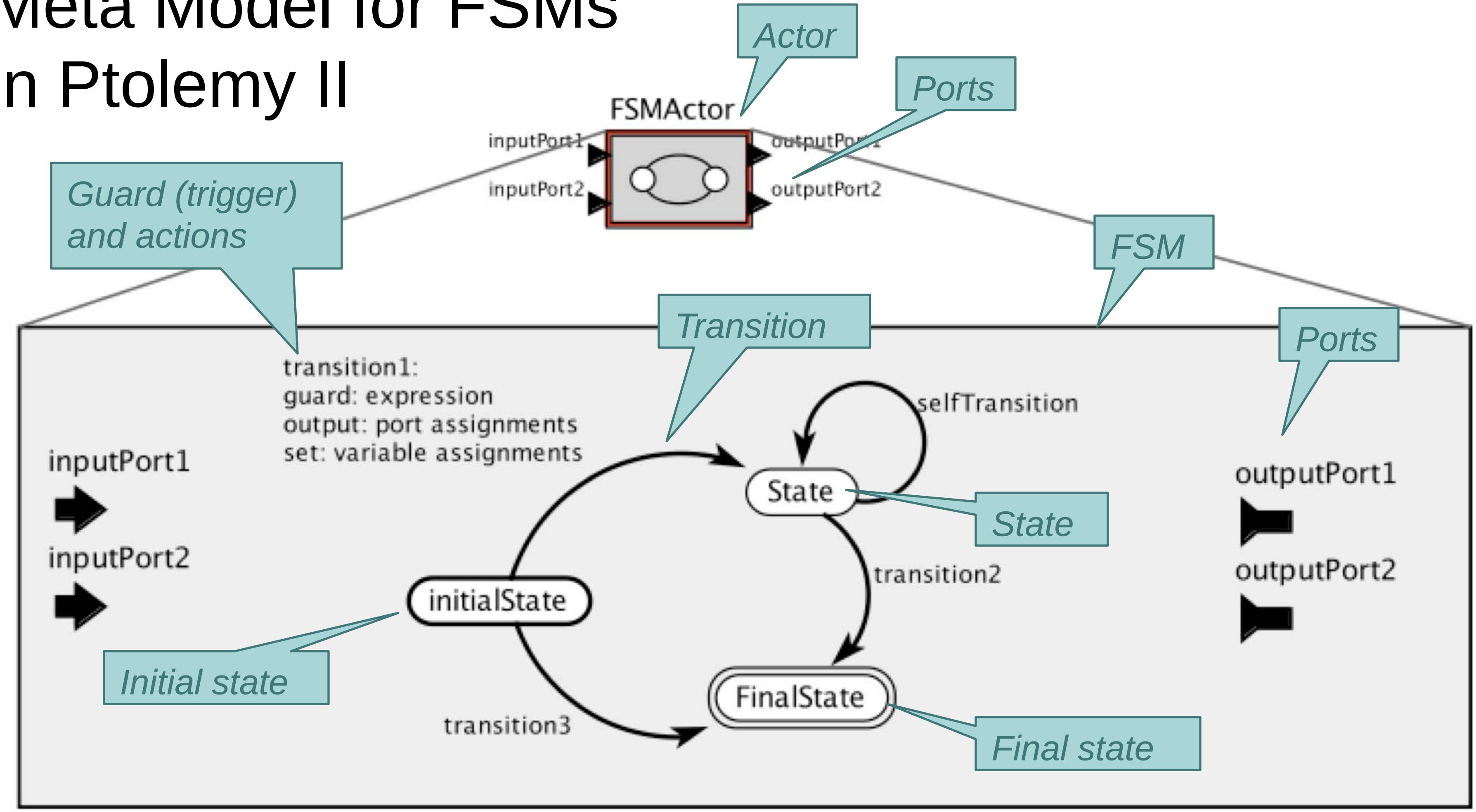
Cooperative control system example includes two timed modal models. E.g.:



Set the desired speed to the smaller of the default speed and the speed of the leading vehicle.

Set the desired speed to a constant.

Meta Model for FSMs in Ptolemy II

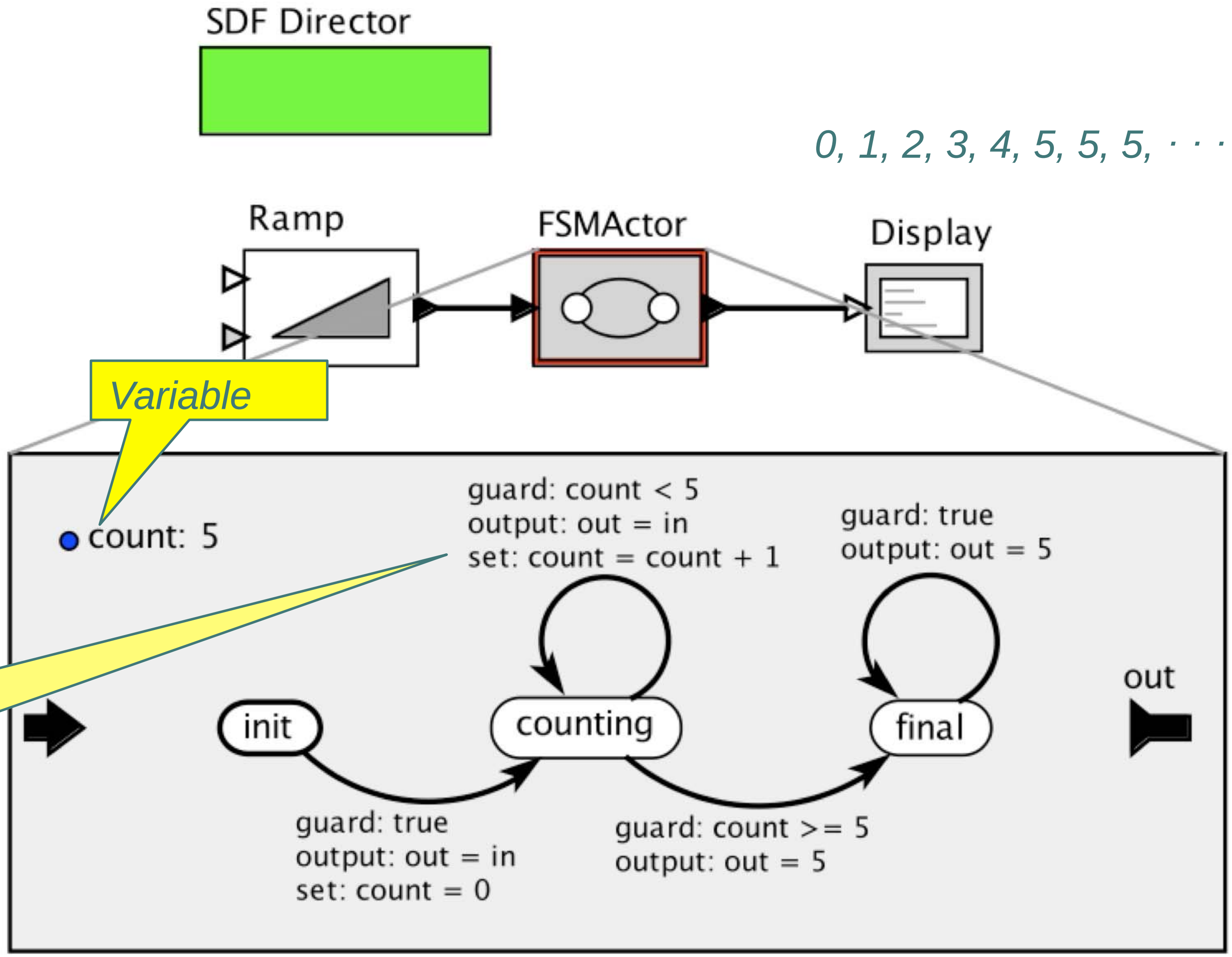


- Initial state indicated in bold
- Guards are expressions that can reference inputs and variables
- Output values can be functions of inputs and variables
- Transition can update variable values (“set” actions)
- Final state terminates execution of the actor

Extended State Machines

Reference and manipulate variables on guards and transitions.

Extended state machines can operate on variables in the model, like “count” in this example.



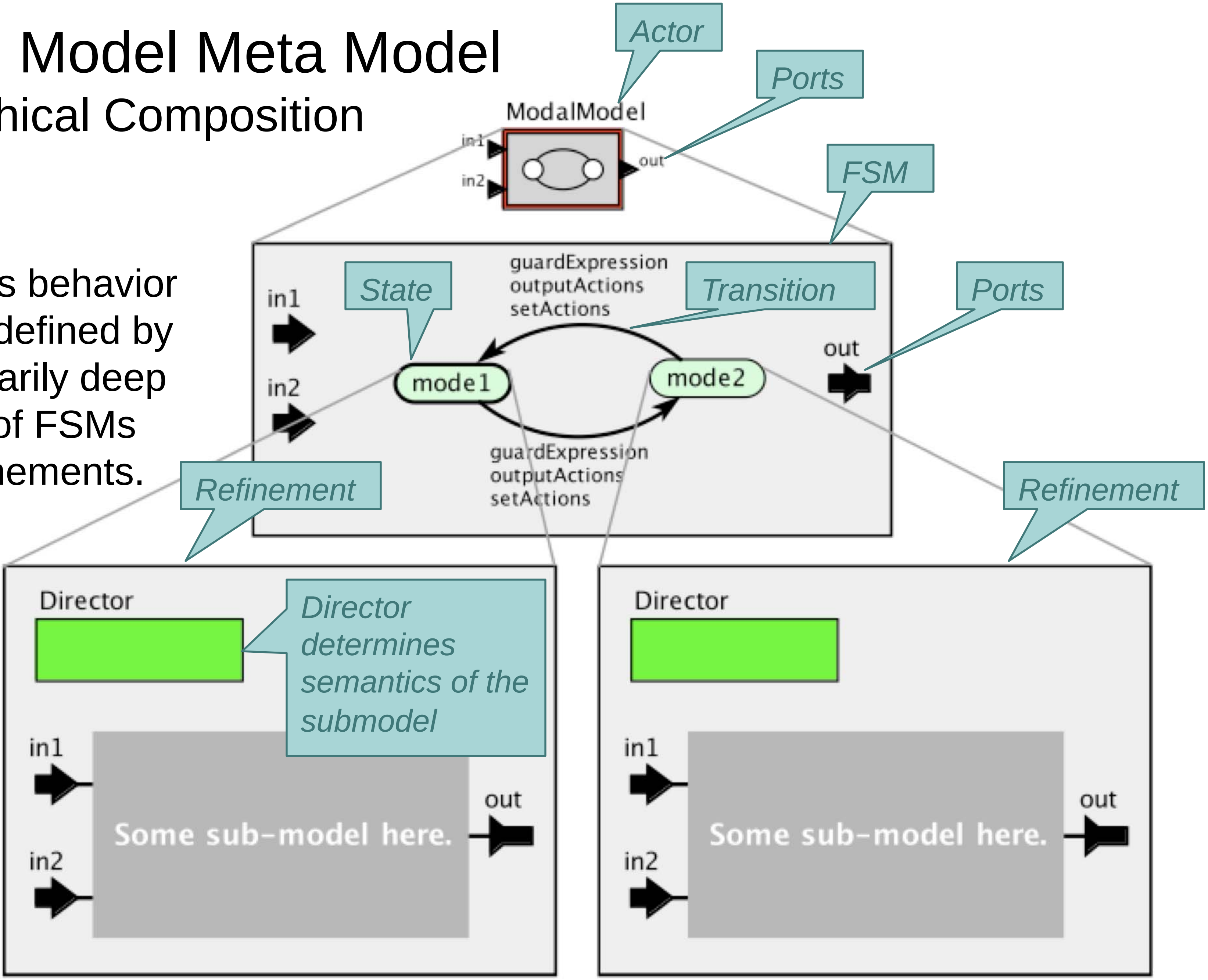
Variable

“Set” actions are distinct from “output” actions. We will see why.

Modal Model Meta Model

Hierarchical Composition

An actor’s behavior may be defined by an arbitrarily deep nesting of FSMs and refinements.



Actor

Ports

FSM

State

Transition

Ports

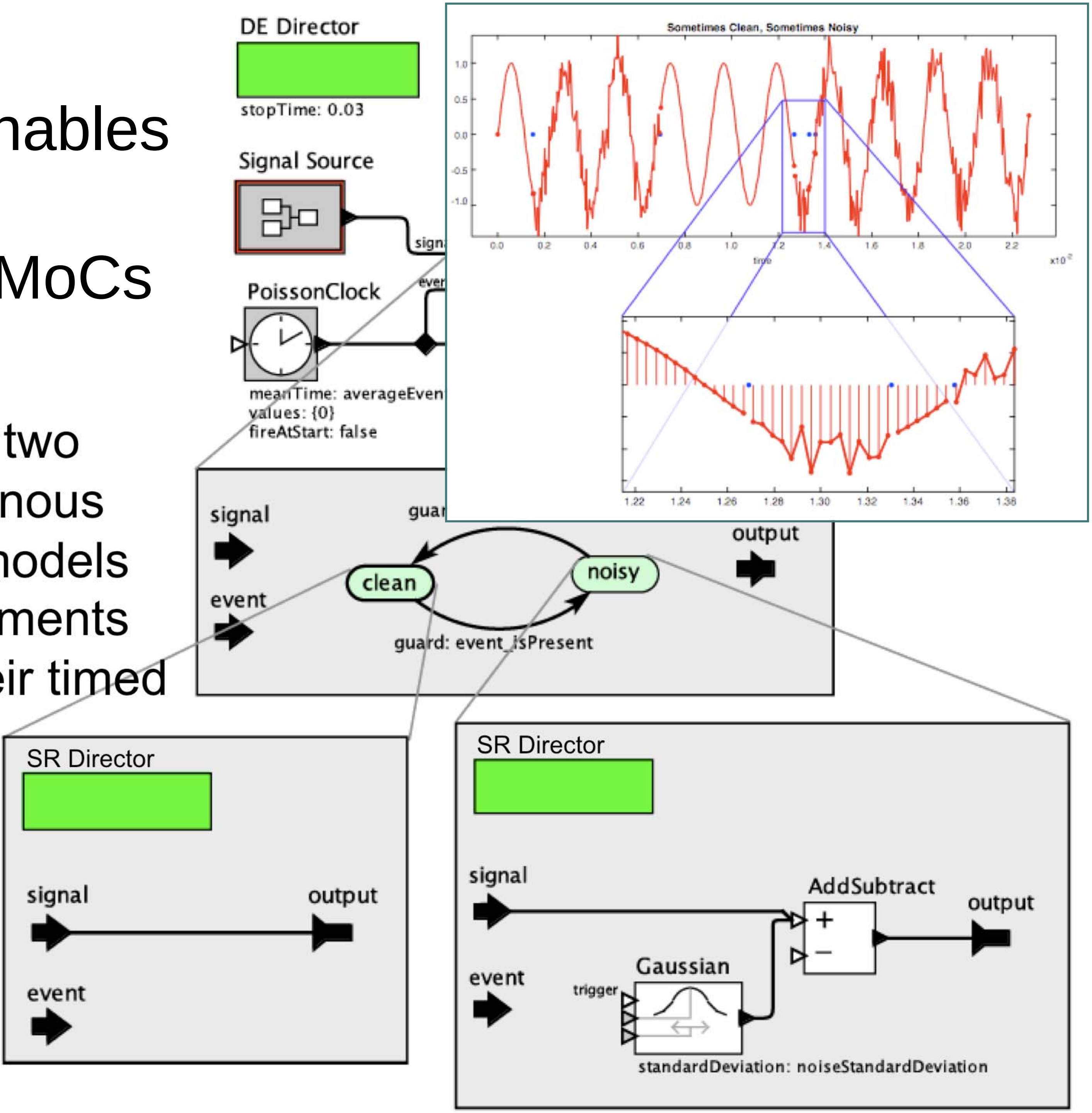
Refinement

Refinement

Director determines semantics of the submodel

Ptolemy II Enables Hierarchical Mixtures of MoCs

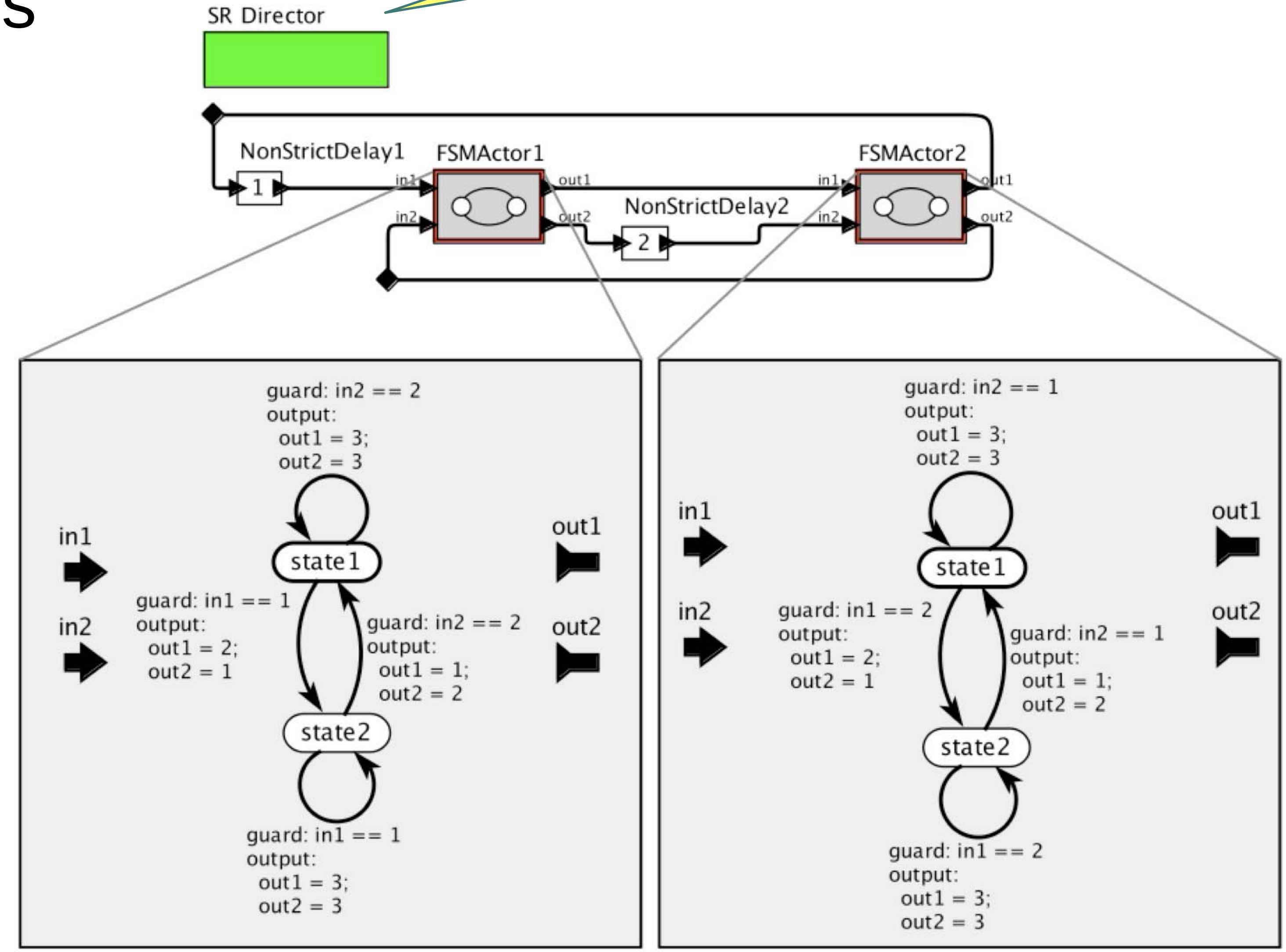
This model has two simple synchronous /reactive (SR) models as mode refinements and models their timed environment using a discrete-event (DE) director



Compare with Statecharts AND states

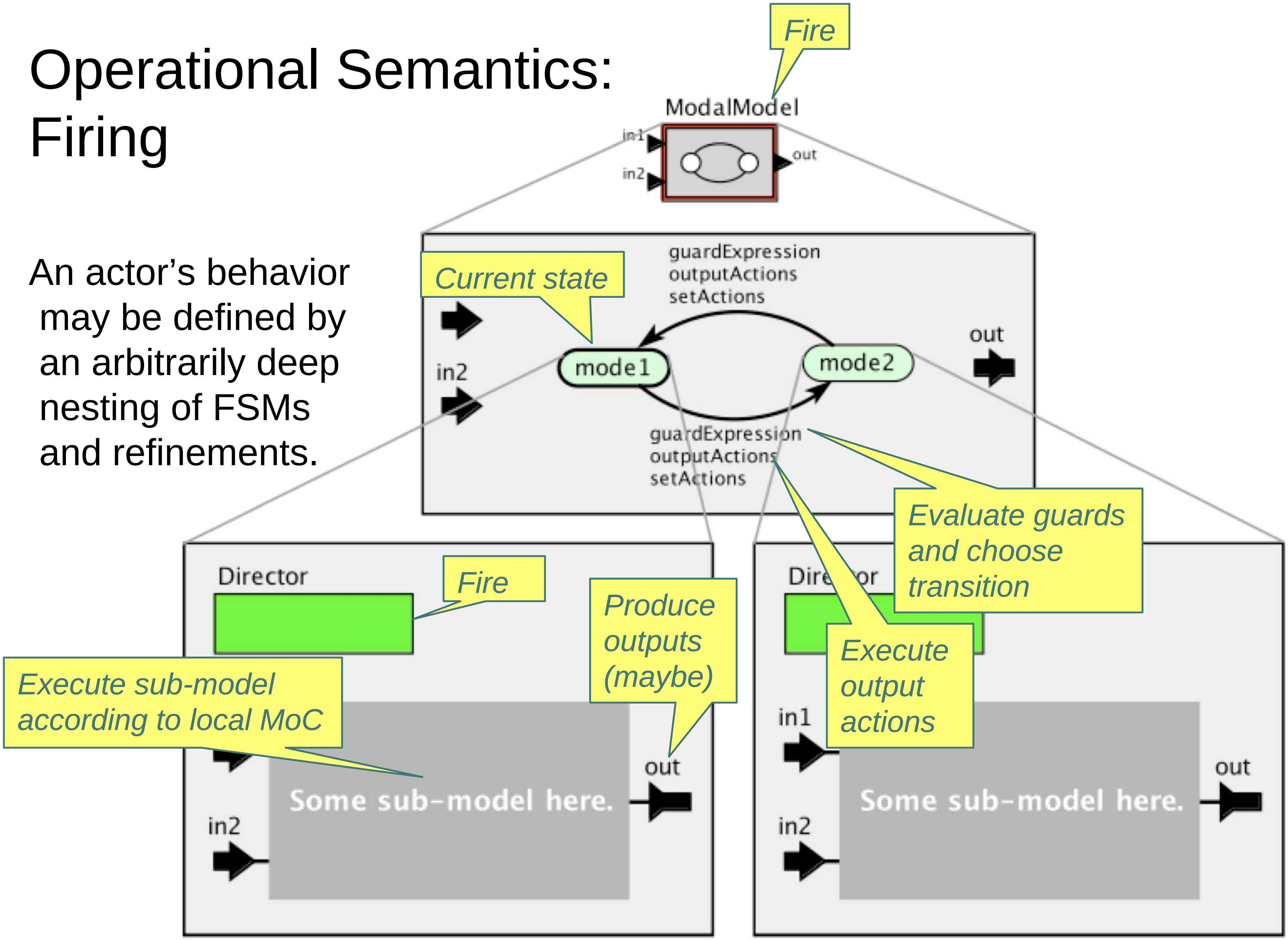
Using a synchronous/reactive (SR) director yields Statechart-like semantics for concurrent state machines.

Here, two FSMs are composed under a synchronous/reactive director, resulting in Statecharts-like AND states.



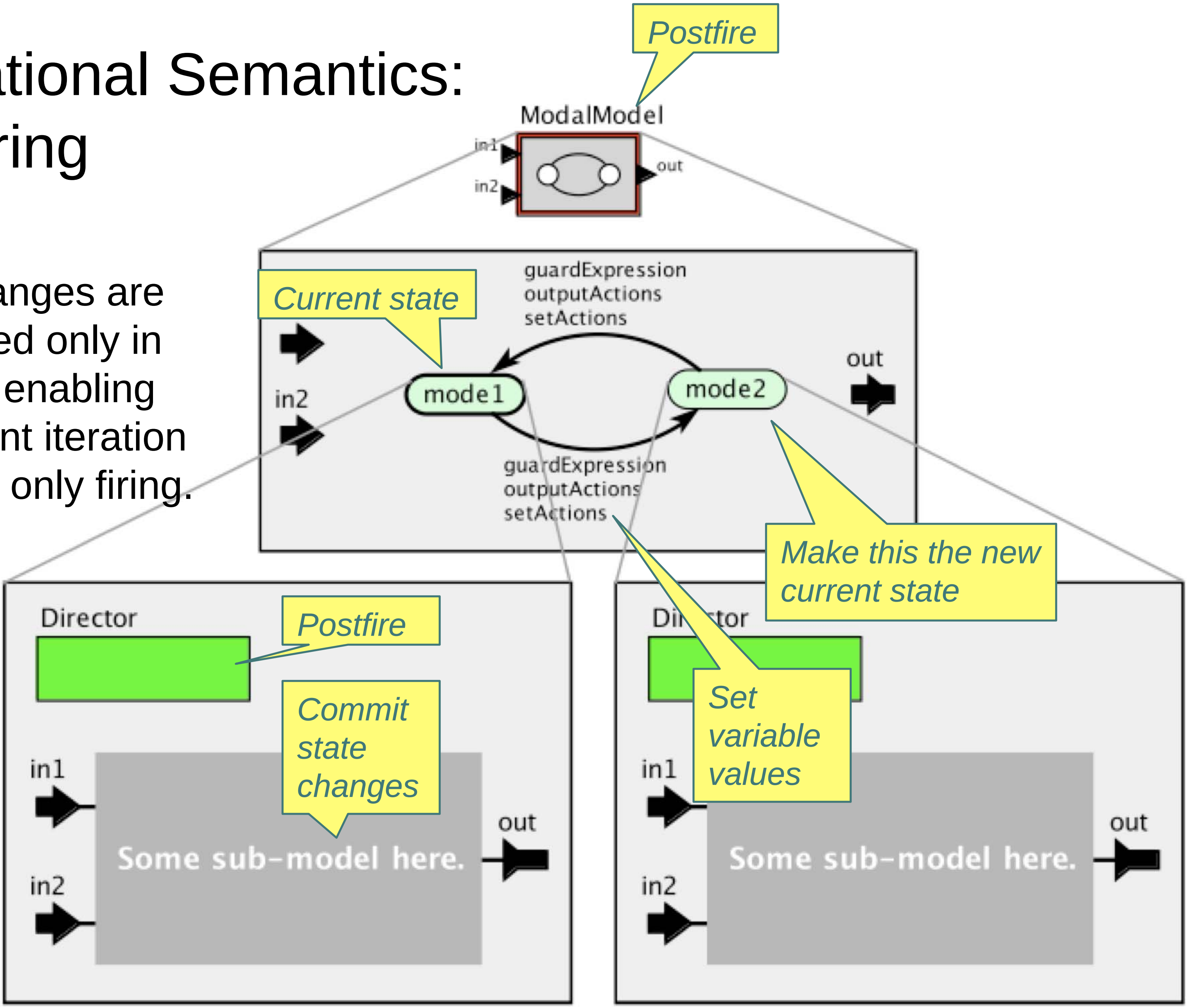
Operational Semantics: Firing

An actor's behavior may be defined by an arbitrarily deep nesting of FSMs and refinements.



Operational Semantics: Postfiring

State changes are committed only in postfire, enabling fixed point iteration by using only firing.



Postfire

Current state

Make this the new current state

Set variable values

Postfire

Commit state changes

Directors Benefiting from Fire/Postfire Separation (which we call the *Actor Abstract Semantics*)

- Synchronous/Reactive (SR)
  - Execution at each tick is defined by a least fixed point of monotonic functions on a finite lattice, where bottom represents “unknown” (getting a constructive semantics)
- Discrete Event (DE)
  - Extends SR by defining a “time between ticks” and providing a mechanism for actors to control this. Time between ticks can be zero (“superdense time”).
- Continuous
  - Extends DE with a “solver” that chooses time between ticks to accurately estimate ODE solutions, and fires all actors on every tick.

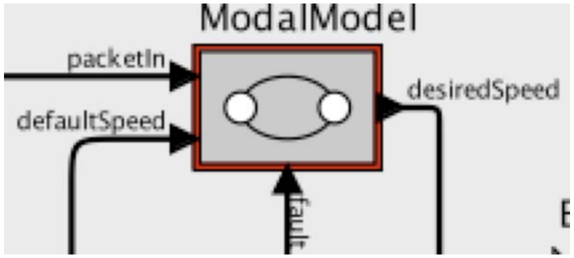
[Lee & Zheng, EMSOFT 07]

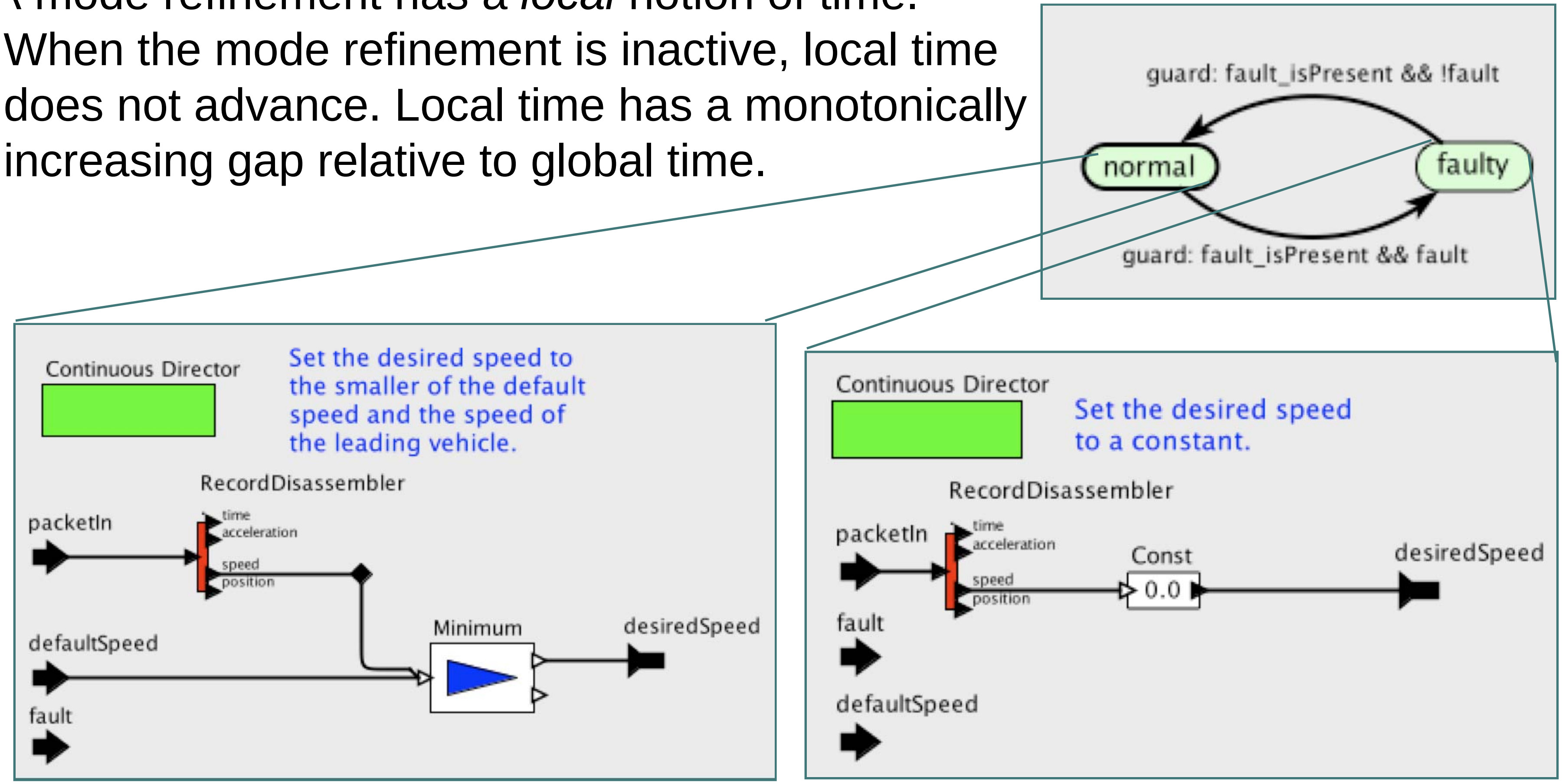
Handling Time in Modal Models

After trying several variants on the semantics of modal time, we settled on this:

A mode refinement has a *local* notion of time. When the mode refinement is inactive, local time does not advance. Local time has a monotonically increasing gap relative to global time.

Cooperative control system example includes two timed modal models. E.g.:

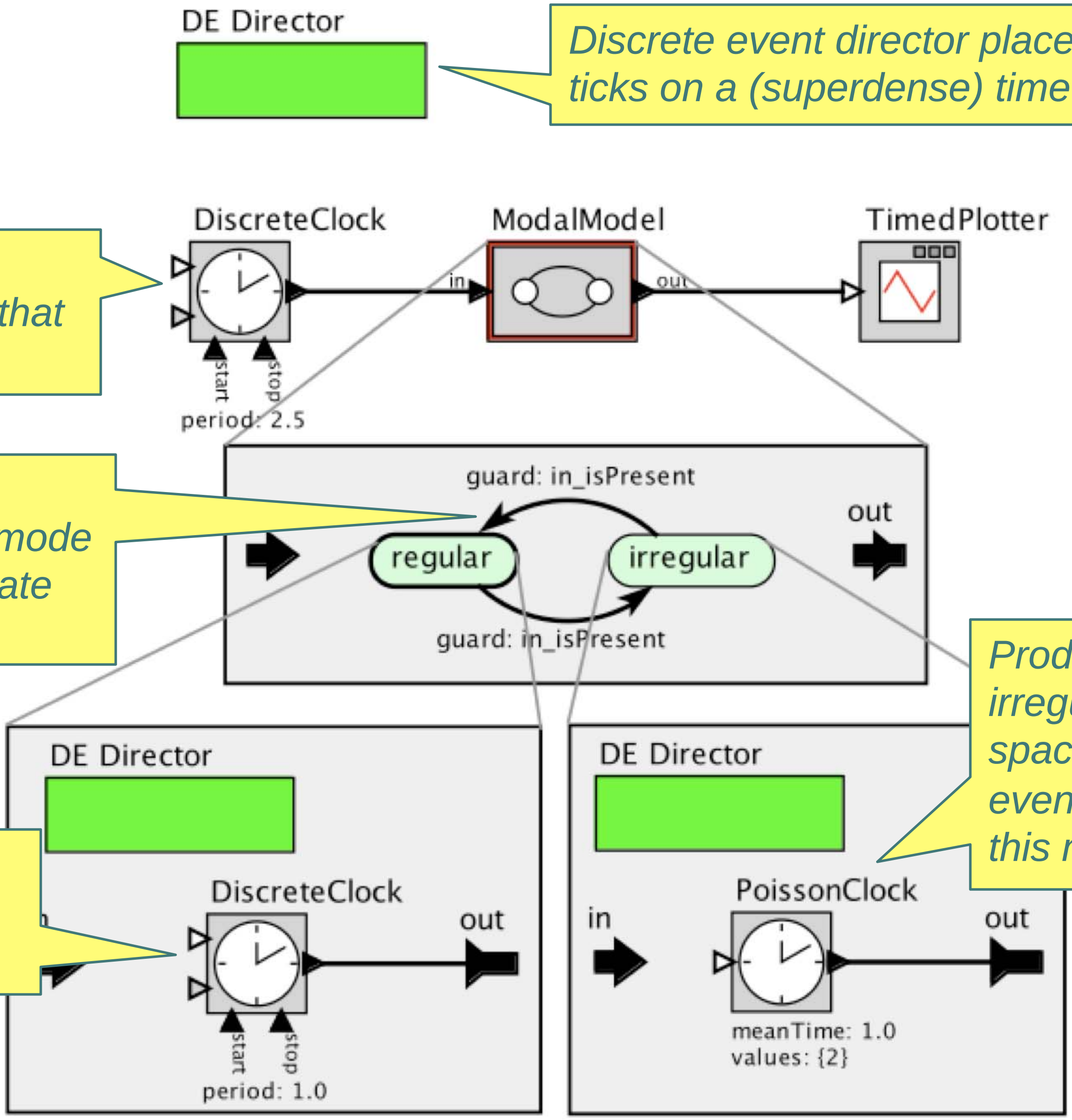




Set the desired speed to the smaller of the default speed and the speed of the leading vehicle.

Set the desired speed to a constant.

Modal Time Example



Discrete event director places ticks on a (superdense) time line.

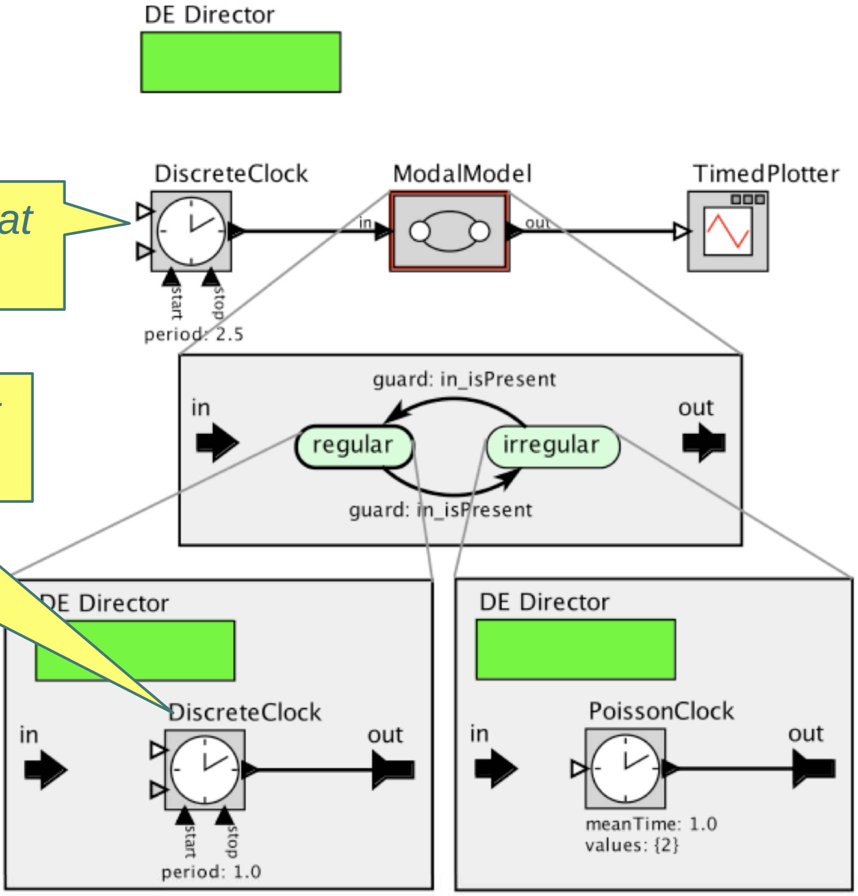
DiscreteClock generates regularly spaced events that trigger mode transitions.

These transitions are “history” transitions, so mode refinements preserve state while suspended.

Produce irregularly spaced events in this mode.

Produce regularly spaced events in this mode.

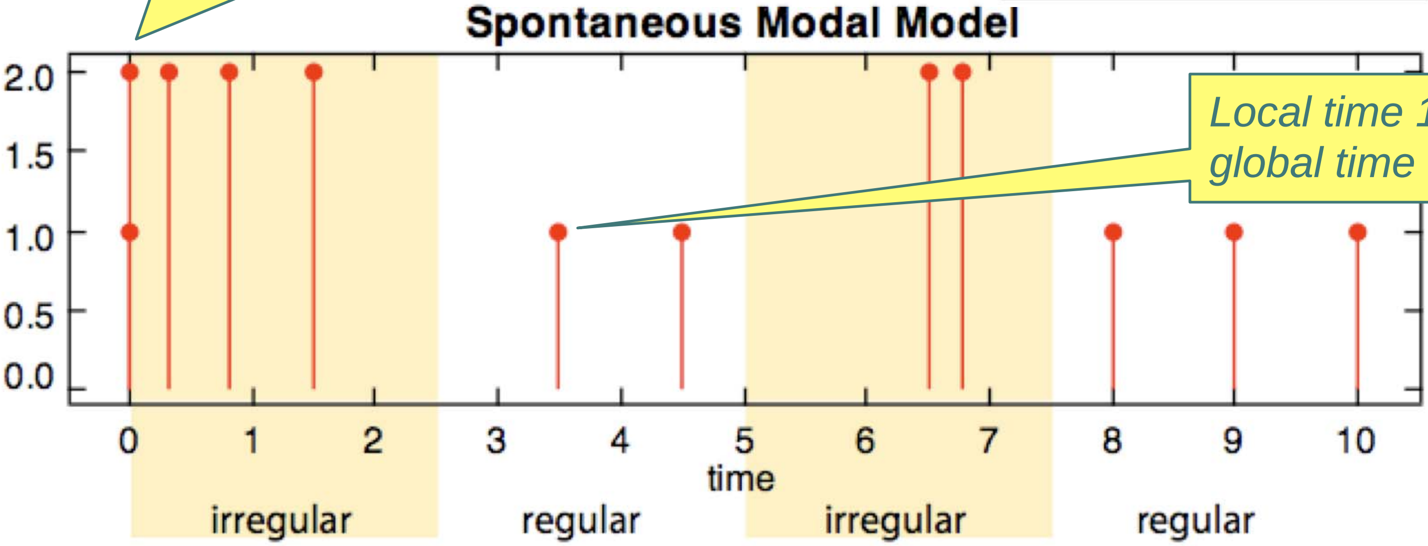
Modal Time Example



Mode transitions triggered at times 0, 2.5, 5, 7.5, etc.

Events with value 1 produced at (local times) 0, 1, 2, 3, etc.

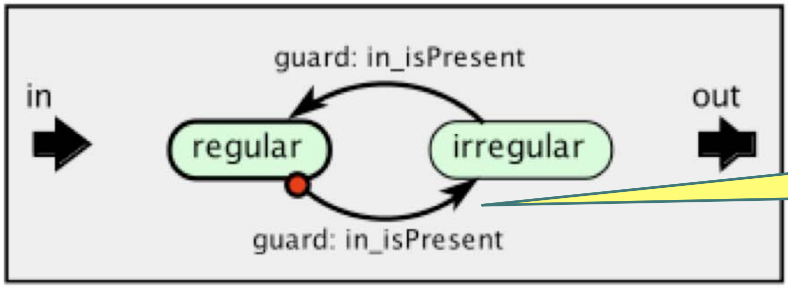
First regular event generated at (global time) 0, then transition is immediately taken. First irregular event generated at (global time) 0, one tick later (in superdense time).



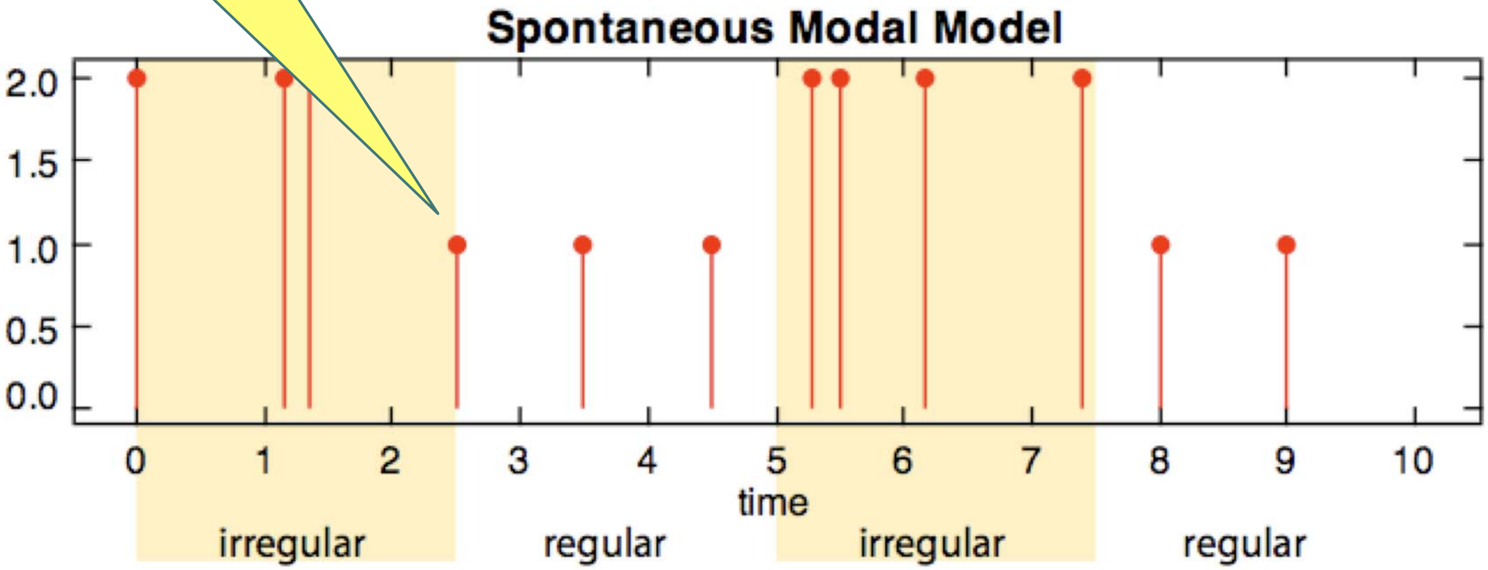
Local time 1 corresponds to global time 3.5 here.

Variant using Preemptive Transition

First regular event is not produced until global time 2.5 (local time 0).

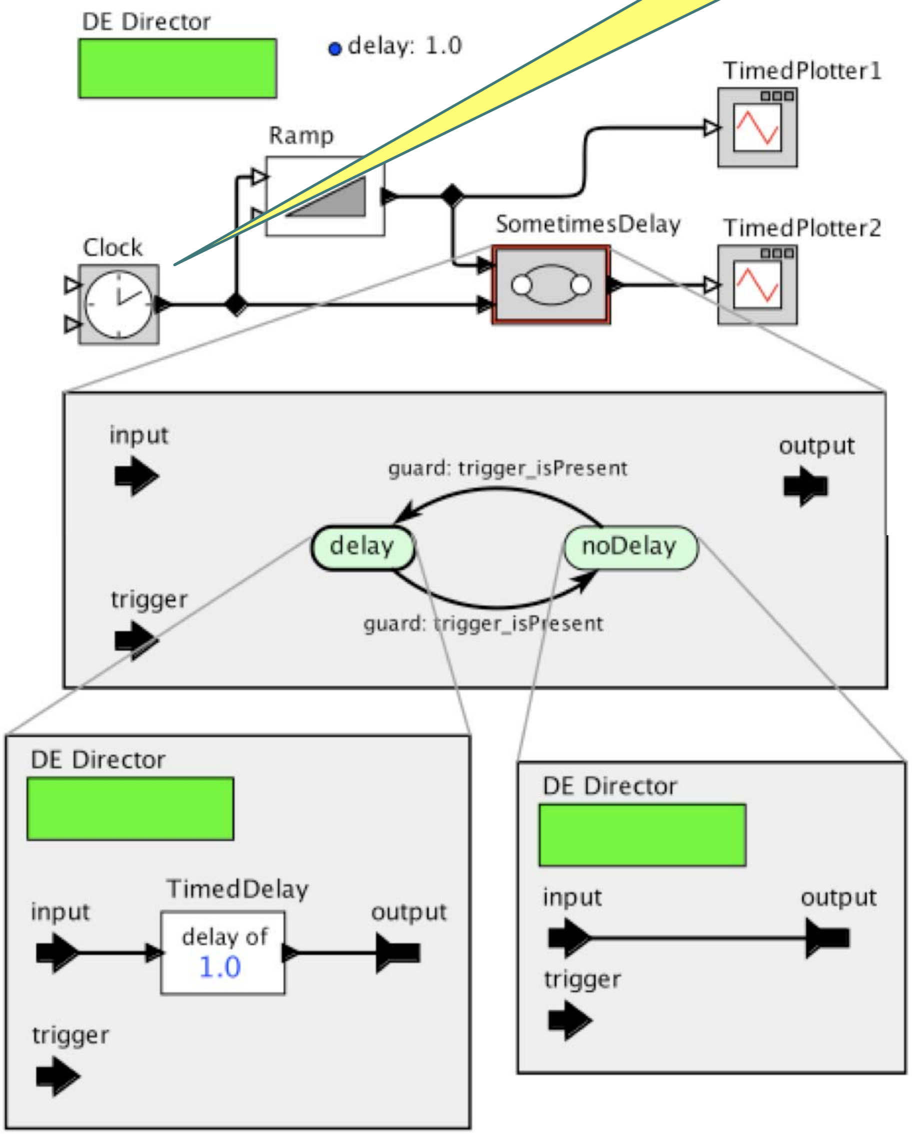


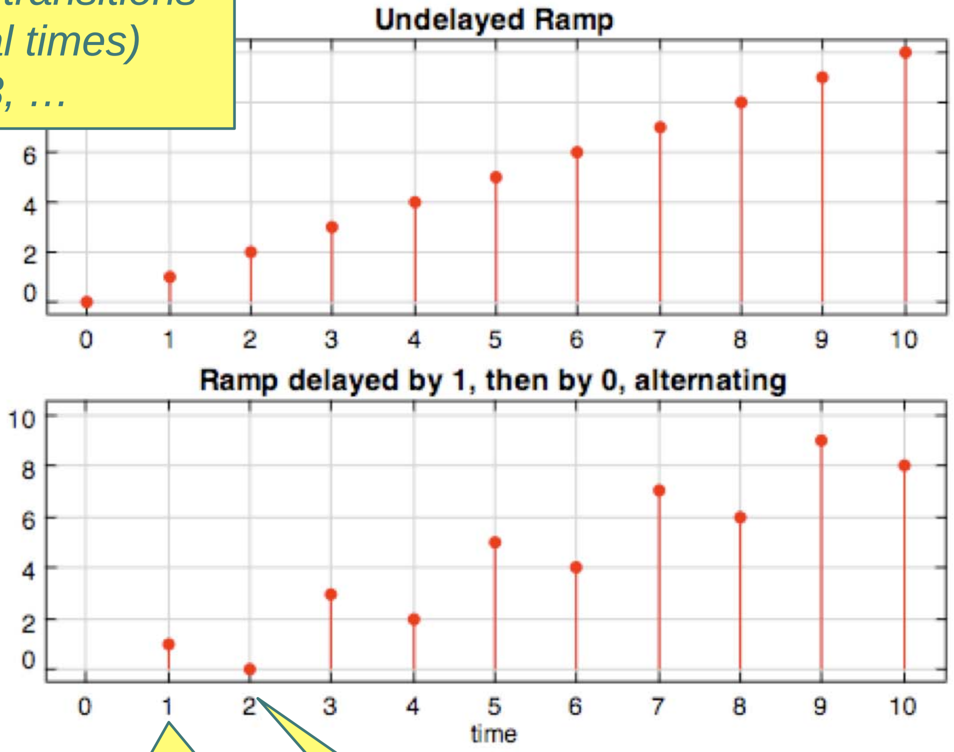
Preemptive transition



Time Delays in Modal Models

Triggers transitions at (global times) 0, 1, 2, 3, …





First output is the second input to the modal model, which goes through the noDelay refinement

Second output is the first input to the modal model, which goes through the delay refinement, which is inactive from time 0 to 1.

Variants for the Semantics of Modal Time that we Tried or Considered, but that Failed

- Mode refinement executes while “inactive” but inputs are not provided and outputs are not observed.
- Time advances while mode is inactive, and mode refinement is responsible for “catching up.”
- Mode refinement is “notified” when it has requested time increments that are not met because it is inactive.
- When a mode refinement is re-activated, it resumes from its first missed event.

All of these led to some very strange models…

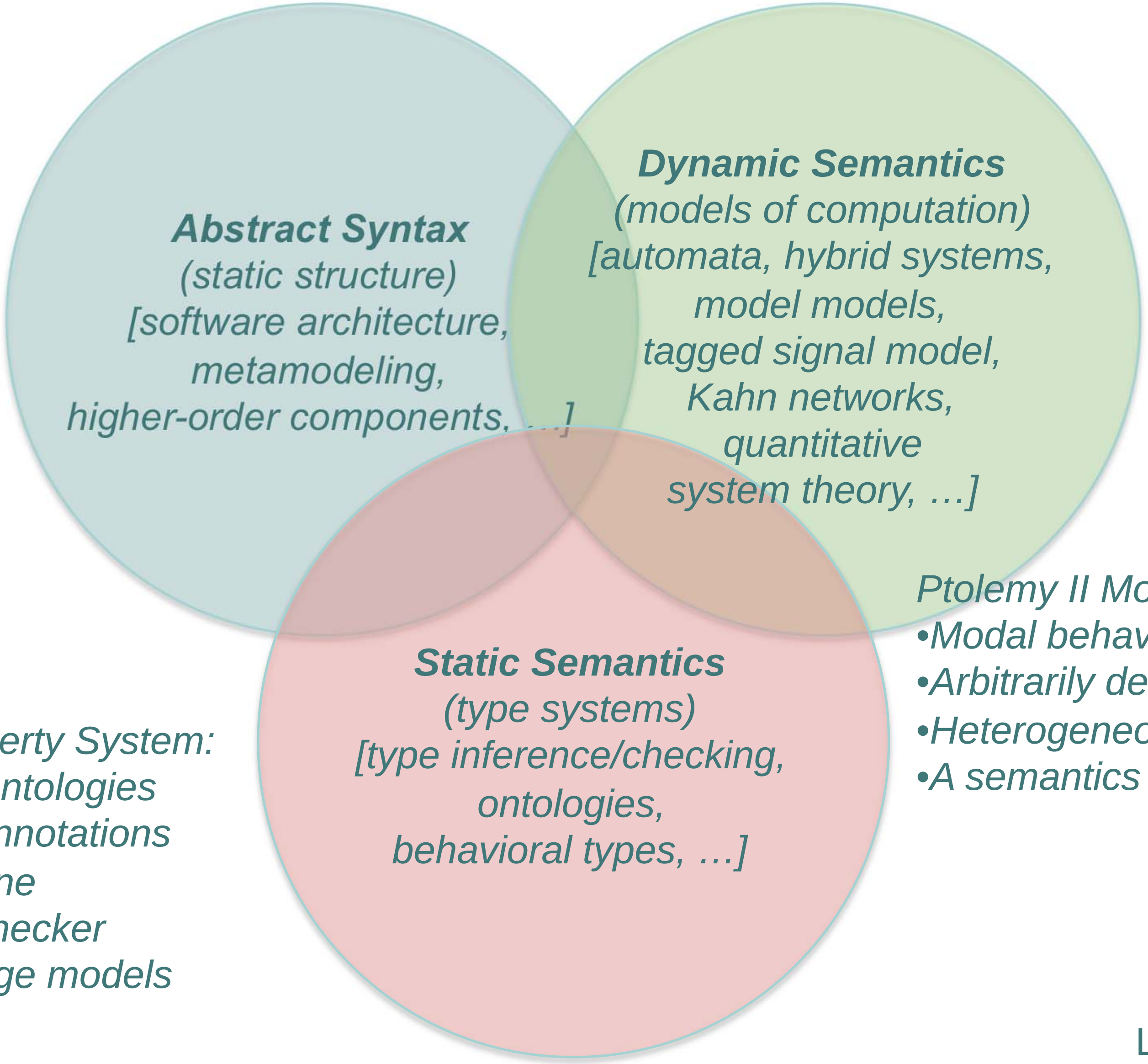
Final solution: Local time does not advance while a mode is inactive. Growing gap between local time and global time.

Conclusion

http://chess.eecs.berkeley.edu/pubs/611.html

http://www.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-151.html

Papers describing this work



Abstract Syntax
(static structure)
[software architecture,
metamodeling,
higher-order components, …]

Dynamic Semantics
(models of computation)
[automata, hybrid systems,
model models,
tagged signal model,
Kahn networks,
quantitative
system theory, …]

Static Semantics
(type systems)
[type inference/checking,
ontologies,
behavioral types, …]

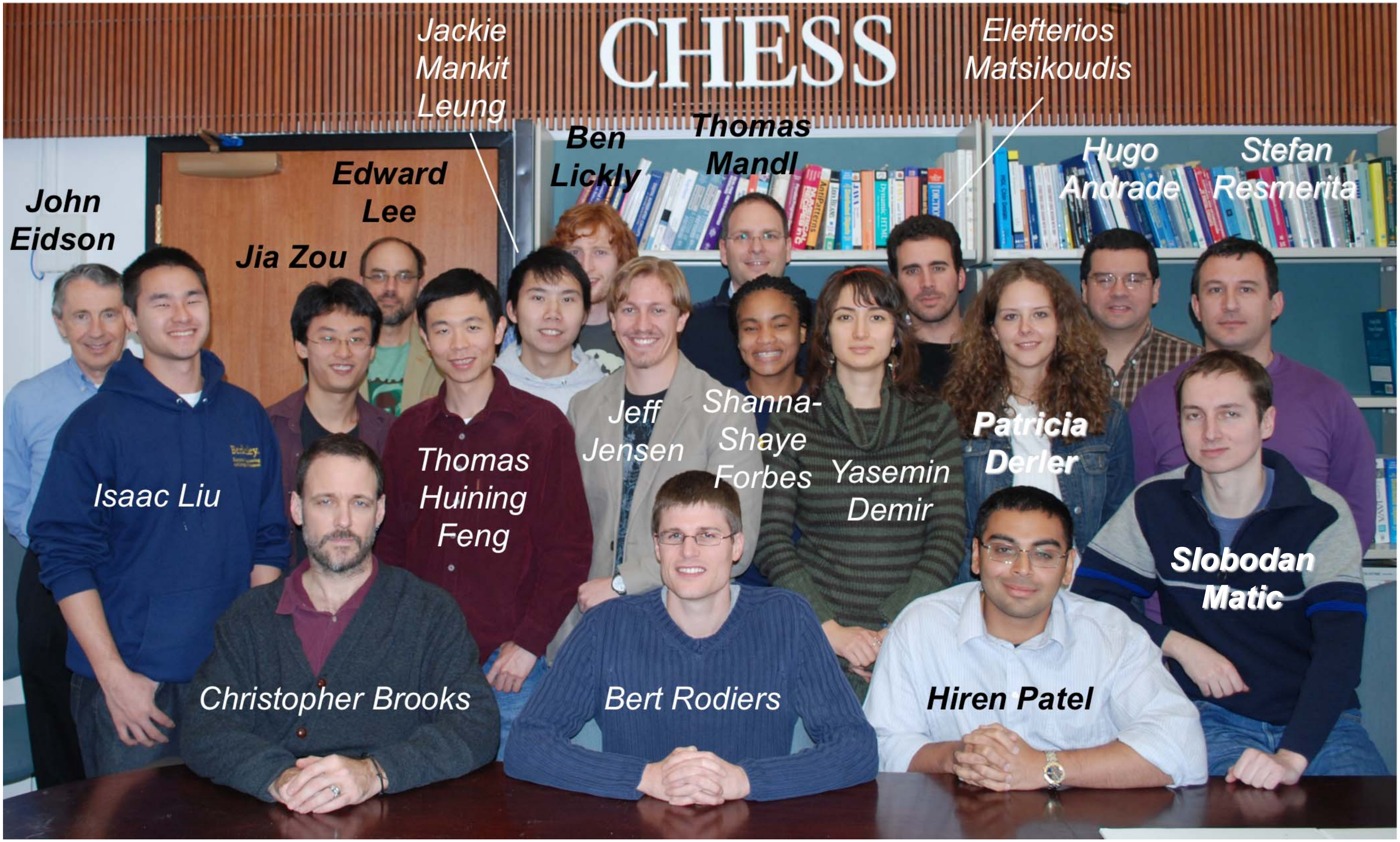
Ptolemy II Modal models:
- *Modal behavior as FSMs*
- *Arbitrarily deep hierarchy*
- *Heterogeneous hierarchy*
- *A semantics of time*

Ptolemy II Property System:
- *User-defined ontologies*
- *A few model annotations*
- *Inference engine*
- *Consistency checker*
- *Scalable to large models*

Acknowledgments:
The Ptolemy Pteam

Plus (not shown):

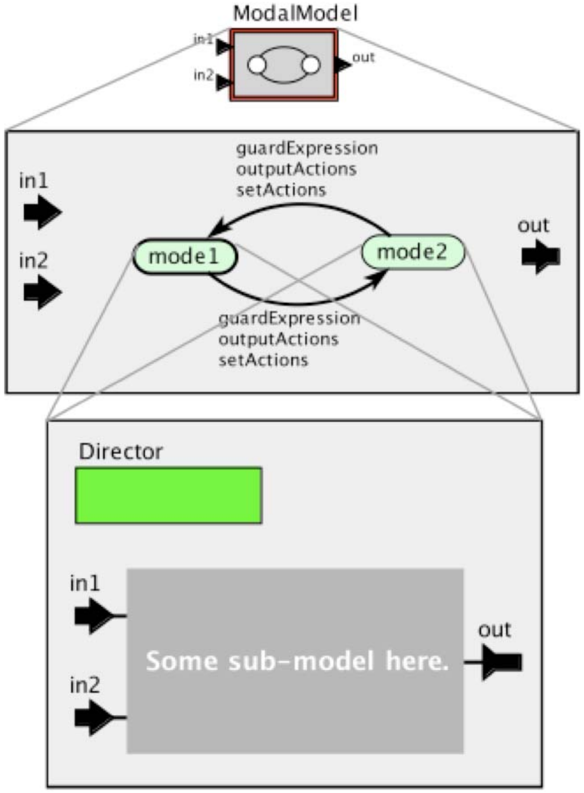
- *Elizabeth Latronico (Bosch)*
- *Charles Shelton (Bosch)*
- *Stavros Tripakis (UCB)*



More Variants of Modal Models Supported in Ptolemy II

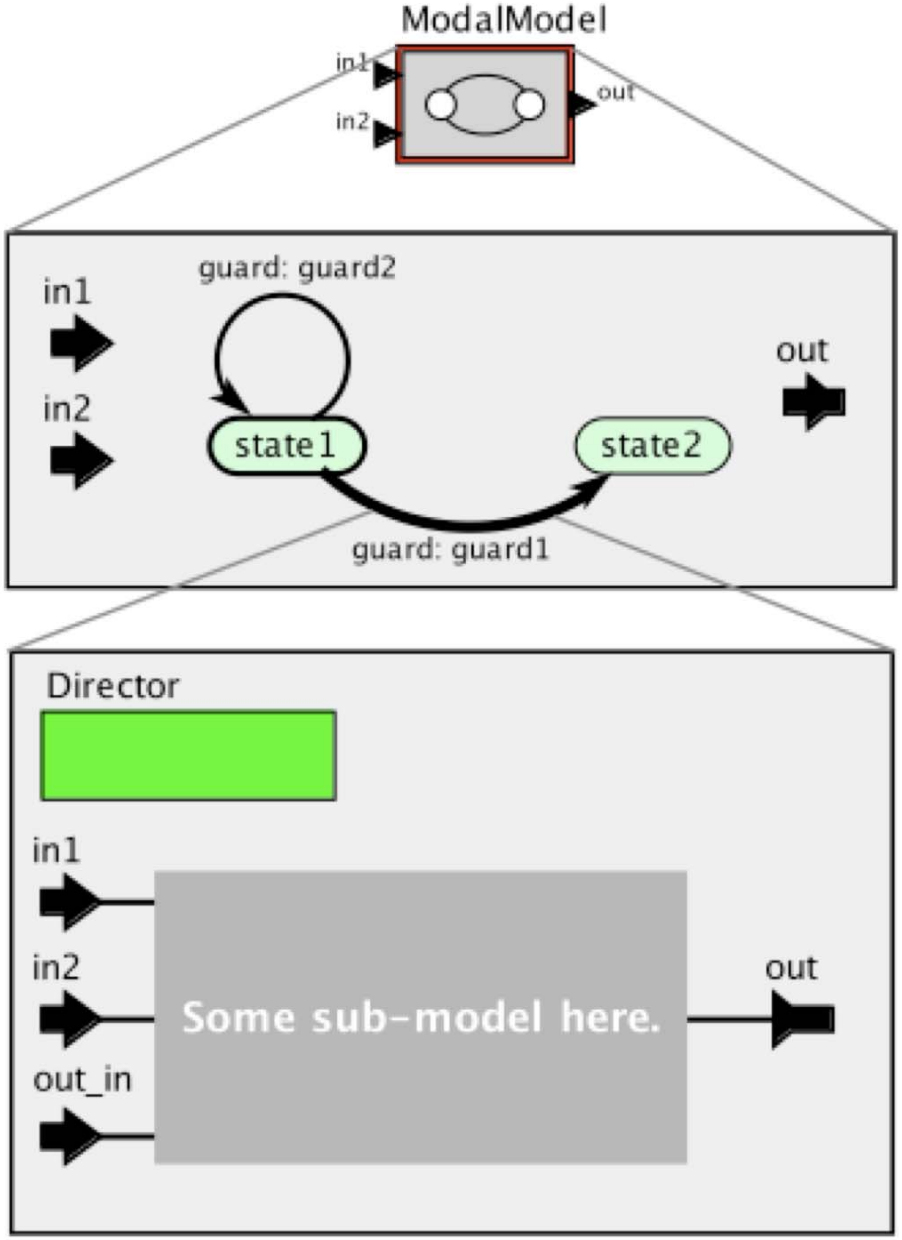
- Transition may be a reset transition
  - Destination refinement is initialized
- Multiple states can share a refinement
  - Facilitates sharing internal actor state across modes
- A state may have multiple refinements
  - Executed in sequence (providing imperative semantics)

Reset transition (vs. history transition)



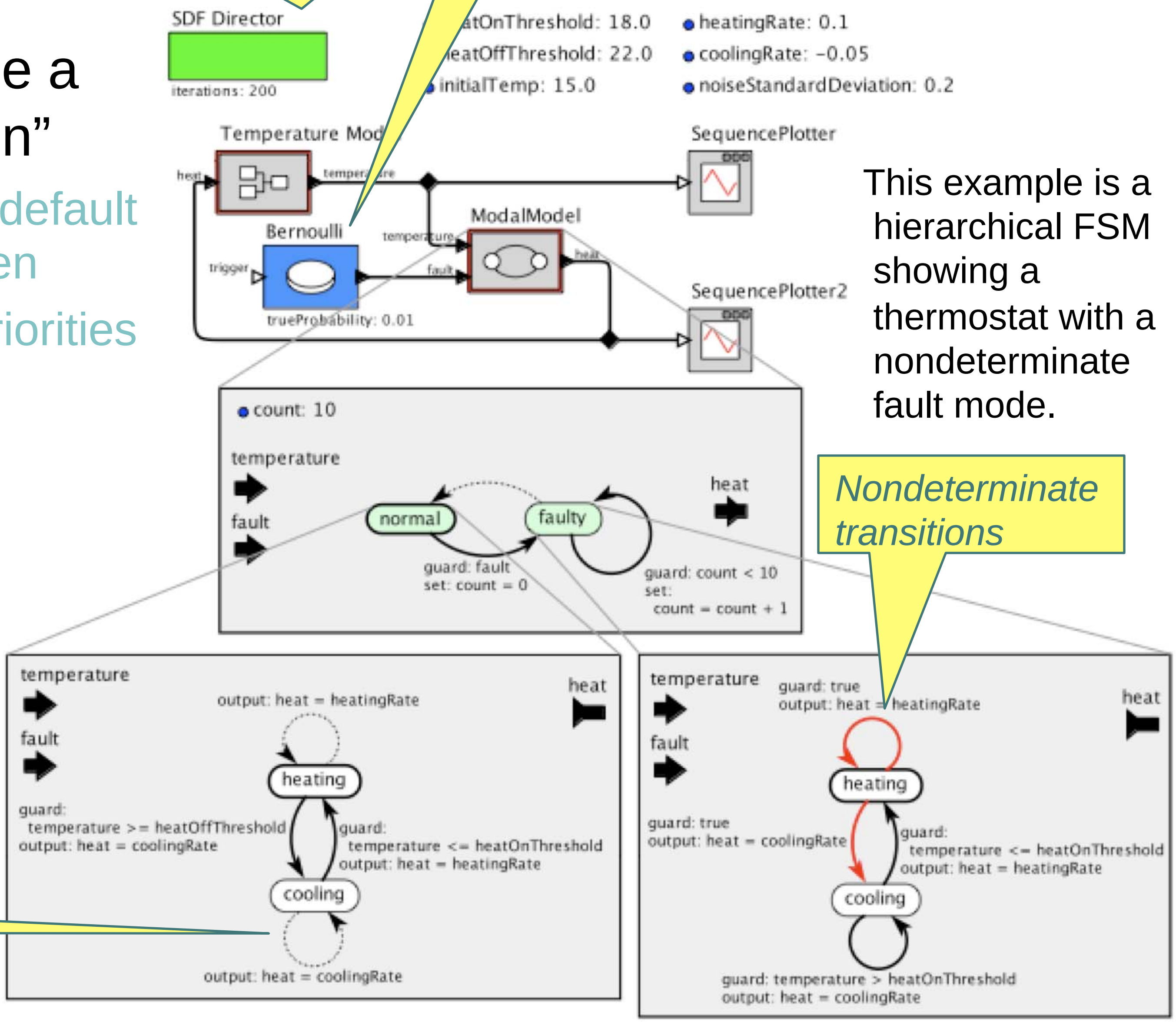
Still More Variants

- Transition may have a refinement
  - Refinement is fired when transition is chosen
  - Postfired when transition is committed
  - Time is that of the environment



And Still More Variants

- Transition may be a "default transition"
  - Taken if no non-default transition is taken
  - Compare with priorities in SyncCharts
- FSMs may be nondeterminate
  - Can mark transitions to permit nondeterminism



Fault model

Dataflow model

Nondeterminate transitions

Default transition

This example is a hierarchical FSM showing a thermostat with a nondeterminate fault mode.