Actor-Oriented Design:
Concurrent Models as Programs

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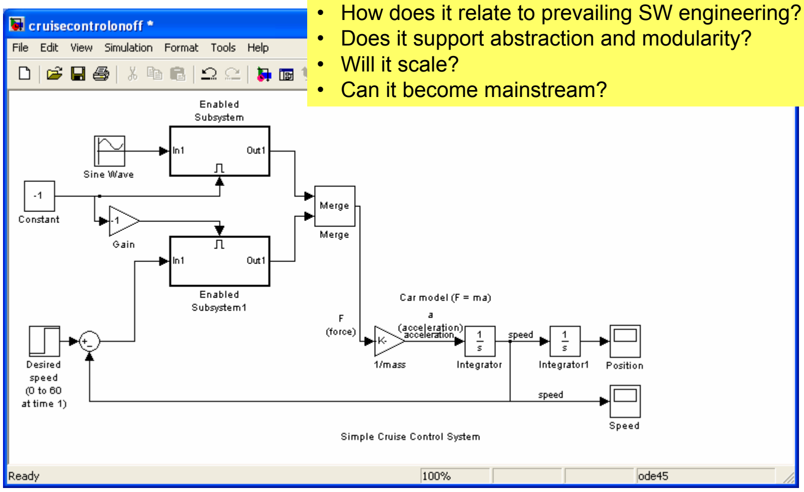
Abstract

Concurrent, domain-specific languages such as Simulink, LabVIEW, Modelica, VHDL, SystemC, and OPNET provide modularization mechanisms that are significantly different from those in prevailing object-oriented languages such as C++ and Java. In these languages, components are concurrent objects that communicate via messaging, rather than abstract data structures that interact via procedure calls. Although the concurrency and communication semantics differ considerably between languages, they share enough common features that we consider them to be a family. We call them *actor-oriented* languages.

Actor-oriented languages, like object-oriented languages, are about modularity of software. I will argue that we can adapt for actor-oriented languages many (if not all) of the innovations of OO design, including concepts such as the separation of interface from implementation, strong typing of interfaces, subtyping, classes, inheritance, and aspects. I will show some preliminary implementations of these mechanisms in a Berkeley system called Ptolemy II.

The Questions

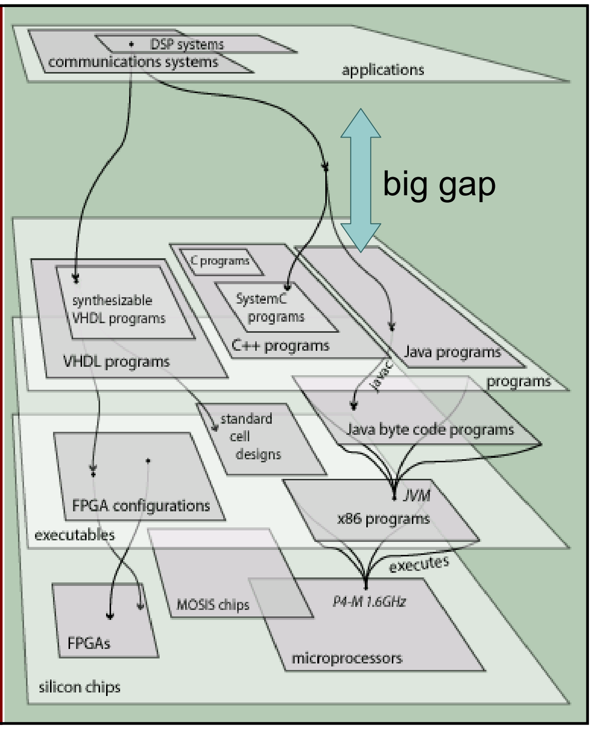
- Is this a good way to do design?
- How does it relate to prevailing SW engineering?
- Does it support abstraction and modularity?
- Will it scale?
- Can it become mainstream?



Platforms

A *platform* is a set of designs.

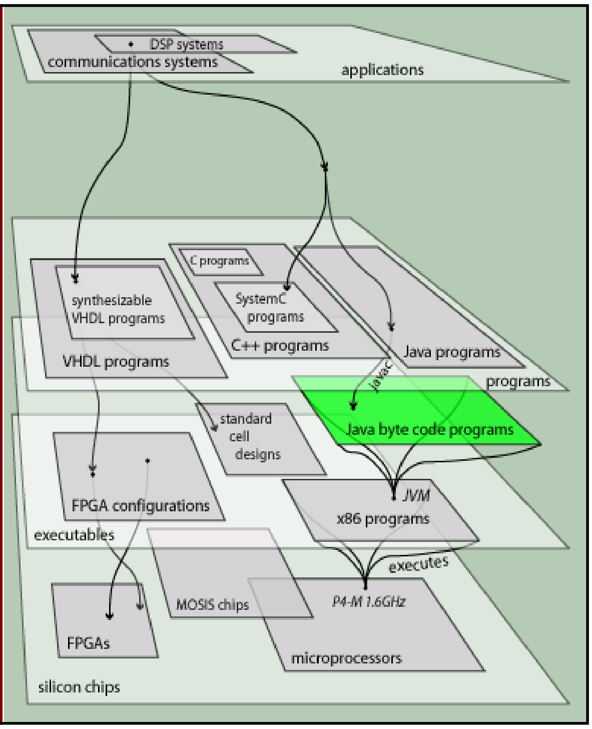
Relations between platforms represent design processes.


big gap

Progress

Many useful technical developments amount to creation of new platforms.

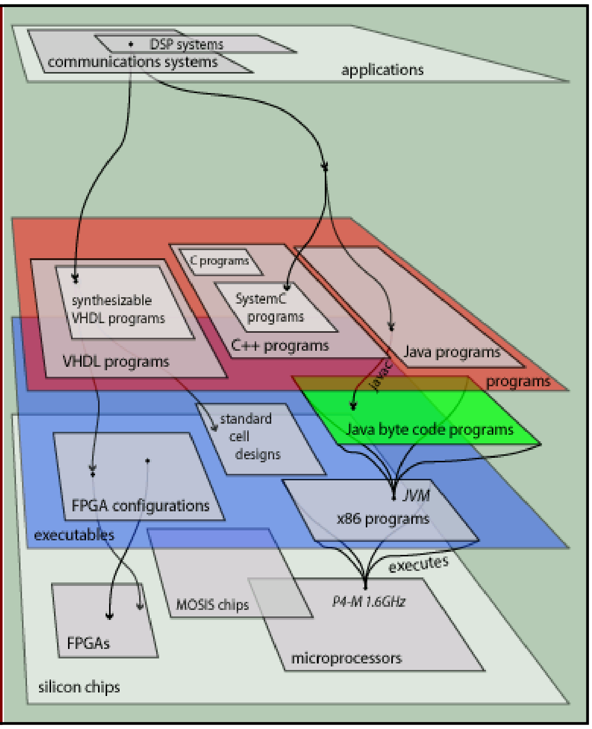
- microarchitectures
- operating systems
- virtual machines
- processor cores
- configurable ISAs



Recent Action

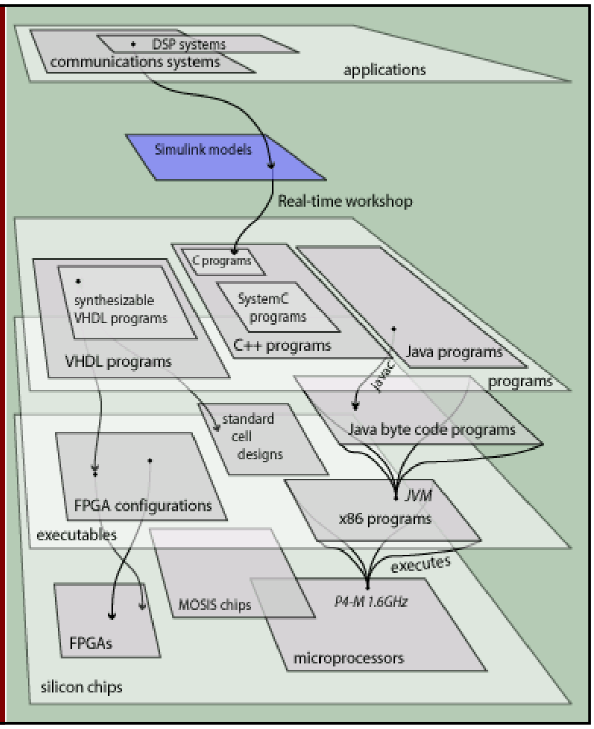
Giving the red platforms useful modeling properties (e.g. verification, SystemC, UML, MDA)

Getting from red platforms to blue platforms (e.g. correctness, efficiency, synthesis of tools)



Better Platforms

Platforms with modeling properties that reflect requirements of the application, not accidental properties of the implementation.



How to View This Design

From above: Signal flow graph with linear, time-invariant components.

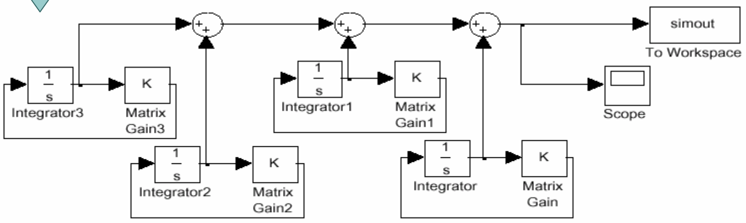


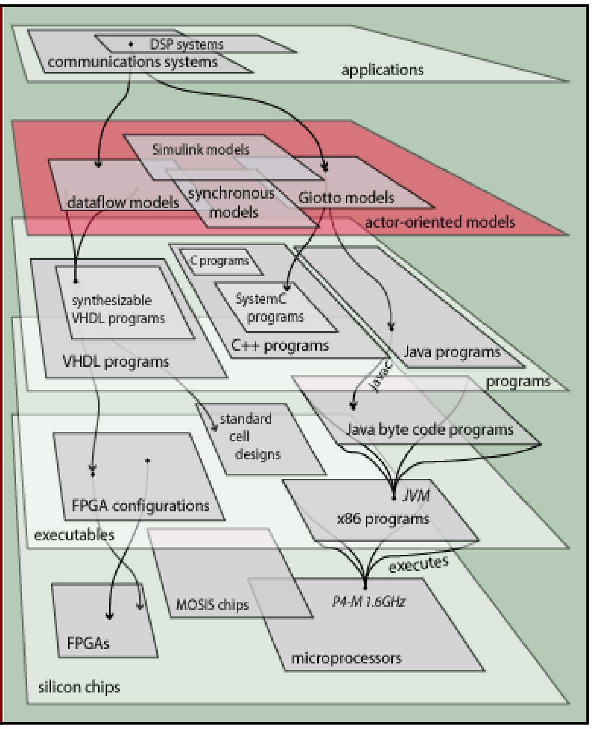
Figure C.12: A block diagram generating a plucked string sound with a fundmental and three harmonics.

From below: Synchronous concurrent composition of components

Actor-Oriented Platforms

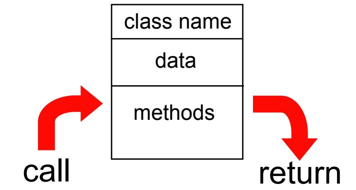
Actor oriented models compose concurrent components according to a model of computation.

Time and concurrency become key parts of the programming model.



Actor-Oriented Design

Object orientation:



class name

data

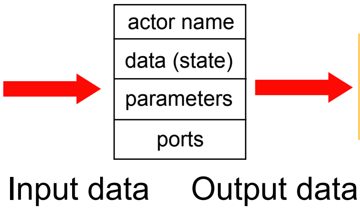
methods

call

return

What flows through an object is sequential control

Actor orientation:



actor name

data (state)

parameters

ports

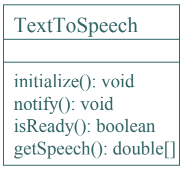
Input data

Output data

What flows through an object is streams of data

Actor Orientation vs. Object Orientation

Object oriented

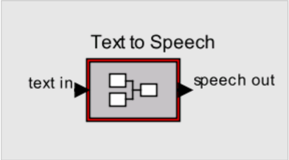


TextToSpeech

initialize(): void
notify(): void
isReady(): boolean
getSpeech(): double[]

OO interface definition gives procedures that have to be invoked in an order not specified as part of the interface definition.

Actor oriented



actor-oriented interface definition says "Give me text and I'll give you speech"

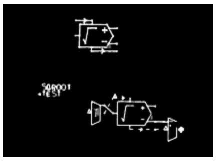
- Identified limitations of object orientation:
  - Says little or nothing about concurrency and time
  - Concurrency typically expressed with threads, monitors, semaphores
  - Components tend to implement low-level communication protocols
  - Re-use potential is disappointing

The First (?) Actor-Oriented Programming Language

The On-Line Graphical Specification of Computer Procedures
W. R. Sutherland, Ph.D. Thesis, MIT, 1966

MIT Lincoln Labs TX-2 Computer

Bert Sutherland with a light pen



Bert Sutherland used the first acknowledged object-oriented framework (Sketchpad, created by his brother, Ivan Sutherland) to create the first actor-oriented programming framework.

Partially constructed actor-oriented model with a class definition (top) and instance (below).

Your Speaker in 1966

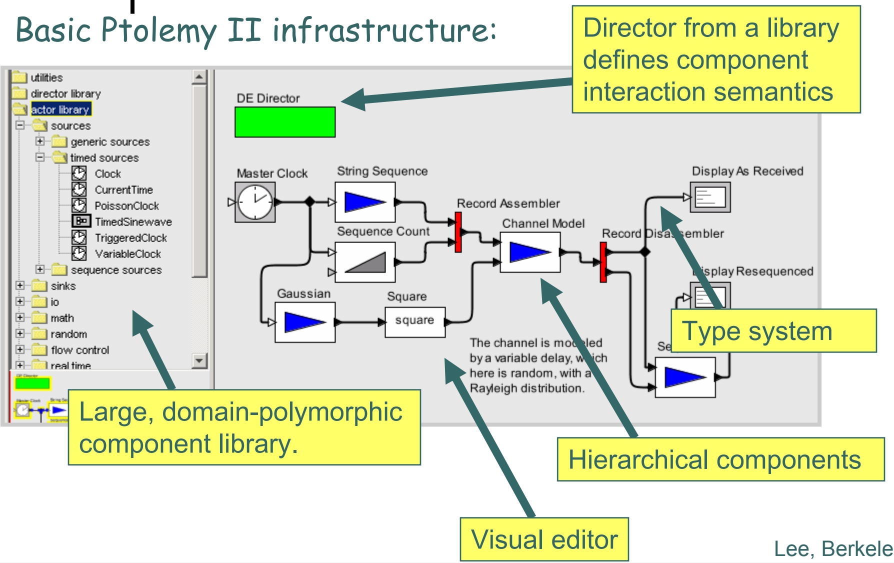
Modern Examples of Actor-Oriented Component Frameworks

- Simulink (The MathWorks)
- Labview (National Instruments)
- Modelica (Linkoping)
- OPNET (Opnet Technologies)
- Polis & Metropolis (UC Berkeley)
- Gabriel, Ptolemy, and Ptolemy II (UC Berkeley)
- OCP, open control platform (Boeing)
- GME, actor-oriented meta-modeling (Vanderbilt)
- SPW, signal processing worksystem (Cadence)
- System studio (Synopsys)
- ROOM, real-time object-oriented modeling (Rational)
- Easy5 (Boeing)
- Port-based objects (U of Maryland)
- I/O automata (MIT)
- VHDL, Verilog, SystemC (Various)
- …

Except Ptolemy, all of these define a fixed model of computation.

Ptolemy II Framework for Experimenting with AO Design

Basic Ptolemy II infrastructure:



The channel is modeled by a variable delay, which here is random, with a Rayleigh distribution.

Director from a library defines component interaction semantics

Type system

Large, domain-polymorphic component library.

Hierarchical components

Visual editor

Actors in 2004: “Capsules” (UML-RT) and “Composite Structures” (UML-2)

- UML-RT borrowed from Selic’s ROOM the notion of “capsules,” which structurally look like actors.
- UML-2 is introducing the notion of “composite structures,” which also look like actors.
- UML capsules and composite structures specify abstract syntax (and a concrete syntax), but no semantics.
- What this says is that there is huge potential for actor-oriented design to be done wrong…

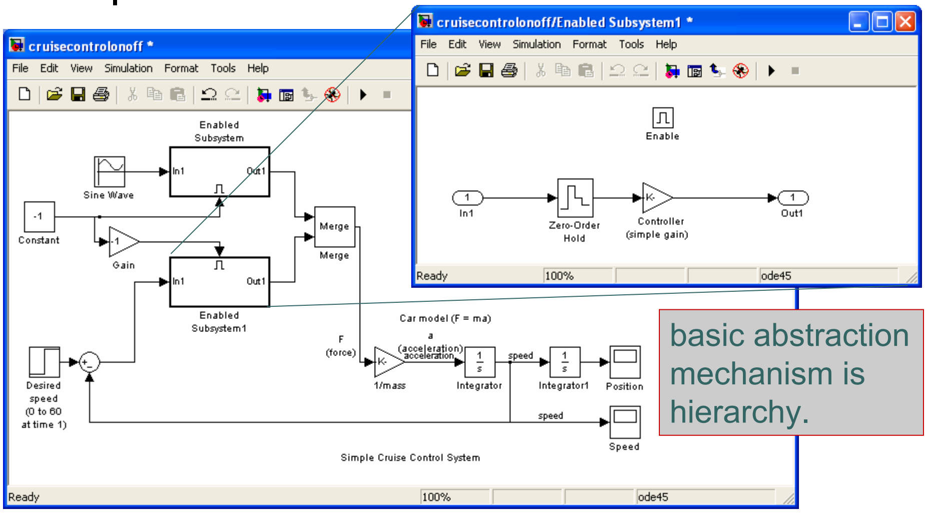
Why Use the Term "Actors"

- The term "actors" was introduced in the 1970's by Carl Hewitt of MIT to describe autonomous reasoning agents.
- The term evolved through the work of Gul Agha and others to refer to a family of concurrent models of computation, irrespective of whether they were being used to realize autonomous reasoning agents.
- The term "actor" has also been used since 1974 in the dataflow community in the same way, to represent a concurrent model of computation.
- But UML uses the term "actor" in its use cases.

Does Actor-Oriented Design Offer Best-Of-Class SW Engineering Methods?

- Abstraction
  - procedures/methods
  - classes
- Modularity
  - subclasses
  - inheritance
  - interfaces
  - polymorphism
  - aspects
- Correctness
  - type systems

Example of an Actor-Oriented Framework: Simulink



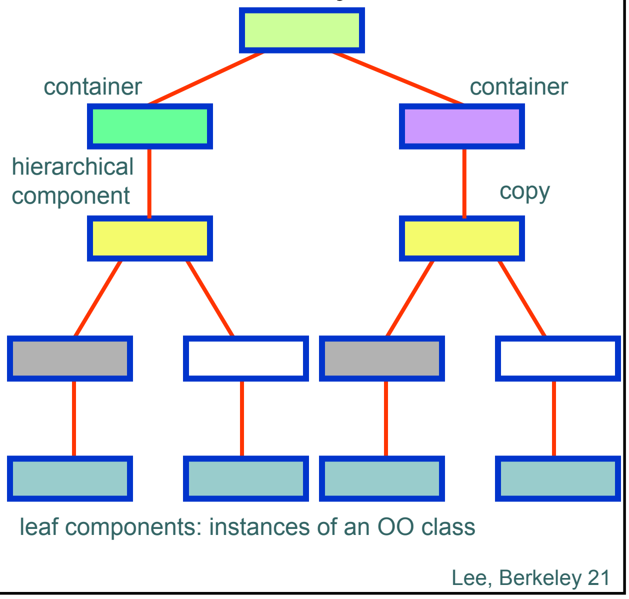
basic abstraction mechanism is hierarchy.

Observation

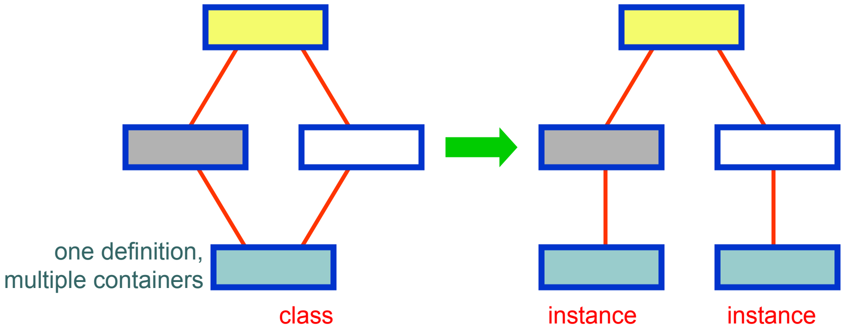
By itself, hierarchy is a very weak abstraction mechanism.

Tree Structured Hierarchy

- Does not represent common *class* definitions. Only instances.
- Multiple instances of the same hierarchical component are *copies*.



Alternative Hierarchy: Roles and Instances

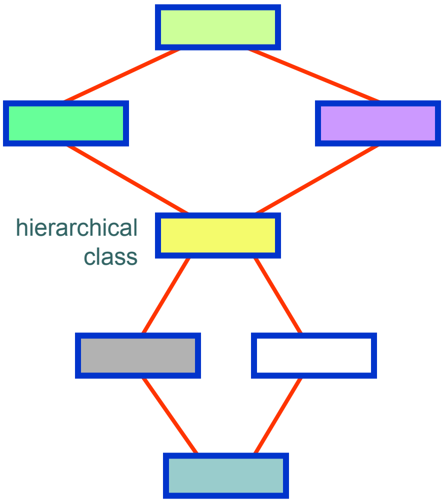


role hierarchy
(“design-time” view)

instance hierarchy
(“run time” view)

Role Hierarchy

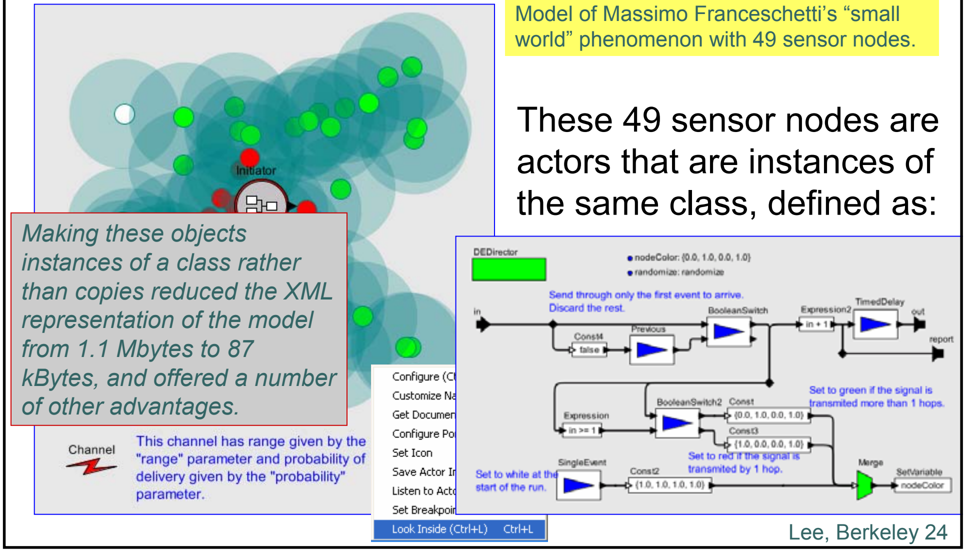
- Multiple instances of the same hierarchical component are represented by *classes* with multiple containers.
- This makes hierarchical components more like leaf components.



A Motivating Application: Modeling Sensor Networks

Model of Massimo Franceschetti's "small world" phenomenon with 49 sensor nodes.

These 49 sensor nodes are actors that are instances of the same class, defined as:



Making these objects instances of a class rather than copies reduced the XML representation of the model from 1.1 Mbytes to 87 kBytes, and offered a number of other advantages.

This channel has range given by the "range" parameter and probability of delivery given by the "probability" parameter.

Send through only the first event to arrive. Discard the rest.

Set to green if the signal is transmited more than 1 hops.

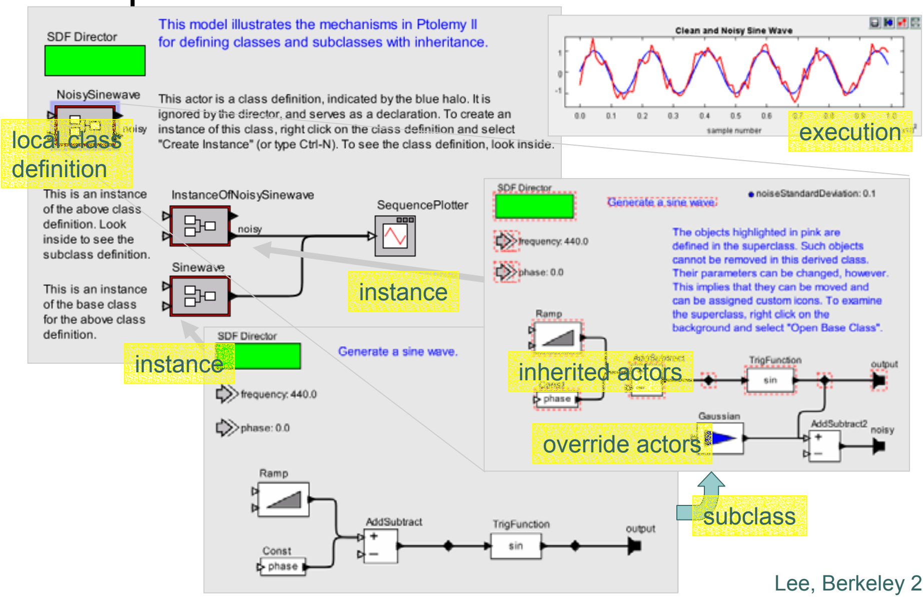
Set to red if the signal is transmited by 1 hop.

Set to white at the start of the run.

Subclasses, Inheritance? Interfaces, Subtypes? Aspects?

- Now that we have classes, can we bring in more of the modern programming world?
  - subclasses?
  - inheritance?
  - interfaces?
  - subtypes?
  - aspects?

Example Using AO Classes



This model illustrates the mechanisms in Ptolemy II for defining classes and subclasses with inheritance.

This actor is a class definition, indicated by the blue halo. It is ignored by the director, and serves as a declaration. To create an instance of this class, right click on the class definition and select "Create Instance" (or type Ctrl-N). To see the class definition, look inside.

This is an instance of the above class definition. Look inside to see the subclass definition.

This is an instance of the base class for the above class definition.

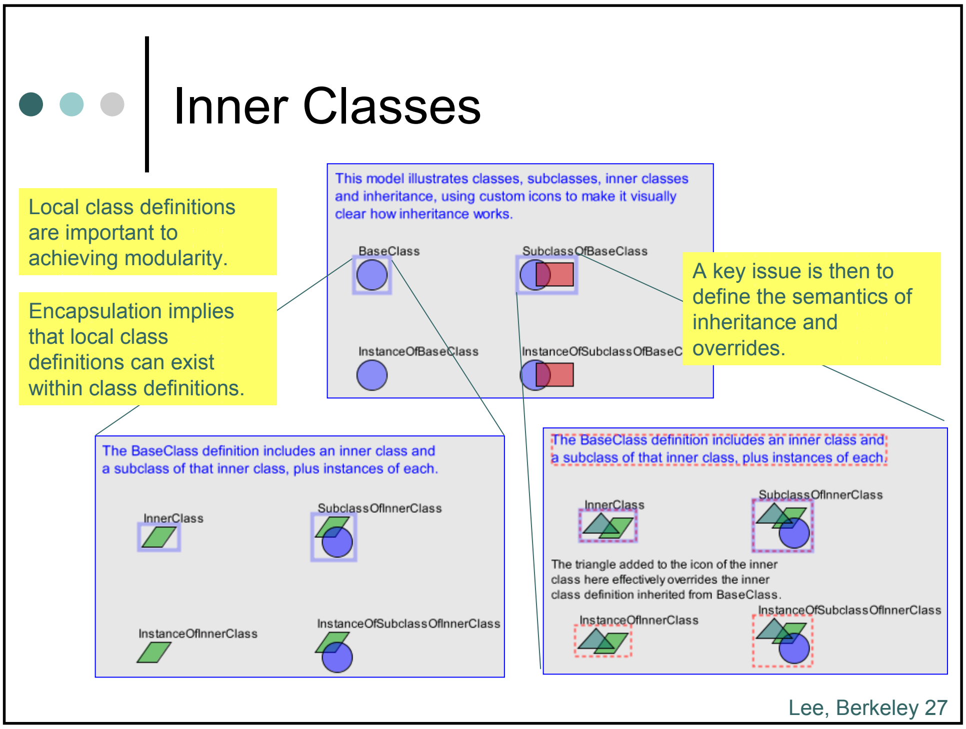
The objects highlighted in pink are defined in the superclass. Such objects cannot be removed in this derived class. Their parameters can be changed, however. This implies that they can be moved and can be assigned custom icons. To examine the superclass, right click on the background and select "Open Base Class".

Generate a sine wave.

noiseStandardDeviation: 0.1

frequency: 440.0

phase: 0.0



Inner Classes

Local class definitions are important to achieving modularity.

Encapsulation implies that local class definitions can exist within class definitions.

This model illustrates classes, subclasses, inner classes and inheritance, using custom icons to make it visually clear how inheritance works.

A key issue is then to define the semantics of inheritance and overrides.

The BaseClass definition includes an inner class and a subclass of that inner class, plus instances of each.

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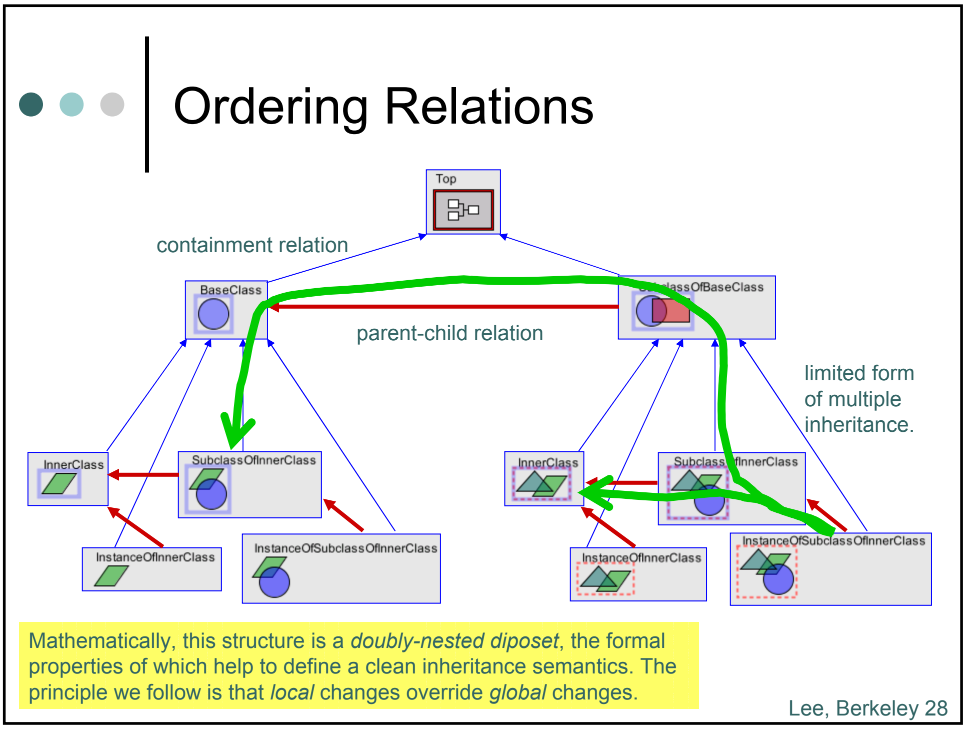
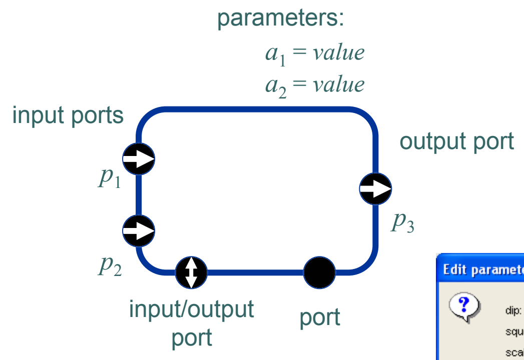
The triangle added to the icon of the inner class here effectively overrides the inner class definition inherited from BaseClass.



Ordering Relations

Mathematically, this structure is a *doubly-nested diposet*, the formal properties of which help to define a clean inheritance semantics. The principle we follow is that *local* changes override *global* changes.

Defining Actor Interfaces: Ports and Parameters


parameters:

$a_1 = value$

$a_2 = value$

input ports

p_1

p_2

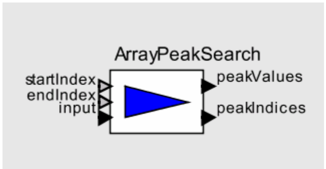
output port

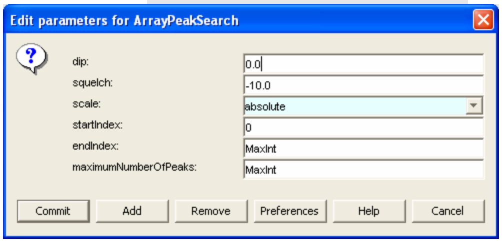
p_3

input/output port

port

Example:




Edit parameters for ArrayPeakSearch

dip: 0.0

squelch: -10.0

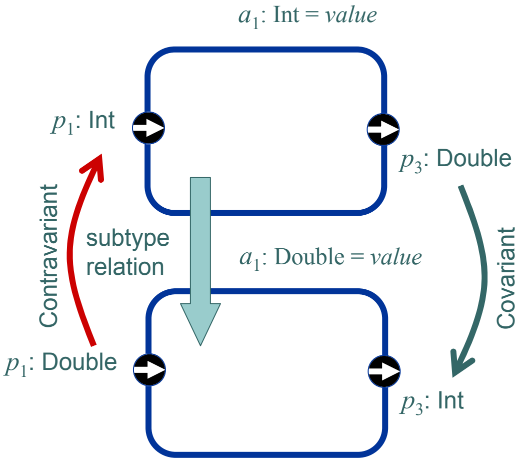
scale: absolute

startIndex: 0

endIndex: MaxInt

maximumNumberOfPeaks: MaxInt

Actor Subtypes


a_1: Int = $value$

p_1: Int

p_3: Double

subtype relation

Contravariant

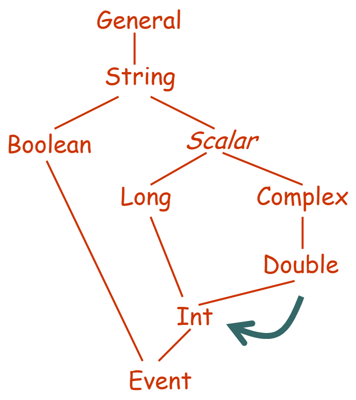
Covariant

a_1: Double = $value$

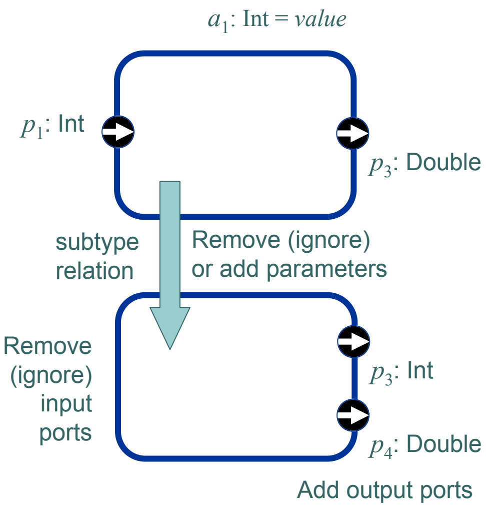
p_1: Double

p_3: Int

Example of a simple type lattice:



Actor Subtypes (cont)



a_1: Int = *value*

p_1: Int

p_3: Double

subtype relation

Remove (ignore) or add parameters

Remove (ignore) input ports

p_3: Int

p_4: Double

Add output ports

Subtypes can have:

- Fewer input ports
- More output ports

Of course, the types of these can have co/contravariant relationships with the supertype.

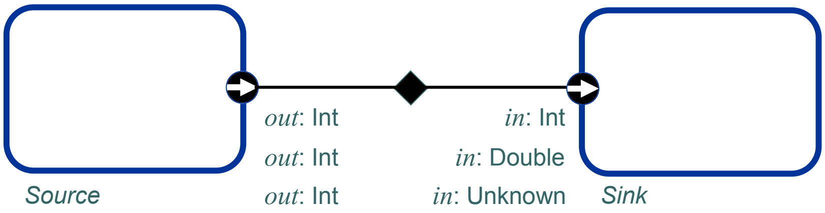
Observations

- Subtypes can remove (or ignore) parameters and also add new parameters because parameters always have a default value (unlike inputs, which a subtype cannot add)
- Subtypes cannot modify the types of parameters (unlike ports). Co/contravariant at the same time.
- PortParameters are ports with default values. They can be removed or added just like parameters because they provide default values.
- Are there similar exceptions to co/contravariance in OO languages?

Composing Actors

A connection implies a type constraint. Can:

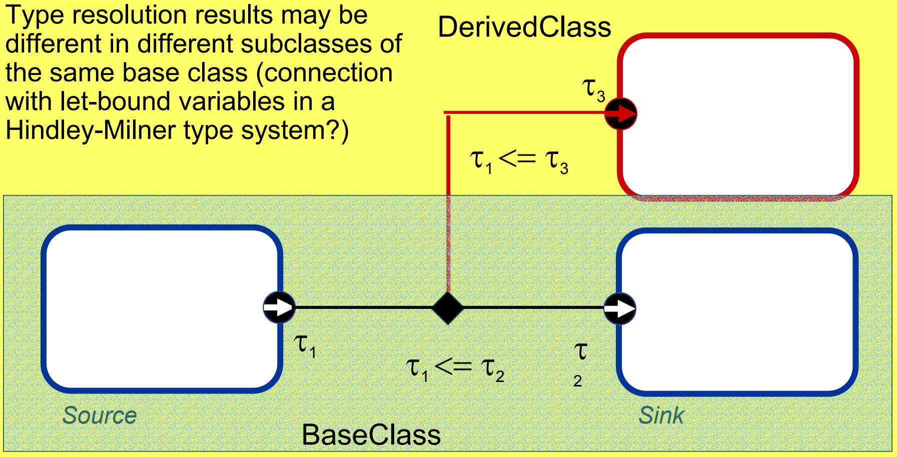
- check compatibility
- perform conversions
- infer types



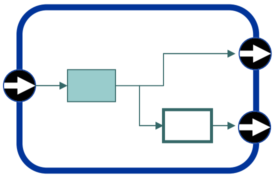
The Ptolemy II type system does all three.

What Happens to Type Constraints When a Subclass Adds Connections?

Type resolution results may be different in different subclasses of the same base class (connection with let-bound variables in a Hindley-Milner type system?)



Abstract Actors?



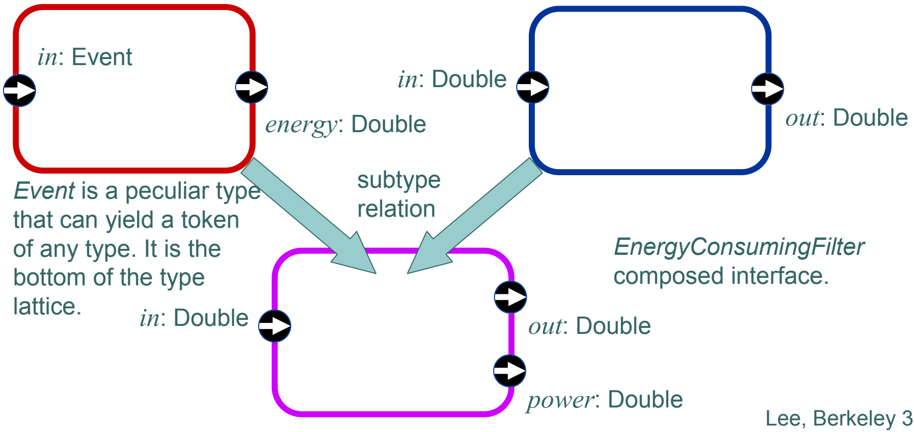
Suppose one of the contained actors is an interface only. Such a class definition cannot be instantiated (it is abstract). Concrete subclasses would have to provide implementations for the interface.

Is this useful?

Implementing Multiple Interfaces An Example

EnergyConsumer interface has a single output port that produces a Double representing the energy consumed by a firing.

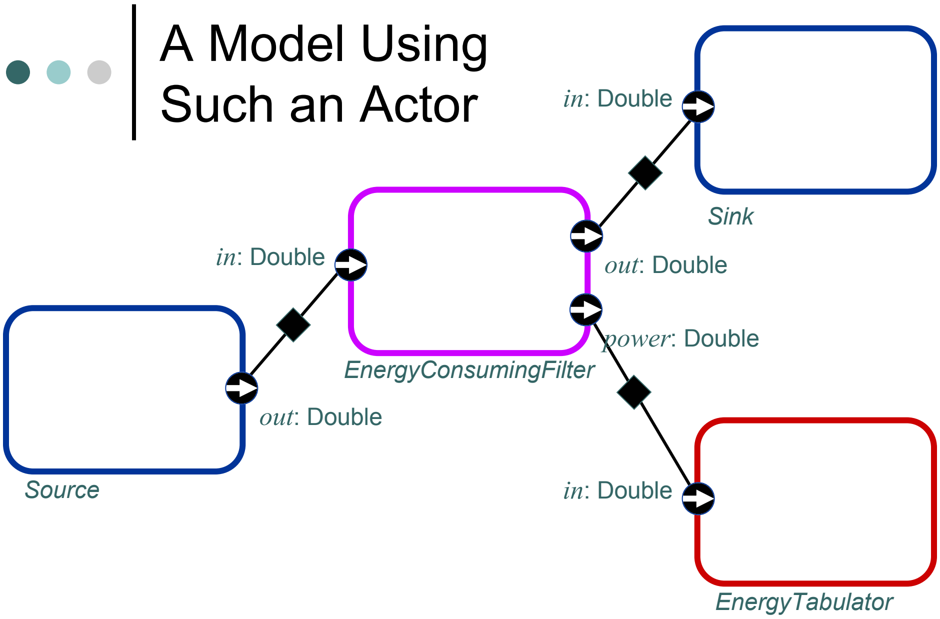
Filter interface for a stream transformer component.



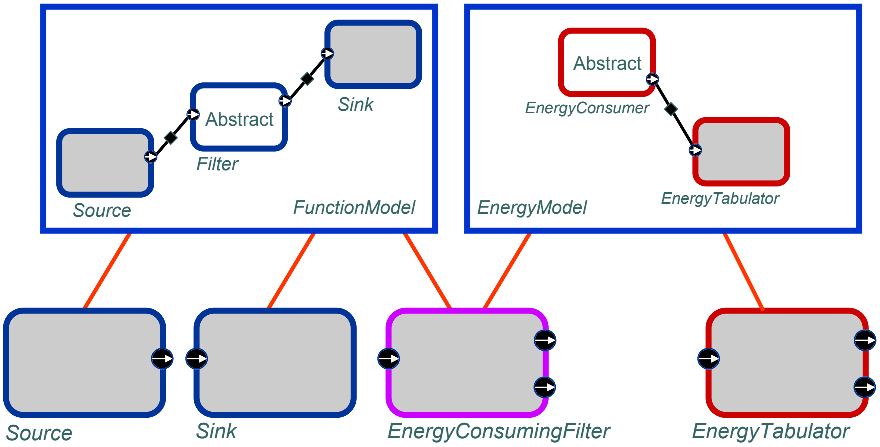
Event is a peculiar type that can yield a token of any type. It is the bottom of the type lattice.

EnergyConsumingFilter composed interface.

A Model Using Such an Actor



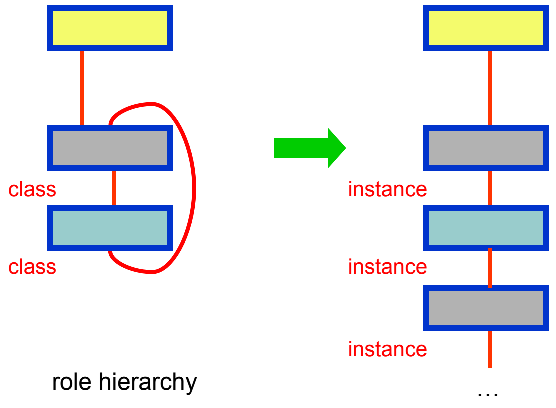
Heterarchy? Multi-View Modeling? Aspects?



This is *multi-view modeling*, similar to what GME (Vanderbilt) can do.

Is this an *actor-oriented* version of *aspect-oriented* programming?

Recursive Containment Can Hierarchical Classes Contain Instances of Themselves?



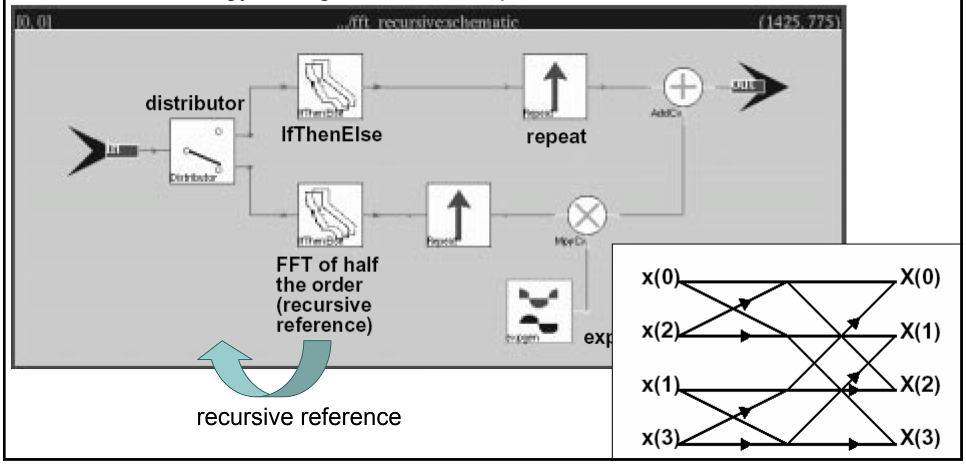
role hierarchy

instance hierarchy

Note that in this case, unrolling cannot occur at “compile time”.

Primitive Realization of this in Ptolemy Classic

FFT implementation in Ptolemy Classic (1995) used a partial evaluation strategy on higher-order components.



recursive reference

Conclusion

- Actor-oriented design remains a relatively immature area, but one that is progressing rapidly.
- It has huge potential.
- Many questions remain…