Actor Networks

Edward A. Lee

Robert S. Pepper Distinguished Professor

Chair of EECS

UC Berkeley

Invited Talk

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Key Concepts in Model-Based Design

- Specifications are executable models.
- Models are composed to form designs.
- Models evolve during design.
- Deployed code is generated from models.
- Modeling languages have formal semantics.
- Modeling languages themselves are modeled.

For general-purpose software, this is about

- Object-oriented design

For embedded systems, this is about

- Time
- Concurrency

What We Have Learned

Embedded systems
demand a different approach to computation.

Instead of a Program Specifying…

$$f : \{0,1\}^* \rightarrow \{0,1\}^*$$

… a (partial) function from bit sequences to bit sequences …

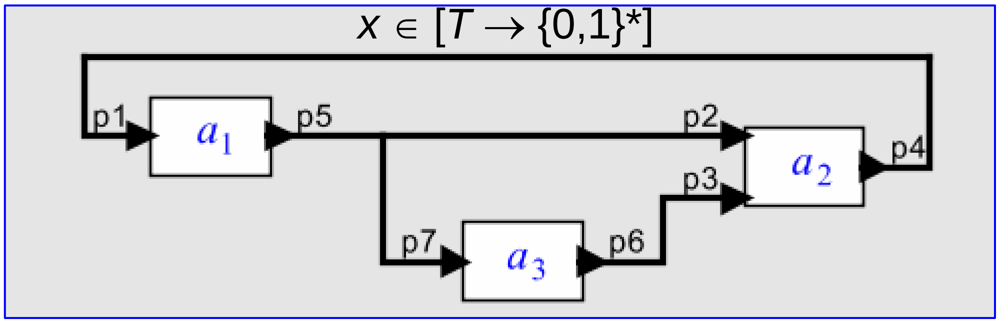
… A Program Should Specify

$$f : [T \to \{0,1\}^*]^P \to [T \to \{0,1\}^*]^P$$

"actor" *"signal"* *"signal"*

…where T is a (partially) ordered set representing time, precedence ordering, causality, synchronization, etc.

This Leads to What We Call Actor-Oriented Component Composition



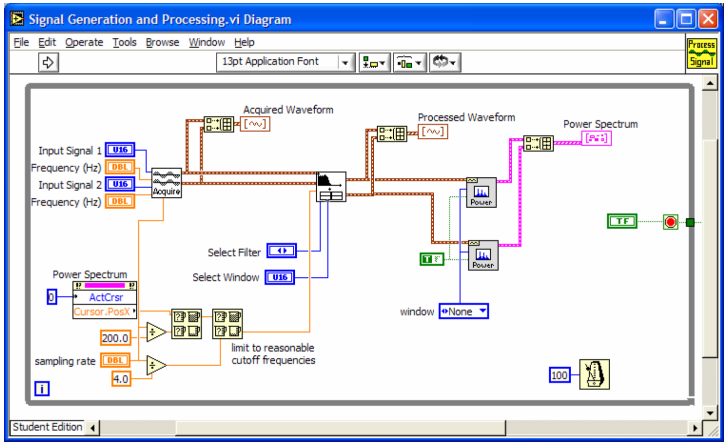
- Cascade connections
- Parallel connections
- Feedback connections

If actors are functions on signals, then the nontrivial part of this is feedback.

Some of the Possible Models of Computation:

- *Time-Triggered*
- *Discrete Events*
- *Dataflow*
- *Rendezvous*
- *Synchronous/Reactive*
- *Continuous Time*
- *Mixtures of the above*
- *…*

Examples of Actor-Oriented "Languages"



- CORBA event service (distributed push-pull)
- LabVIEW (dataflow, National Instruments)
- Modelica (continuous-time, Linkoping)
- OPNET (discrete events, Opnet Technologies)
- Occam (rendezvous)
- ROOM and UML-2 (dataflow, Rational, IBM)
- SCADE and synchronous languages (synchronous/reactive)
- SDL (process networks)
- Simulink (Continuous-time, The MathWorks)
- SPW (synchronous dataflow, Cadence, CoWare)
- VHDL, Verilog (discrete events, Cadence, Synopsys, ...)
- …

Many of these are domain specific.

Many of these have visual syntaxes.

The semantics of these differ considerably, but all can be modeled as

$$f : [T \to \{0,1\}^*]^P \to [T \to \{0,1\}^*]^P$$

with appropriate choices of the set T.

The Catch…

$$f : [T \to \{0,1\}^*]^P \to [T \to \{0,1\}^*]^P$$

- This is not what (mainstream) programming languages do.
- This is not what (mainstream) software component technologies do.
- This is not what (most) semantic theories do.

Let's deal with this one first…

How much Theory is Based on $f : \{0,1\}^* \to \{0,1\}^*$?

- Effectively computable functions [Turing, Church]
- Operational semantics as sequences of transformations of state [Various]
- Denotational semantics as functions mapping a syntax into a function that maps state into state [Winskel]
- Equivalence as bisimulation [Milner]
- Verification as model checking [Various]
- …

See [Lee, FORMATS 2006] for further discussion of this.

Our Approach to a More Suitable Theory: The Tagged Signal Model

[Lee & Sangiovanni-Vincentelli, 1998]

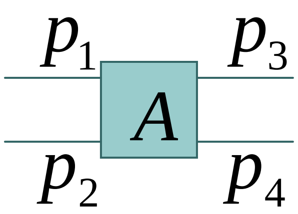
- A set of *values* V and a set of *tags* T
- An *event* is $e \in T \times V$
- A *signal* s is a set of events. I.e. $s \subset T \times V$
- A *functional signal* is a (partial) function $s: T \to V$
- The set of all signals $S = 2^{T \times V}$

Related models:

- Interaction Categories [Abramsky, 1995]
- Interaction Semantics [Talcott, 1996]
- Abstract Behavioral Types [Arbab, 2005]

Actors, Ports, and Behaviors

An *actor* has N *ports* P

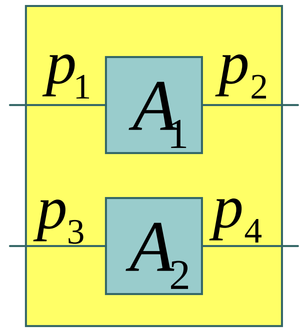


A behavior is a tuple of signals $\sigma = S^N$

An *actor* is a set of *behaviors* $A \subset S^N$

Actor Composition

Composition is simple intersection



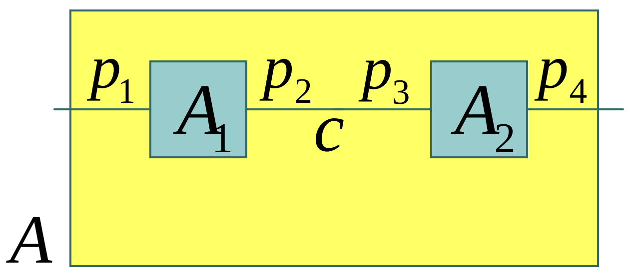
$$A_1 \subset S^4$$

$$A_2 \subset S^4$$

$$A = A_1 \cap A_2$$

Connectors

Connectors are (typically) trivial actors.

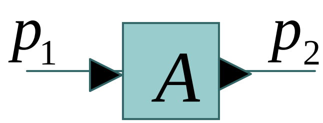


$$c \subset S^4, \quad \mathbf{s} \in c \Rightarrow \mathbf{s}_2 = \mathbf{s}_3$$

$$A = A_1 \cap A_2 \cap c$$

Functional Actors

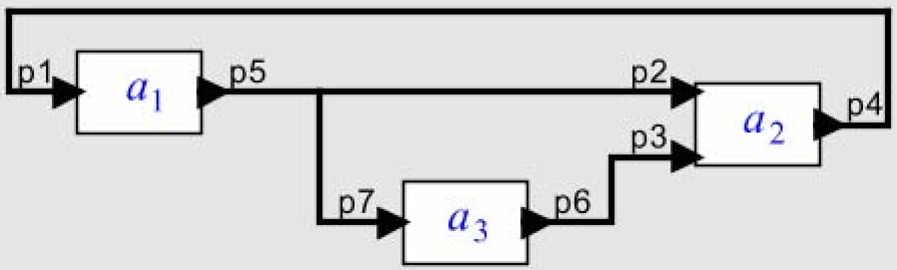
- Ports become inputs or outputs.
- Actors become functions from inputs to outputs.



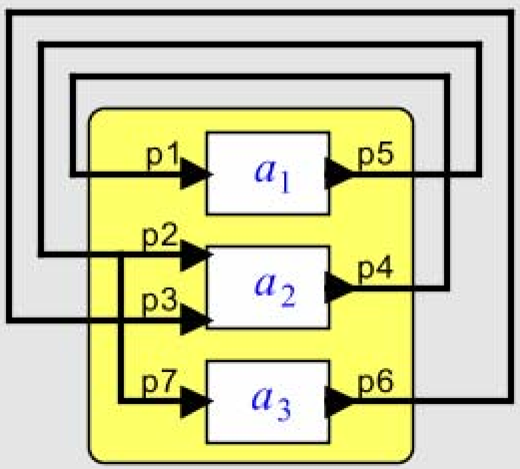
$$A \subset S^4$$

$$\forall \mathbf{s}, \mathbf{s}' \in A,\ \mathbf{s}_1 = \mathbf{s}'_1 \Rightarrow \mathbf{s}_2 = \mathbf{s}'_2$$

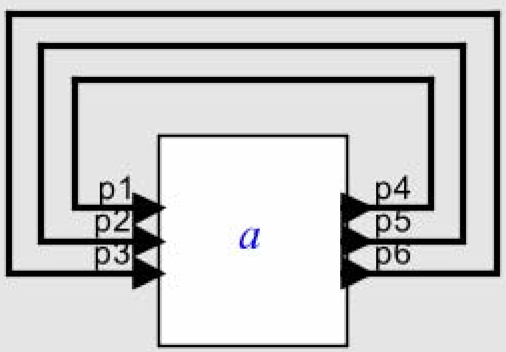
For Functional Actors, Arbitrary Composition has a Fixed-Point Semantics



(a)



(b)



(c)

Structure of the Tag Set

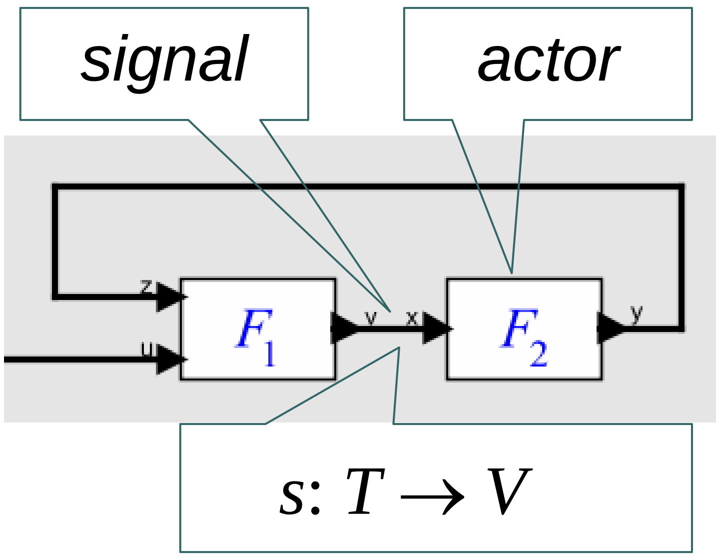
The algebraic properties of the tag set T are determined by the concurrency model, e.g.:

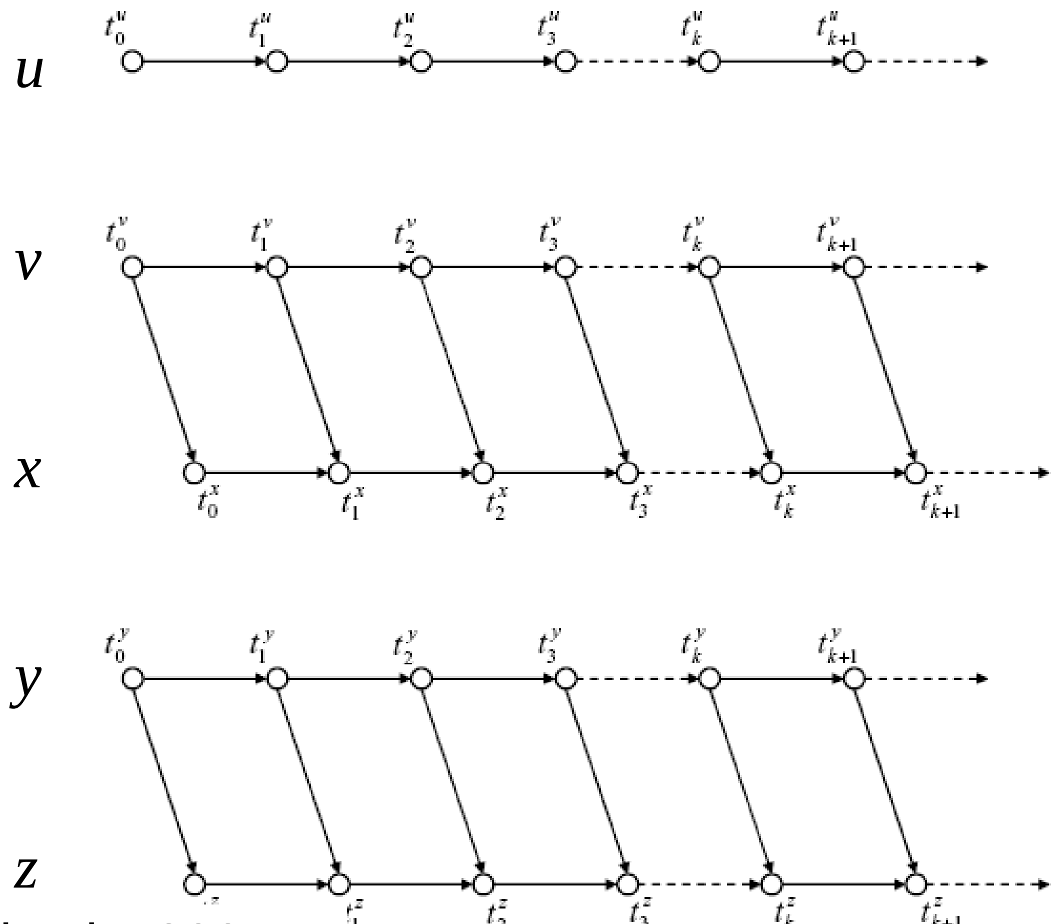
- Process Networks
- Synchronous/Reactive
- Time-Triggered
- Discrete Events
- Dataflow
- Rendezvous
- Continuous Time
- Hybrid Systems
- …

Associated with these may be a richer model of the connectors between actors.

Example of a Partially Ordered Tag Set *T* for Kahn Process Networks

Ordering constraints on tags imposed by communication:

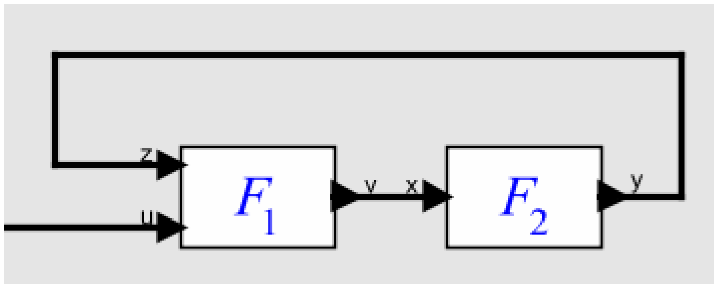




Each signal maps a totally ordered subset of T into values.

Example from Xiaojun Liu, Ph.D. Thesis, 2005.

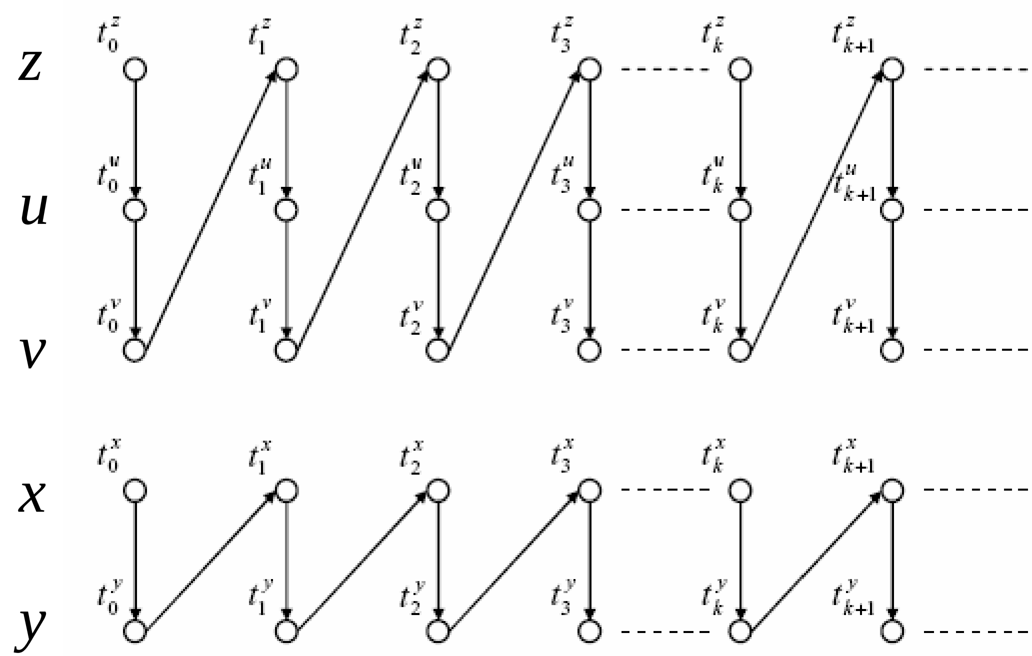
Example: Tag Set *T* for Kahn Process Networks




```
Actor F1(in z, u; out v)
{
  repeat {
    t1 = receive(z)
    t2 = receive(u)
    send(v, t1 + t2)
  }
}
```

```
Actor F2(in x; out y)
{
  repeat {
    t = receive(x)
    send(v, t)
  }
}
```

Ordering constraints on tags imposed by computation:



Composition of these constraints with the previous reveals deadlock.

Example from Xiaojun Liu, Ph.D. Thesis, 2005.

Totally Ordered Tag Sets

- Example: $T = \mathbb{N}$
  (synchronous languages)
- Example: $T = \mathbb{R}_0 \times \mathbb{N}$, with lexicographic order ("super dense time").
  - Used to model
    - hardware,
    - continuous dynamics,
    - hybrid systems,
    - embedded software

See [Liu, Matsikoudis, Lee, CONCUR 2006].

Recall The Catch…

$$f : [T \to \{0,1\}^*]^P \to [T \to \{0,1\}^*]^P$$

- This is not what (mainstream) programming languages do.
- This is not what (mainstream) software component technologies do.
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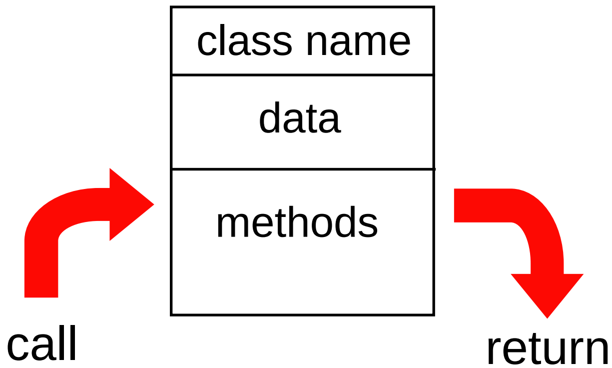
Let's look at the second problem next…

Actor-Oriented Design

Established component interactions:

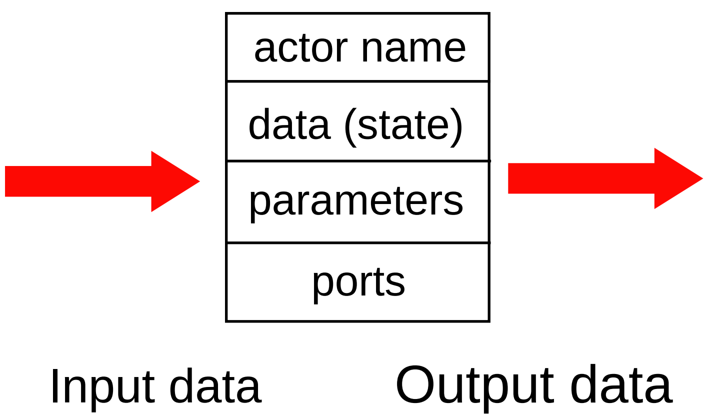


What flows through an object is sequential control

Things happen to objects

The alternative: “Actor oriented:”

Actors make things happen

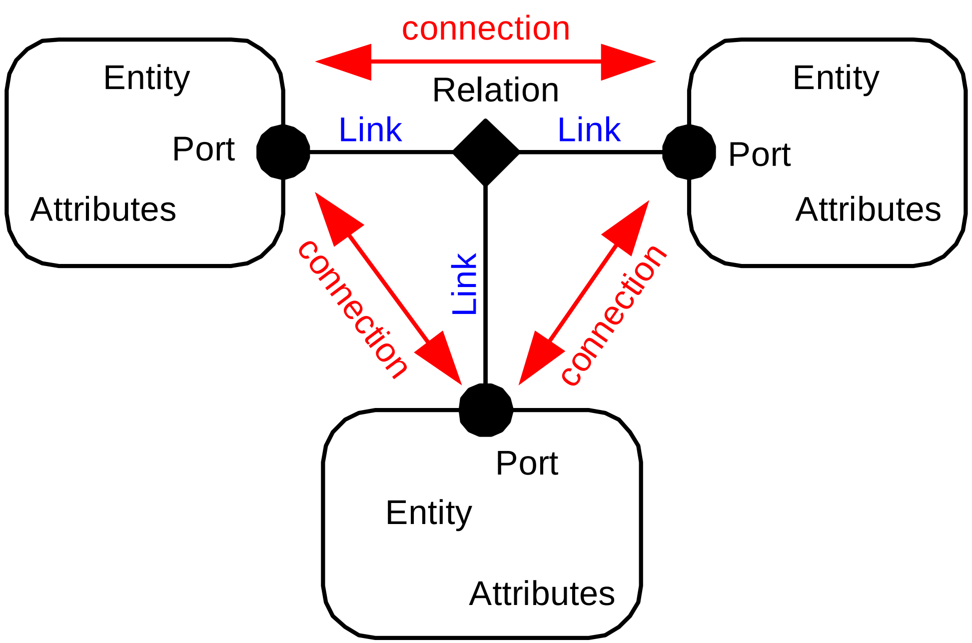


What flows through an object is evolving data

The Key To Success: Separation of Concerns

- Abstract Syntax
- Concrete Syntax
- Syntax-Based Static Analysis: e.g. Type Systems
- Abstract Semantics
- Concrete Semantics
- Semantics-Based Static Analysis: e.g. Verification

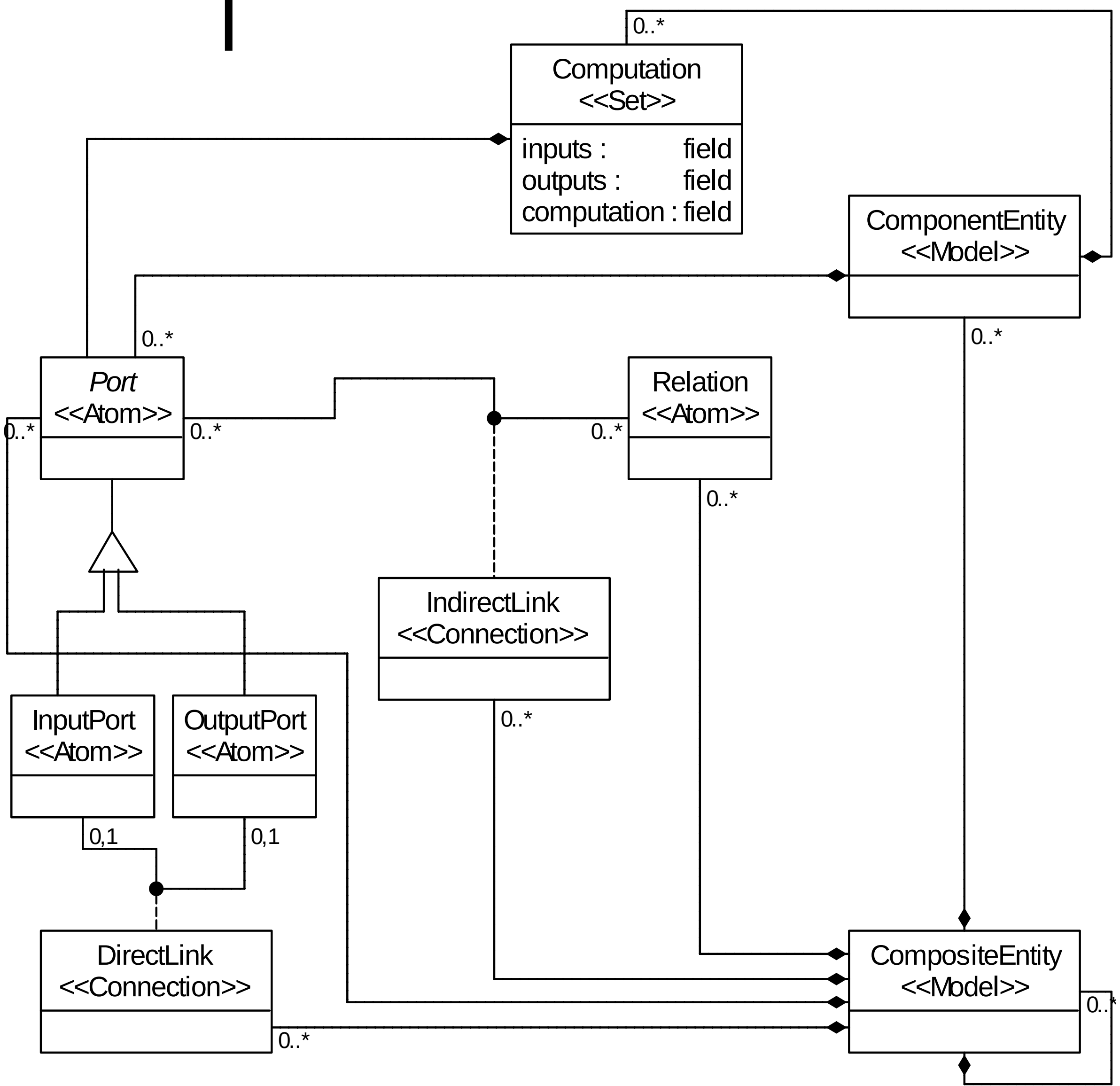
An Abstract Syntax



- Entities
- Attributes on entities (parameters)
- Ports in entities
- Links between ports
- Width on links (channels)
- Hierarchy

Abstract syntaxes can be formalized.
See [Jackson and Sztipanovits, EMSOFT 2006]

Meta-Modeling of an Abstract Syntax



Using GME (from Vanderbilt) an abstract syntax is specified as an object model (in UML) with constraints (in OCL), or alternatively, with MOF.

Such a spec can be used to synthesize visual editors and models transformers.

Meta-model of Ptolemy II abstract syntax, constructed in GME by H. Y. Zheng.

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Concrete Syntax

Example concrete syntax in XML:

```
...
<entity name="FFT" class="ptolemy.domains.sdf.lib.FFT">
    <property name="order" class="ptolemy.data.expr.Parameter" value="order">
    </property>
    <port name="input" class="ptolemy.domains.sdf.kernel.SDFIOPort">
       ...
    </port>
    ...
</entity>
...
<link port="FFT.input" relation="relation"/>
<link port="AbsoluteValue2.output" relation="relation"/>
...
```

XML and XSLT have made concrete syntax even less important than it used to be. Going a step further, GReAT (from Vanderbilt) works with GME to synthesize model transformers from meta models.

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See [Lee and Neuendorffer, MEMOCODE 2004] and [Xiong, PhD Thesis, 2002] for actor-oriented type systems.

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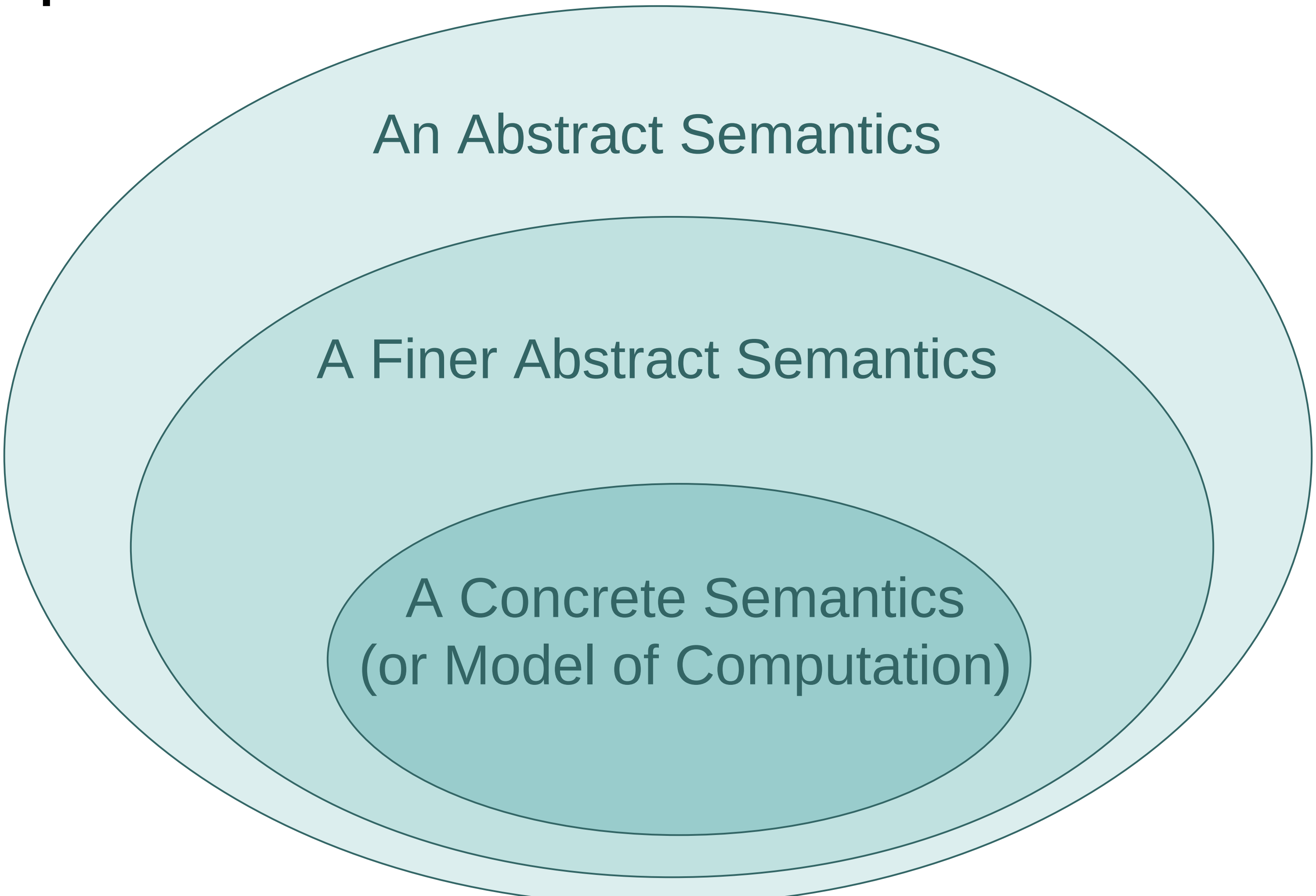
Where We Are Headed



Tagged Signal Abstract Semantics

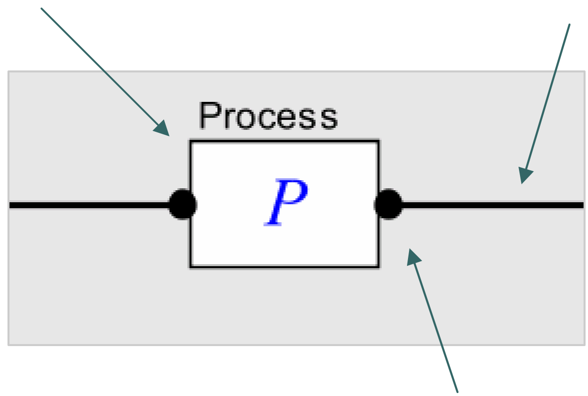
Tagged Signal Abstract Semantics:

an actor is a subset of the signals with which it interacts.

signal is a set of events.

$$P \subset S_1 \times S_2$$

$s_1 \in S_1$



$s_2 \in S_2$

port may be an input or an output, or neither or both. It is irrelevant.

This outlines a general *abstract semantics* that gets specialized. When it becomes concrete you have a *model of computation.*

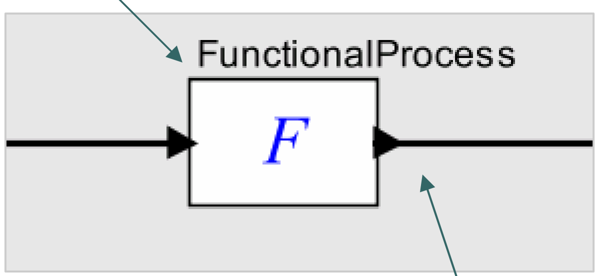
A Finer Abstraction Semantics

Functional Abstract Semantics:

An actor is now a function from
input signals to output signals.

$$F : S_1 \to S_2$$

$s_1 \in S_1$



$s_2 \in S_2$

port is now either an
input or an output (or both).

This outlines an *abstract semantics* for deterministic producer/consumer actors.

Another Finer Abstract Semantics

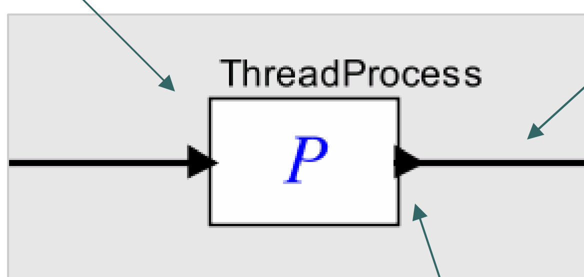
Process Networks Abstract Semantics:

An actor is a sequence of operations on its signals where the operations are the associative operation of a *monoid*

sets of signals are *monoids*, which allows us to incrementally construct them. E.g.
- stream
- event sequence
- rendezvous points …

$$P \subset S_1 \times S_2$$

$s_1 \in S_1$



$s_2 \in S_2$

Actor is not necessarily functional (can be nondeterministic).

port is either an input or an output or both.

This outlines an abstract semantics for actors constructed as processes that incrementally read and write port data.

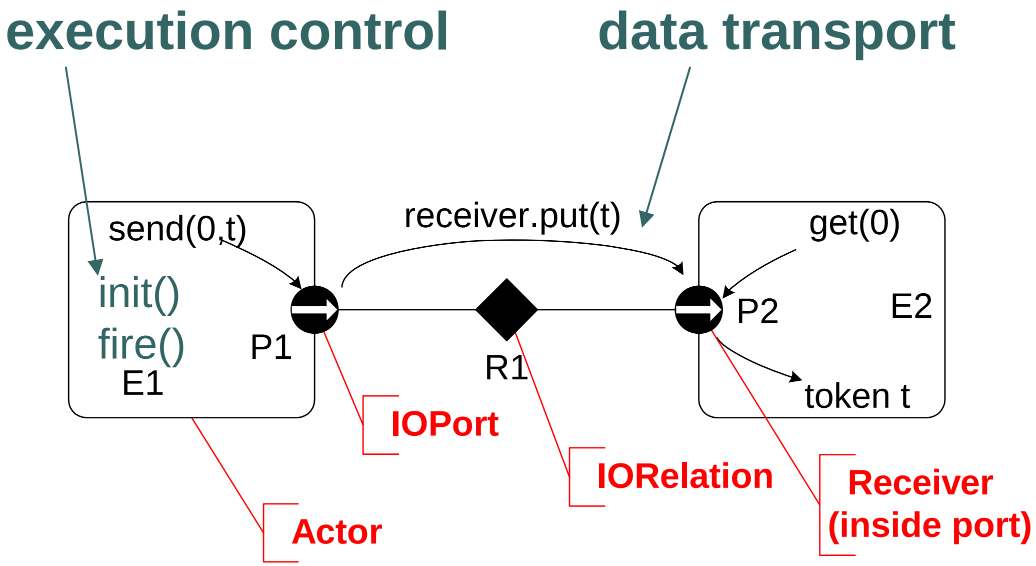
Concrete Semantics that Conform with the Process Networks Abstract Semantics

- Communicating Sequential Processes (CSP) [Hoare]
- Calculus of Concurrent Systems (CCS) [Milner]
- Kahn Process Networks (KPN) [Kahn]
- Nondeterministic extensions of KPN [Various]
- Actors [Hewitt]

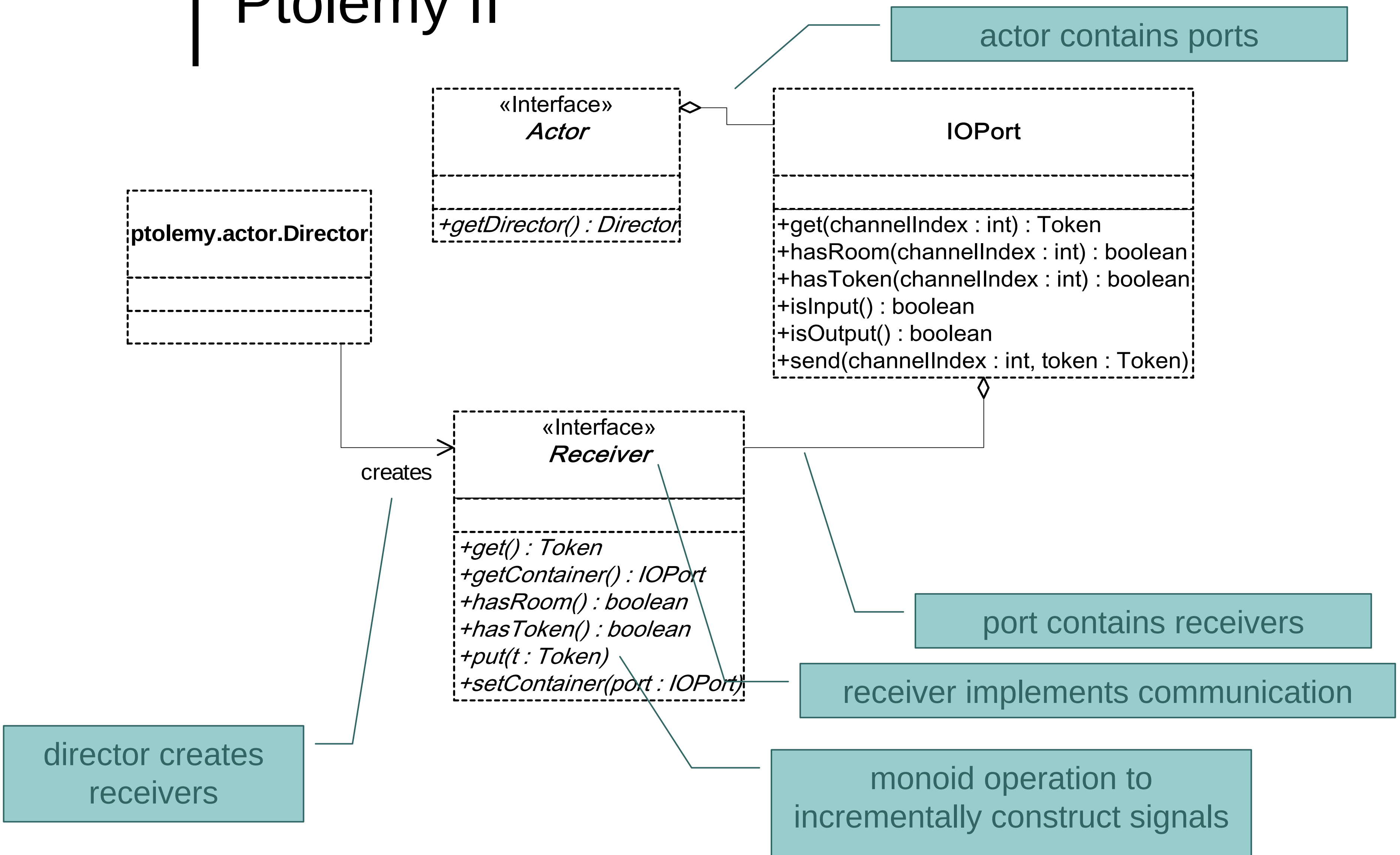
Some Implementations:

- Occam, Lucid, and Ada languages
- Ptolemy Classic and Ptolemy II (PN and CSP domains)
- System C
- Metropolis

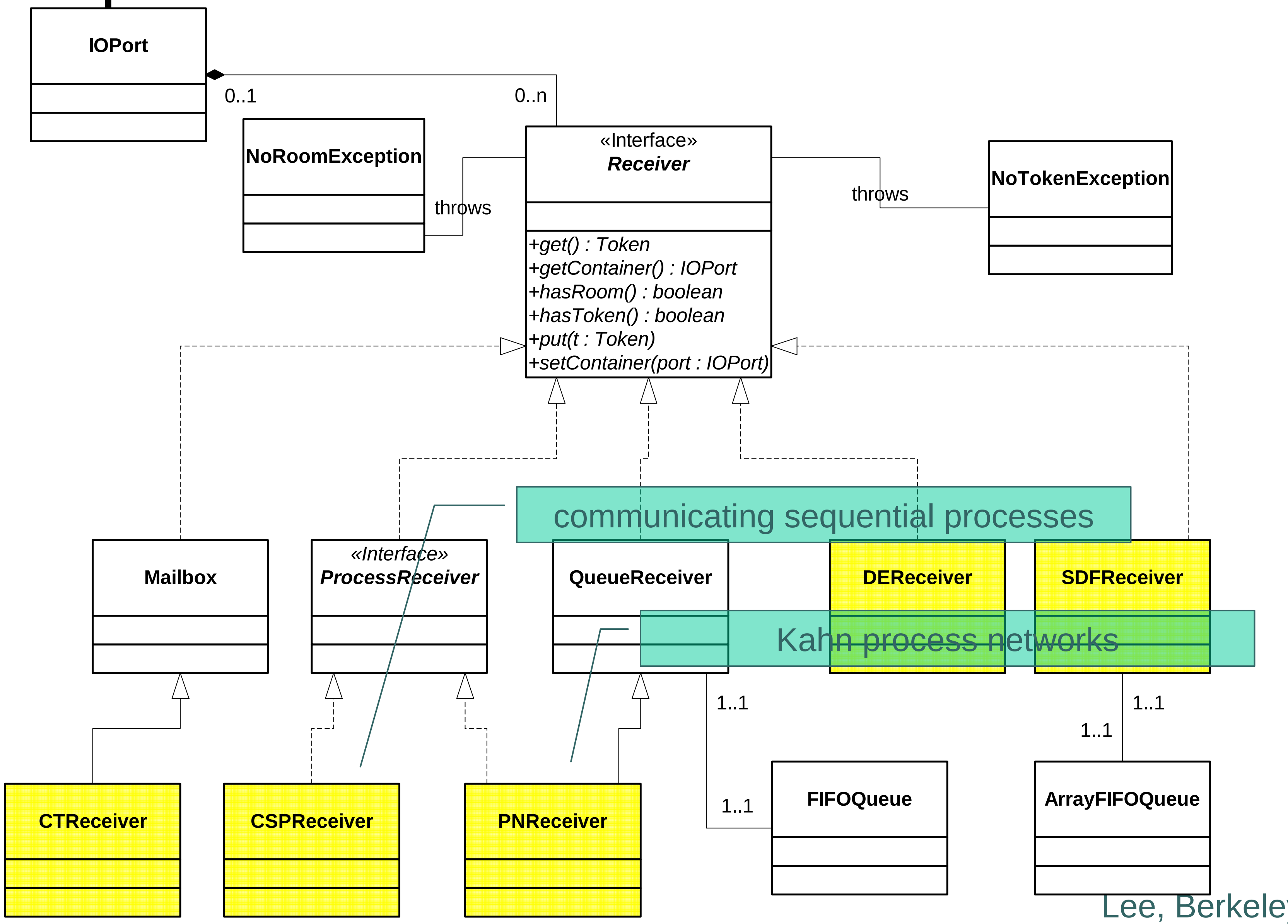
Process Network Abstract Semantics has a Natural Software Implementation



Process Network Abstract Semantics in Ptolemy II



Several Concrete Semantics Refine this Abstract Semantics



A Still Finer Abstract Semantics

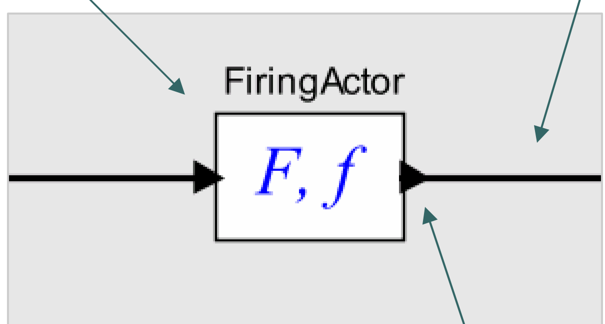
Firing Abstract Semantics:

An actor is still a function from input signals to output signals, but that function now is defined in terms of a firing function.

signals are in monoids (can be incrementally constructed) (e.g. streams, discrete-event signals).

$$F : S_1 \to S_2$$

$s_1 \in S_1$



$s_2 \in S_2$

port is still either an input or an output.

The process function F is the least fixed point of a functional defined in terms of f.

Models of Computation that Conform to the Firing Abstract Semantics

- Dataflow models (all variations)
- Discrete-event models
- Time-driven models (Giotto)

In Ptolemy II, actors written to the *firing abstract semantics* can be used with directors that conform only to the process network abstract semantics.

Such actors are said to be *behaviorally polymorphic*.

Actor Language for the Firing Abstract Semantics: Cal

Cal is an actor language designed to provide statically inferable actor properties w.r.t. the firing abstract semantics. E.g.:

```
actor Select () S, A, B ==> Output:

    action S: [sel], A: [v] ==> [v]
    guard sel end

    action S: [sel], B: [v] ==> [v]
    guard not sel end
end
```

Inferable firing rules and firing functions:

$$U_1 = \{\langle(\text{true}),(v),\bot\rangle : v \in \mathbf{Z}\},\ f_1 : \langle(\text{true}),(v),\bot\rangle \mapsto (v)$$

$$U_2 = \{\langle(\text{false}),\bot,(v)\rangle : v \in \mathbf{Z}\},\ f_2 : \langle(\text{false}),\bot,(v)\rangle \mapsto (v)$$

Thanks to Jorn Janneck, Xilinx

A Still Finer Abstract Semantics

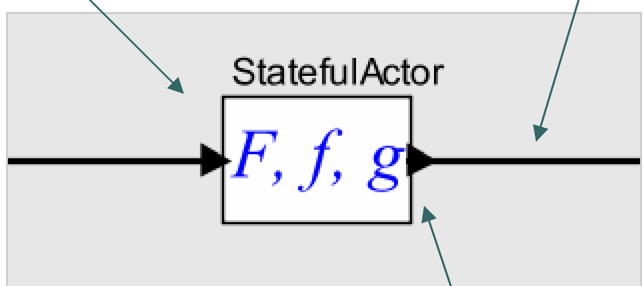
Stateful Firing Abstract Semantics:

An actor is still a function from input signals to output signals, but that function now is defined in terms of two functions.

signals are monoids (can be incrementally constructed) (e.g. streams, discrete-event signals).

$$F : S_1 \to S_2$$

$$s_1 \in S_1$$



$$s_2 \in S_2$$

$$f : S_1 \times \Sigma \to S_2$$

$$g : S_1 \times \Sigma \to \Sigma$$

state space

port is still either an input or an output.

The function f gives outputs in terms of inputs and the current state.
The function g updates the state.

Models of Computation that Conform to the Stateful Firing Abstract Semantics

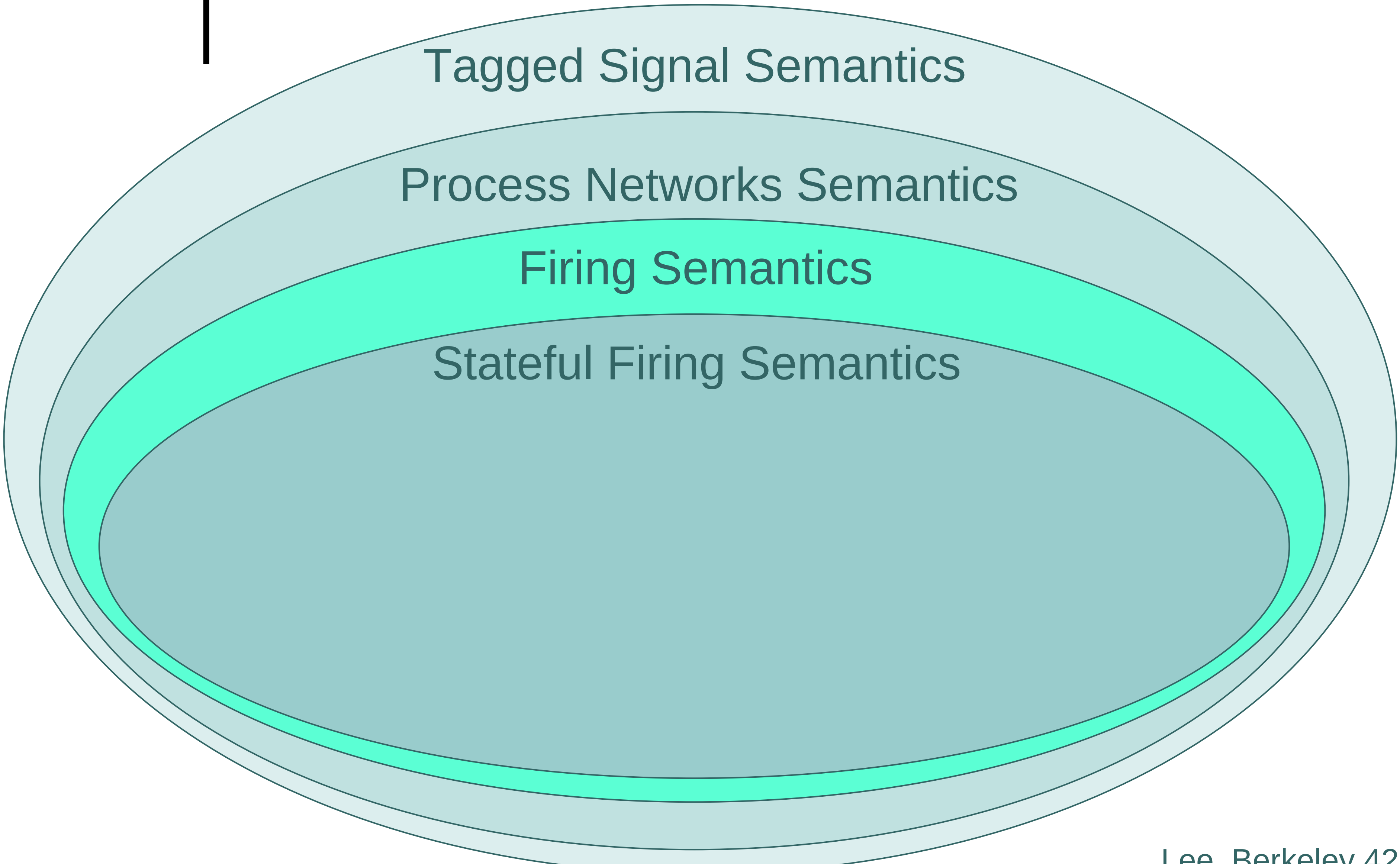
- Synchronous reactive
- Continuous time
- Hybrid systems

Stateful firing supports iteration to a fixed point, which is required for hybrid systems modeling.

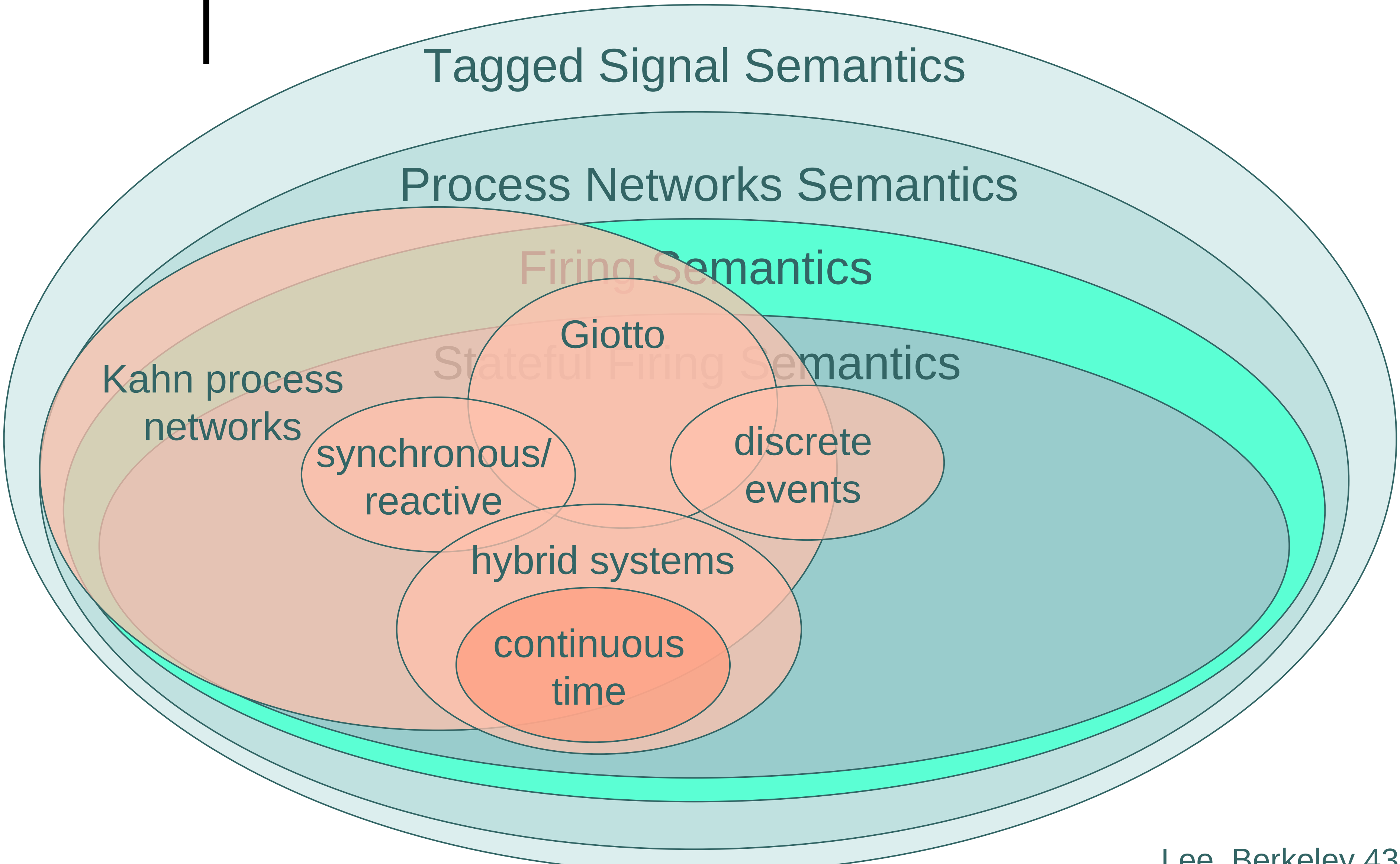
In Ptolemy II, actors written to the stateful firing abstract semantics can be used with directors that conform only to the firing abstract semantics or to the process network abstract semantics.

Such actors are said to be *behaviorally polymorphic*.

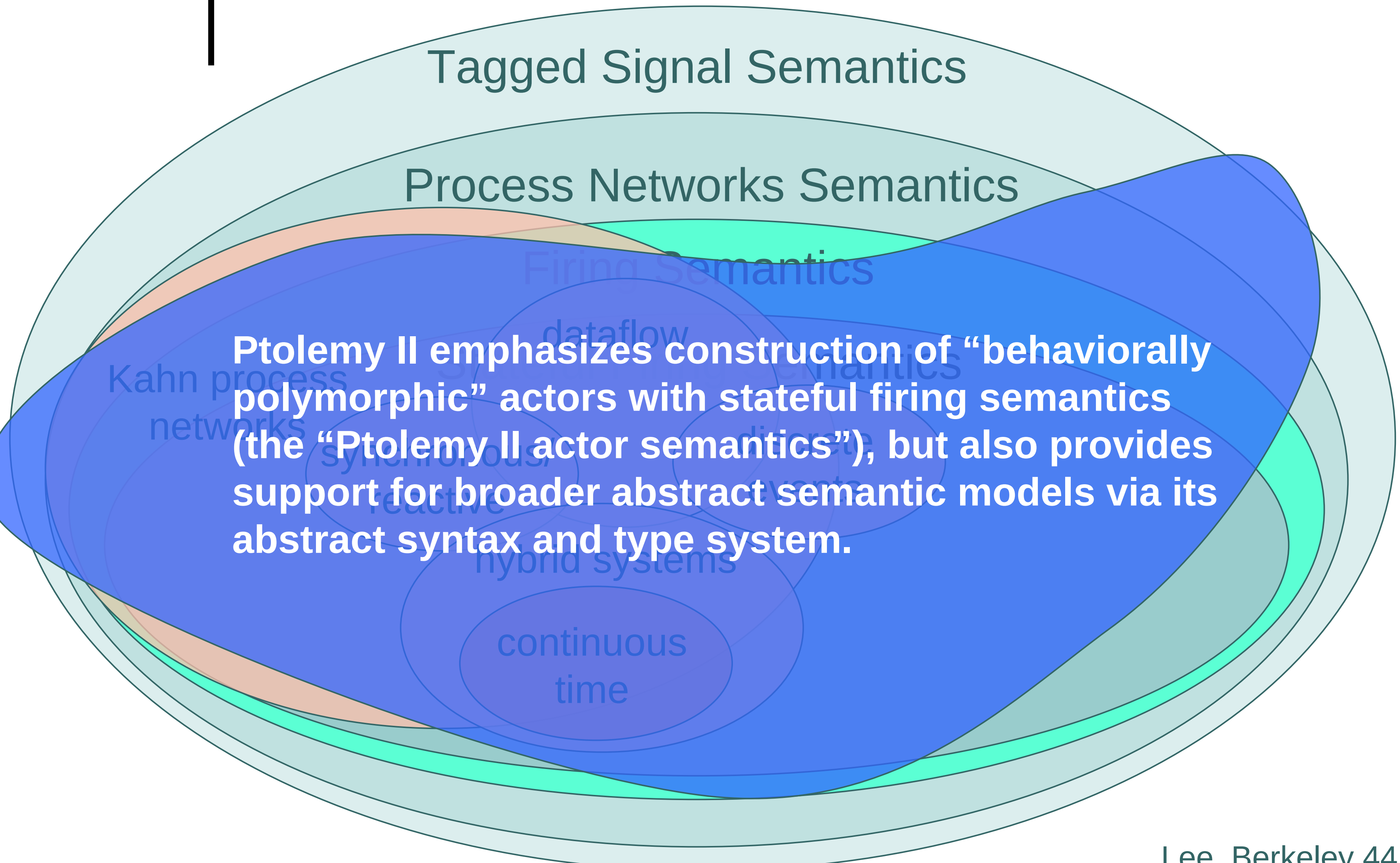
Where We Are


Tagged Signal Semantics
Process Networks Semantics
Firing Semantics
Stateful Firing Semantics

Where We Are


Tagged Signal Semantics
Process Networks Semantics
Firing Semantics
Stateful Firing Semantics
Kahn process networks
Giotto
synchronous/ reactive
discrete events
hybrid systems
continuous time

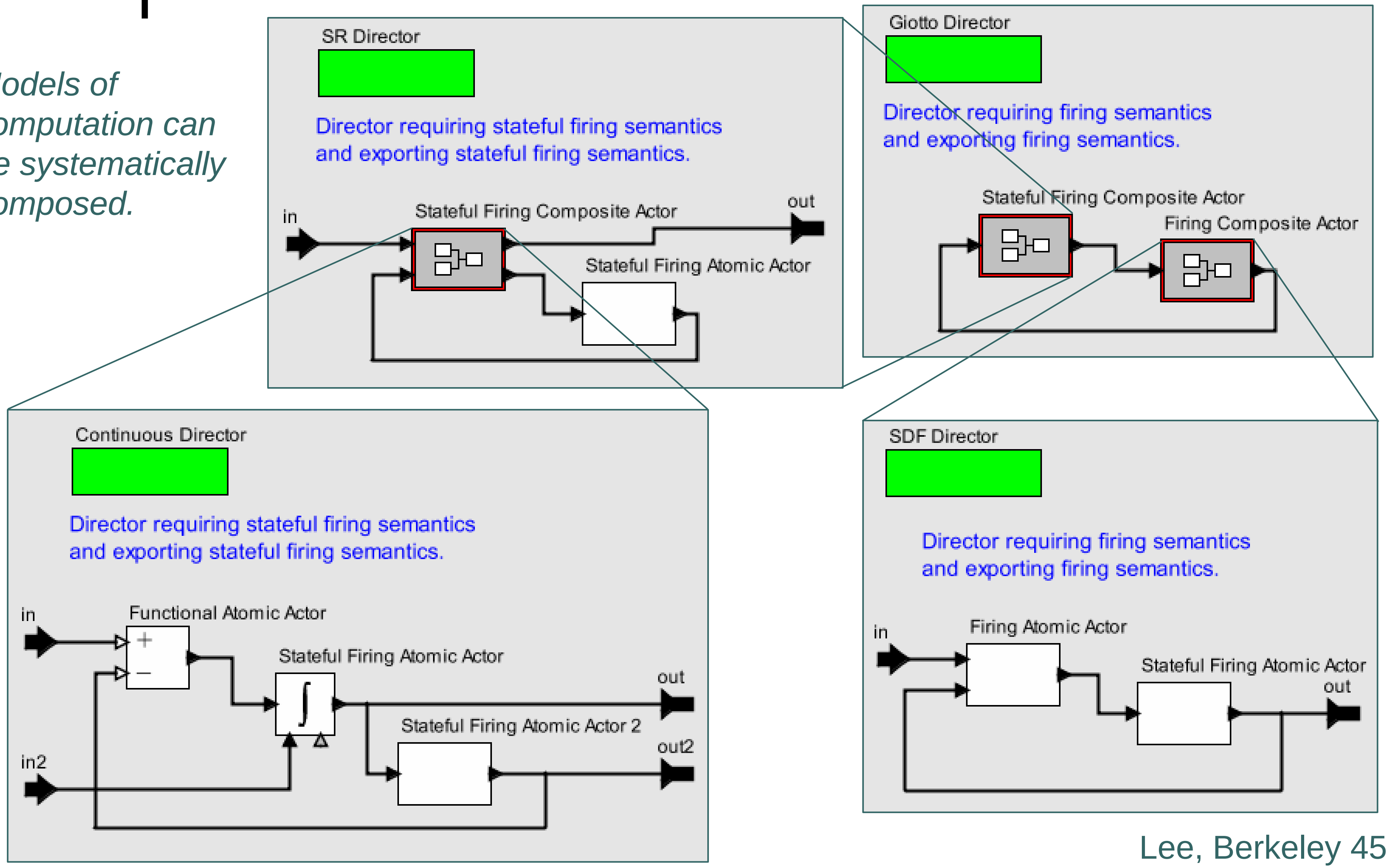
Meta Frameworks: Ptolemy II



Ptolemy II emphasizes construction of "behaviorally polymorphic" actors with stateful firing semantics (the "Ptolemy II actor semantics"), but also provides support for broader abstract semantic models via its abstract syntax and type system.

A Consequence: Heterogeneous Composition Semantics

Models of computation can be systematically composed.



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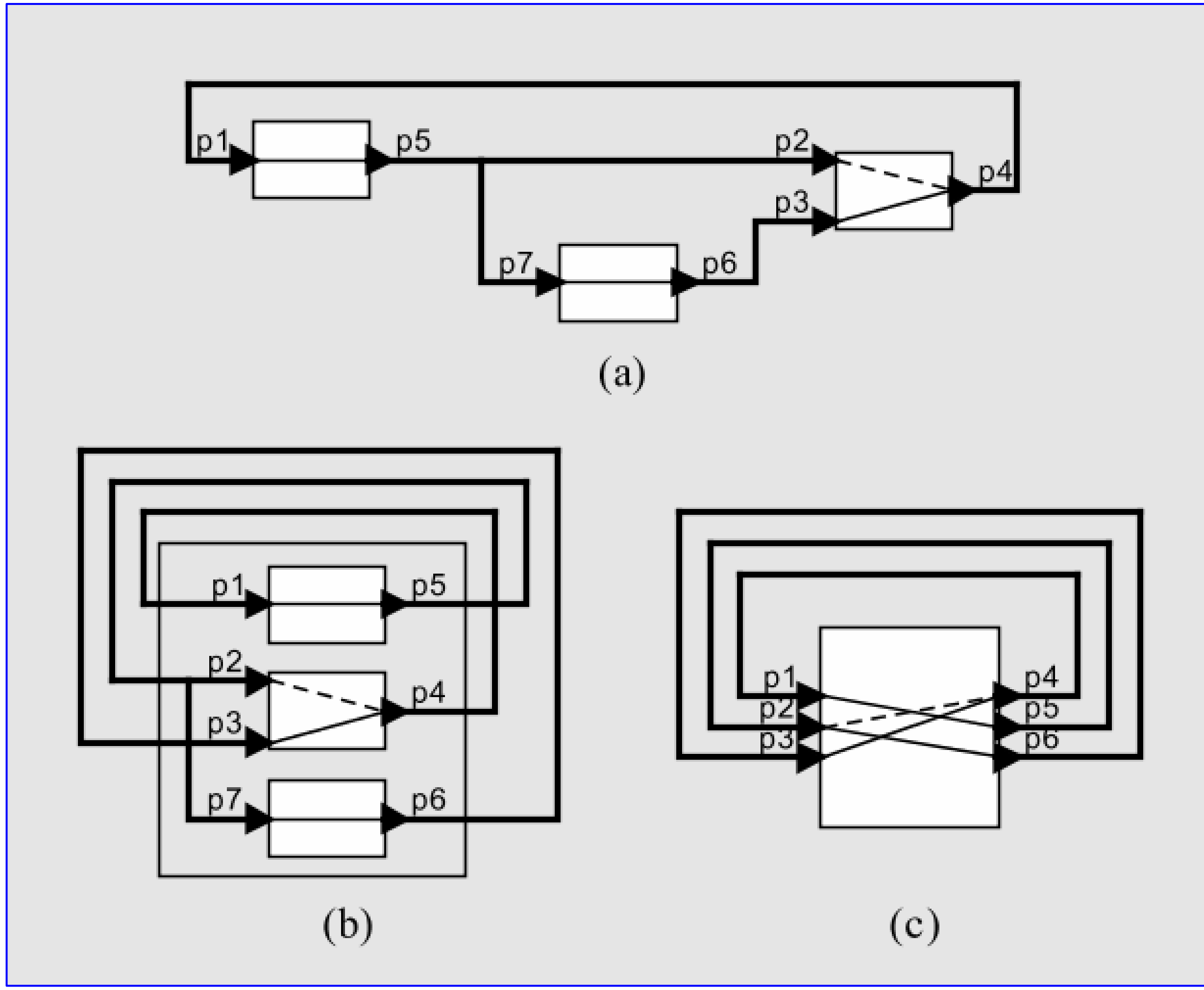
Interface Algebra for Causality Analysis

An algebra of interfaces provides operators for cascade and parallel composition and necessary and sufficient conditions for causality loops, zero-delay loops, and deadlock.



See [Zhou and Lee, EMSOFT 2006]

Recall The Catch…

$$f : [T \to \{0,1\}^*]^P \to [T \to \{0,1\}^*]^P$$

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- This is not what (mainstream) software component technologies do.

- This is not what (most) semantic theories do.

Let's look at the first problem last…

Programming Languages

- Imperative reasoning is simple and useful
- Keep it!

- The problem is that timing is unpredictable.

- Fix this at the architecture level:
  - Replace cache memories with scratchpads
  - Replace dynamic dispatch with pipeline interleaving
  - Define decidable subsets of standard language
  - Deliver rigorous, precise, and tight WCET bounds.

Conclusion

The time is right to create the 21-st century theory of (embedded) computing.

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