Embedded Software
Challenges for the Next 10 Years

Infineon Embedded Software Days
Munich, Sept. 29-30, 2003

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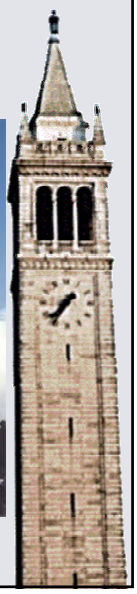


Chess: Center for Hybrid and Embedded Software Systems

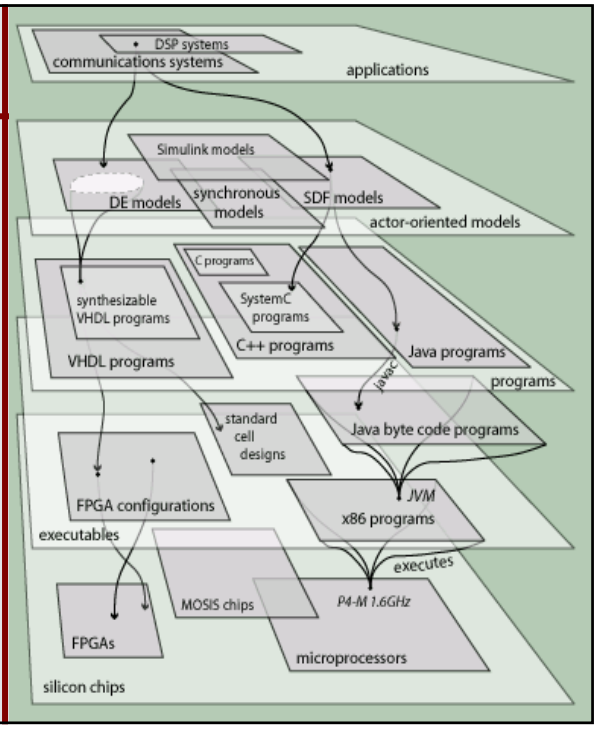
Thesis

- *Embedded software* is not just software on small computers.
- *Time and concurrency* are essential in embedded software.
- *Platforms* are essential in the design of embedded software.
- Platforms need good modeling properties (*model-based design*).
- *Object-oriented design* cannot provide these modeling properties.
- *Actor-oriented design* offers better concurrency and time.
- *Behavioral types* offer a truly practical form of verification.

Platforms

A platform is a set of designs (the rectangles at the right, e.g., the set of all x86 binaries).

Model-based design is specification of designs in platforms with useful modeling properties (e.g., Simulink block diagrams for control systems).

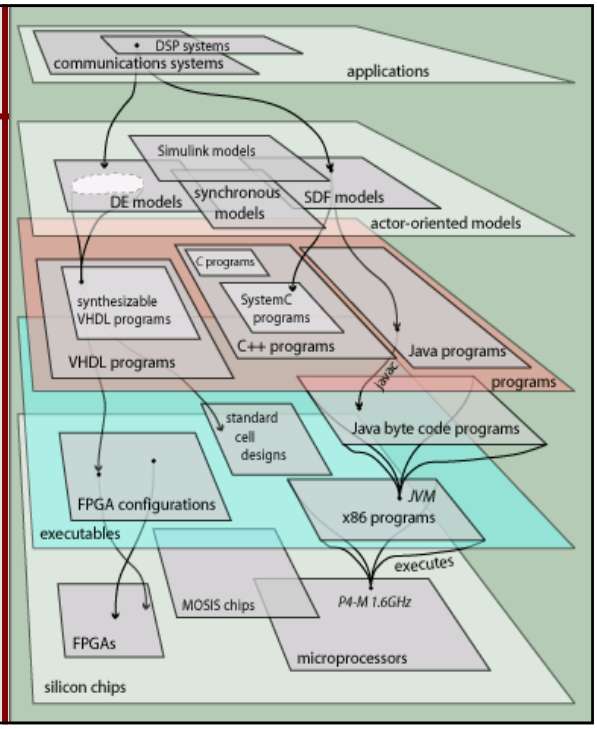


Platforms

Where the Action Has Been:

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

Getting from red platforms to blue platforms.

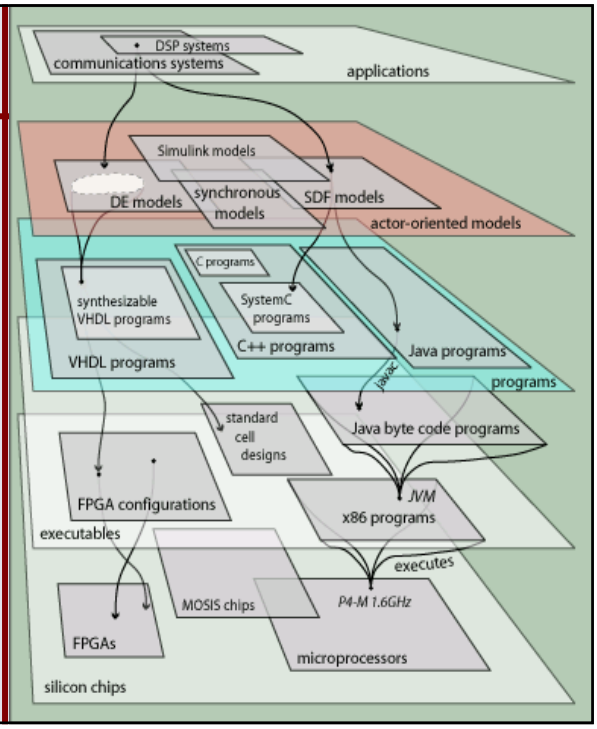


Platforms

Where the Action Will Be:

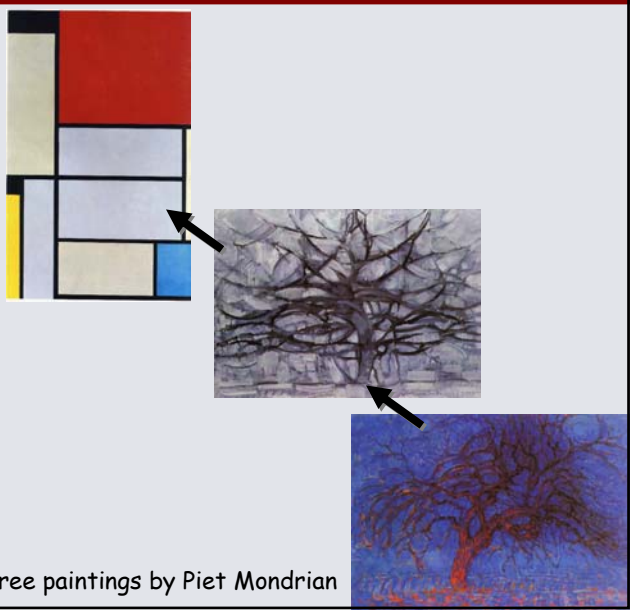
Giving the red platforms useful modeling properties (via models of computation)

Getting from red platforms to blue platforms.



Abstraction

How abstract a design is depends on how many refinement relations separate the design from one that is physically realizable.



Three paintings by Piet Mondrian

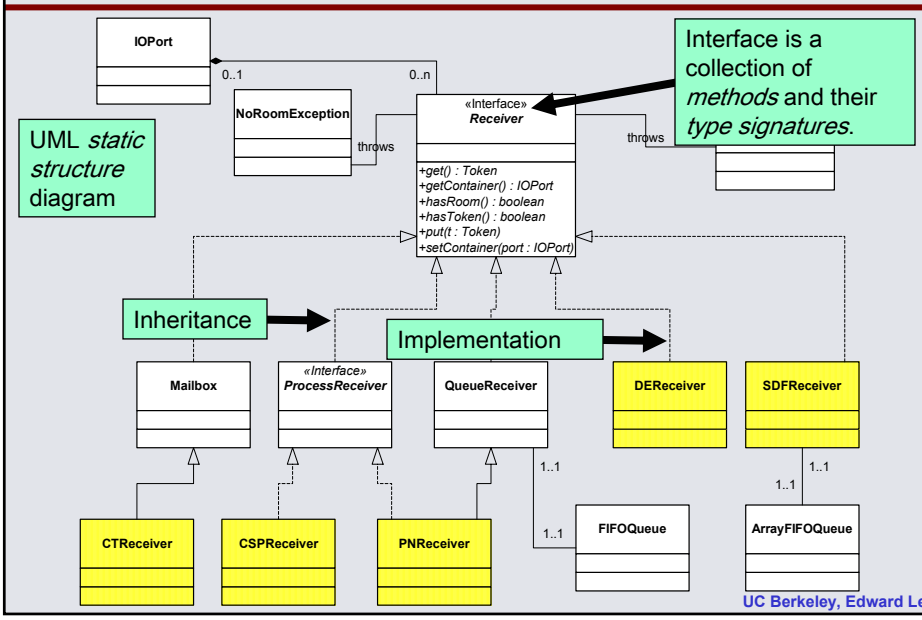
Design Framework

A *design framework* is a collection of platforms and *realizable relations* between platforms where at least one of the platforms is a set of *physically realizable designs*, and for any design in any platform, the transitive closure of the relations from that design includes at least one physically realizable design.

In *model-based design*, a *specification* is a point in a platform with useful modeling properties.

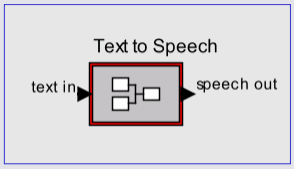
UML and MDA

Trying to Give Useful Modeling Properties to Object-Oriented Designs

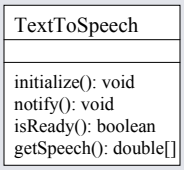


But These Are Fundamentally Rooted in a Procedural Abstraction

- Some Problems:
  - OO says little or nothing about concurrency and time ← Focus on this
  - Components implement low-level communication protocols
  - Re-use potential is disappointing
- Some Partial Solutions
  - Adapter objects (laborious to design and deploy)
  - Model-driven architecture (still fundamentally OO)
  - Executable UML (little or no useful modeling properties)
- Our Solution: *Actor-Oriented Design*

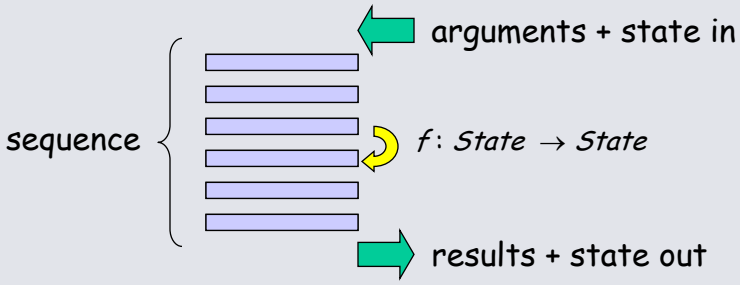


actor-oriented interface definition says "Give me text and I'll give you speech"



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

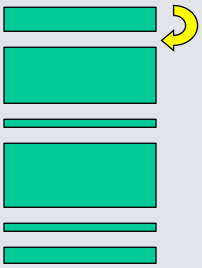
The Turing Abstraction of Computation



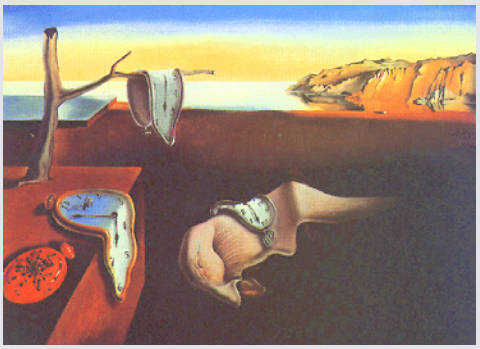
Everything "computable" can be given by a terminating sequential program.

Timing is Irrelevant

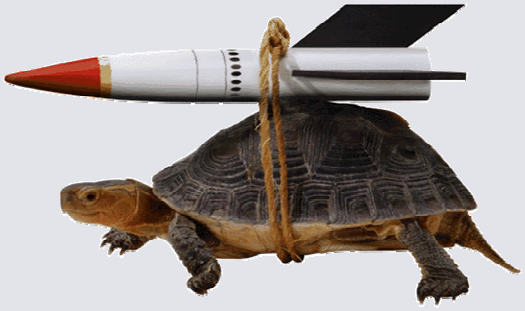
All we need is terminating sequences of state transformations! Simple mathematical structure: function composition.



$f : State \rightarrow State$



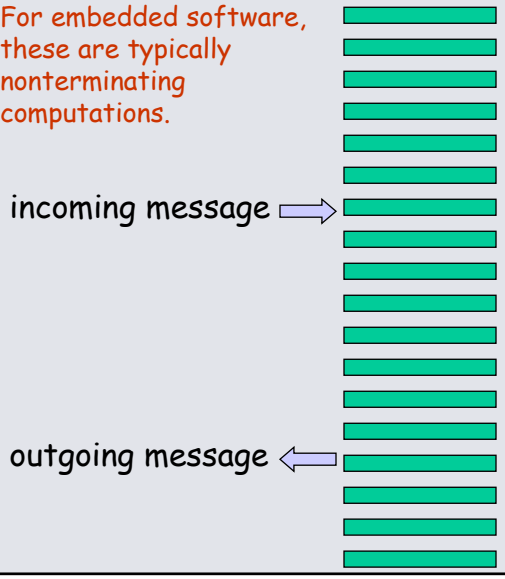
What about "real time"?



Make it faster!

Worse: Processes & Threads are a Terrible Way to Specify Concurrency

For embedded software, these are typically nonterminating computations.

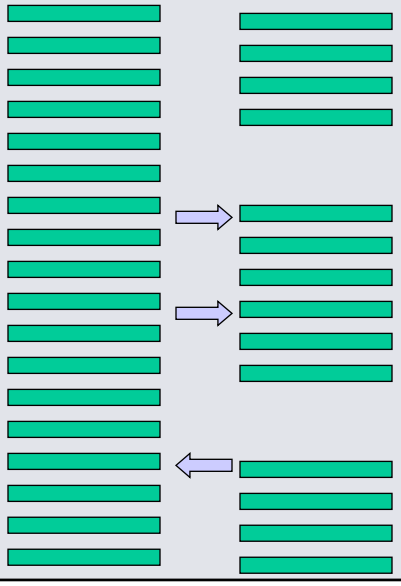


Infinite sequences of state transformations are called "processes" or "threads"

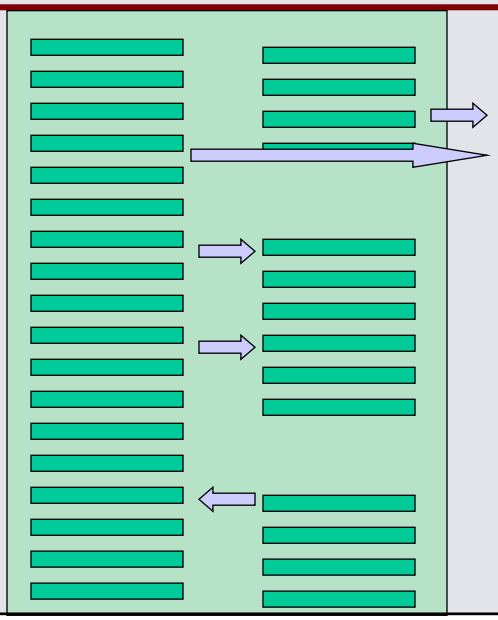
Their "interface" to the outside is a sequence of messages in or out.

Interacting Processes Impose Partial Ordering Constraints on Each Other

Note that UML sequence and activity diagrams (major ways of expressing concurrency in UML), follow this model.

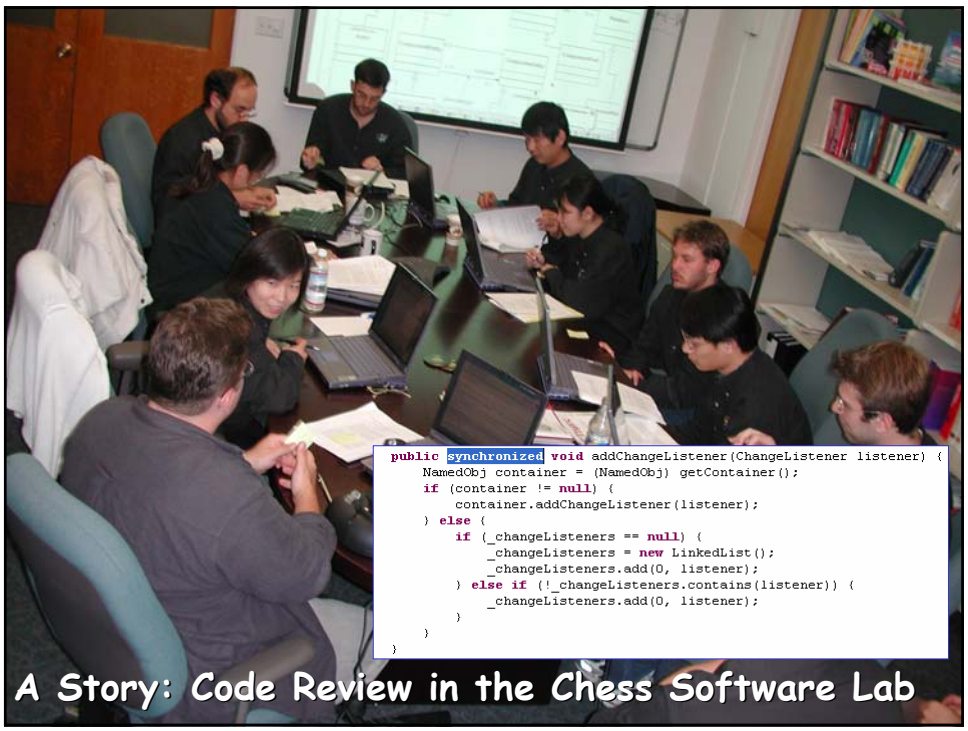


Interacting Processes Impose Partial Ordering Constraints on External Interactions



After composition: External interactions are no longer ordered.

An aggregation of processes is not a process. What is it?



Code Review in the Chess Software Lab
A Typical Story

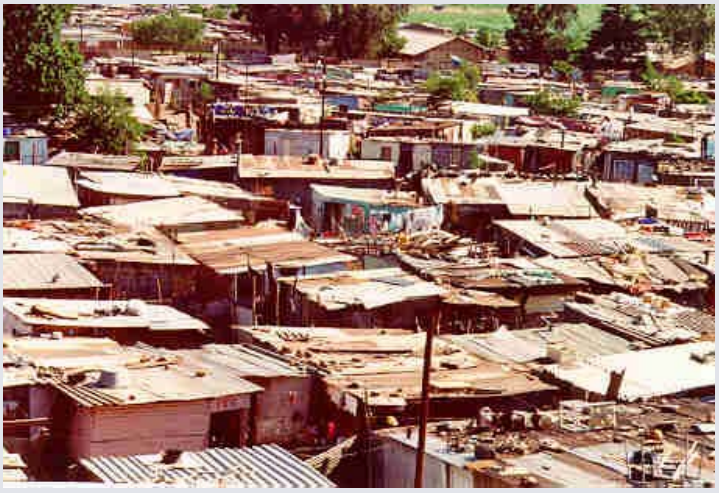
- Code review discovers that a method needs to be synchronized to ensure that multiple threads do not reverse each other's actions.
- No problems had been detected in 4 years of using the code.
- Three days after making the change, users started reporting deadlocks caused by the new mutex.
- Analysis of the deadlock takes weeks, and a correction is difficult.

```
public synchronized void addChangeListener(ChangeListener listener) {
    NamedObj container = (NamedObj) getContainer();
    if (container != null) {
        container.addChangeListener(listener);
    } else {
        if (_changeListeners == null) {
            _changeListeners = new LinkedList();
            _changeListeners.add(0, listener);
        } else if (!_changeListeners.contains(listener)) {
            _changeListeners.add(0, listener);
        }
    }
}
```


What it Feels Like to Use the *synchronized* Keyword in Java

Image "borrowed" from an Iomega advertisement for Y2K software and disk drives, *Scientific American*, September 1999.

Threads, Mutexes, and Semaphores are a *Terrible* Basis for Concurrent Software Architectures

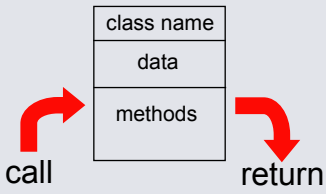


Ad hoc composition. Yet this is the basis for RTOS-based embedded software design.

Is There a Better Mechanism?

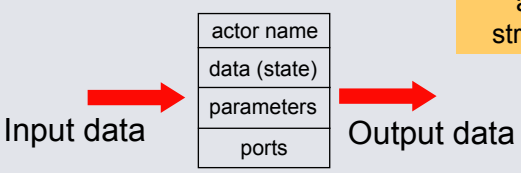
Focus on Actor-Oriented Design

- Object orientation:



What flows through an object is sequential control

- Actor orientation:

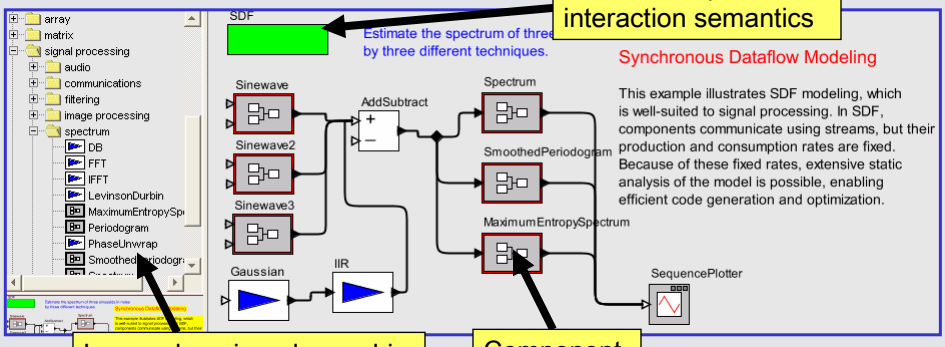


What flows through an object is streams of data

Example of Actor-Oriented Design (in this case, with a visual syntax)

Ptolemy II example:

Director from a library defines component interaction semantics



Large, domain-polymorphic component library.

Component

Key idea: The model of computation is part of the framework within which components are embedded rather than part of the components themselves. Thus, components need to declare behavioral properties.

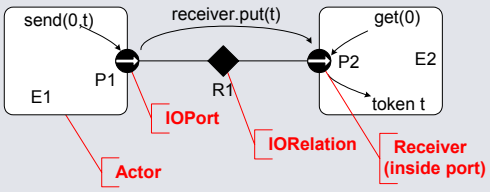
Model of Computation:
- Messaging schema
- Flow of control
- Concurrency

Examples of Actor-Oriented Component Frameworks

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

Actor View of Producer/Consumer Components

Basic Transport:



Models of Computation:

- push/pull
- continuous-time
- dataflow
- rendezvous
- discrete events
- synchronous
- time-driven
- publish/subscribe
- …

Many actor-oriented frameworks assume a producer/consumer metaphor for component interaction.

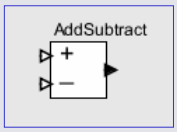
Actor Orientation vs. Object Orientation

- Object Orientation
  - procedural interfaces
  - a class is a type (static structure)
  - type checking for composition
  - separation of interface from implementation
  - subtyping
  - polymorphism
- Actor Orientation
  - concurrent interfaces
  - a behavior is a type
  - type checking for composition of behaviors
  - separation of behavioral interface from implementation
  - behavioral subtyping
  - behavioral polymorphism ⟸ Focus on this

This vision of the future offers a truly practical form of verification, an extension of modern type systems.

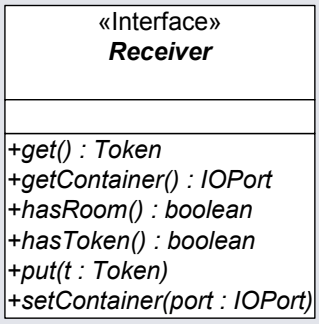
Polymorphism

- Data polymorphism:
  - Add numbers (int, float, double, Complex)
  - Add strings (concatenation)
  - Add composite types (arrays, records, matrices)
  - Add user-defined types
- Behavioral polymorphism:
  - In dataflow, add when all connected inputs have data
  - In a time-triggered model, add when the clock ticks
  - In discrete-event, add when any connected input has data, and add in zero time
  - In process networks, execute an infinite loop in a thread that blocks when reading empty inputs
  - In CSP, execute an infinite loop that performs rendezvous on input or output
  - In push/pull, ports are push or pull (declared or inferred) and behave accordingly
  - In real-time CORBA, priorities are associated with ports and a dispatcher determines when to add



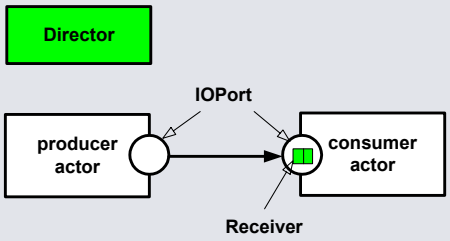
By not choosing among these when defining the component, we get a huge increment in component re-usability. But how do we ensure that the component will work in all these circumstances?

Object-Oriented Approach to Achieving Behavioral Polymorphism

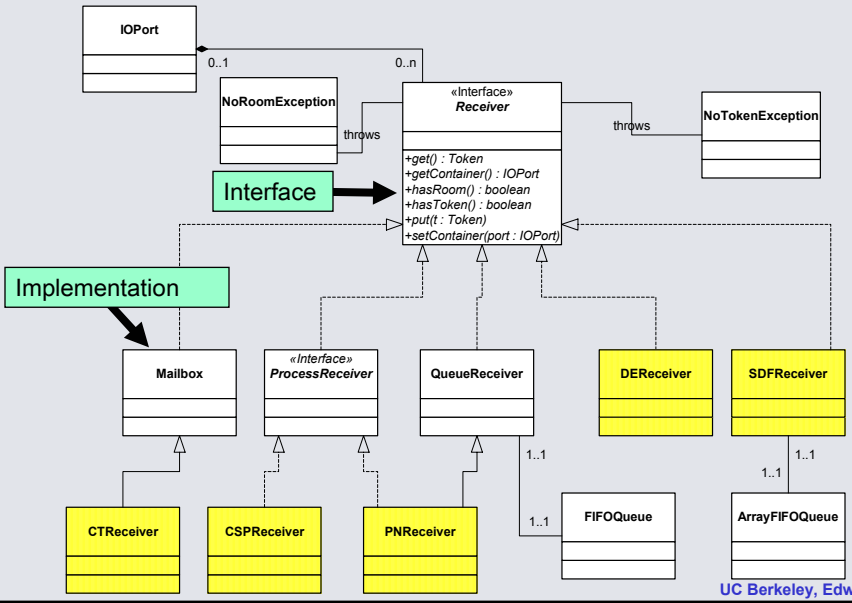


These polymorphic methods implement the communication semantics of a domain in Ptolemy II. The receiver instance used in communication is supplied by the director, not by the component.

Recall: Behavioral polymorphism is the idea that components can be defined to operate with multiple models of computation and multiple middleware frameworks.

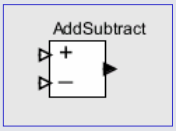


Behavioral Polymorphism
The Object Oriented View



But What If…

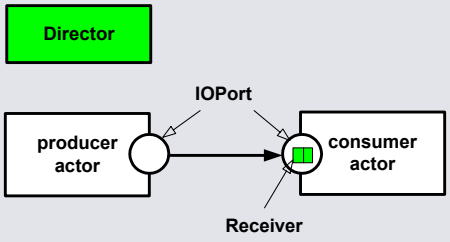
- The component requires data at all connected input ports?
- The component can only perform meaningful operations on two successive inputs?
- The component can produce meaningful output before the input is known (enabling it to break potential deadlocks)?
- The component has a mutex monitor with another component (e.g. to access a common hardware resource)?



None of these is expressed in the object-oriented interface definition, yet each can interfere with behavioral polymorphism.

Behavioral Types – A Practical Approach

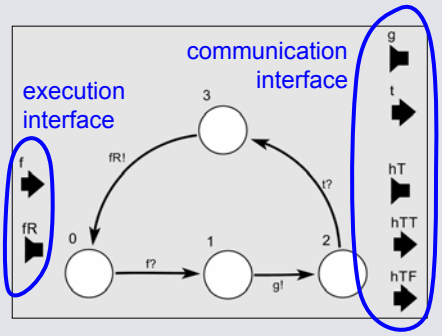
- Capture the dynamic interaction of components in *types*
- Obtain benefits analogous to data typing.
- Call the result *behavioral types*.



- Communication has
  - data types
  - behavioral types
- Components have
  - data type signatures
  - behavioral type signatures
- Components are
  - data polymorphic
  - behaviorally polymorphic

Behavioral Type System

- We capture patterns of component interaction in a type system framework.
- We describe interaction types and component behavior using extended *interface automata* (de Alfaro & Henzinger)
- We do type checking through *automata composition* (detect component incompatibilities)
- Subtyping order is given by the alternating simulation relation, supporting *behavioral polymorphism*.

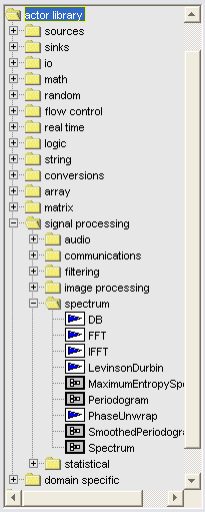


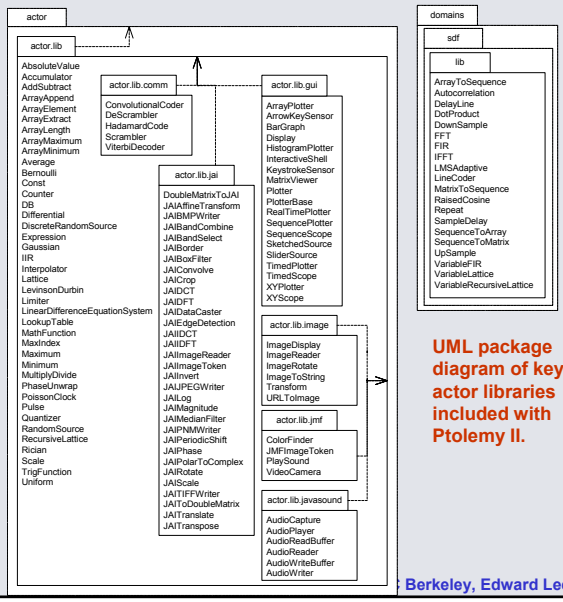
A type signature for a consumer actor.

Verification Via a Behavioral Type System

- Checking behavioral compatibility of components that are composed.
- Checking behavioral compatibility of components and their frameworks.
- Behavioral subtyping enables interface/implementation separation.
- Helps with the definition of behaviorally-polymorphic components.

Enabled by Behavioral Polymorphism (1): More Re-Usable Component Libraries



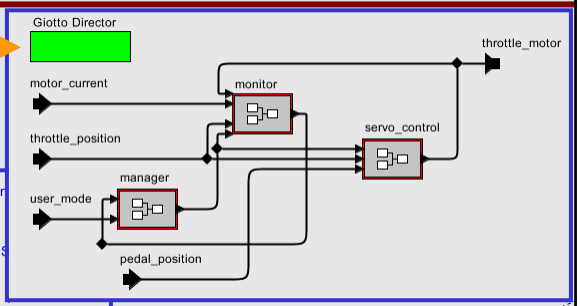


UML package diagram of key actor libraries included with Ptolemy II.

- **Data polymorphic components**
- **Domain polymorphic components**

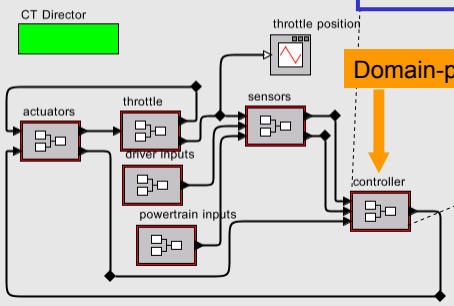
Enabled by Behavioral Polymorphism (2): Hierarchical Heterogeneity

Giotto director indicates a new model of computation.



Heterogeneous model of the UC Berkeley Vehicle Dynar
Electronic Throttle Controller.

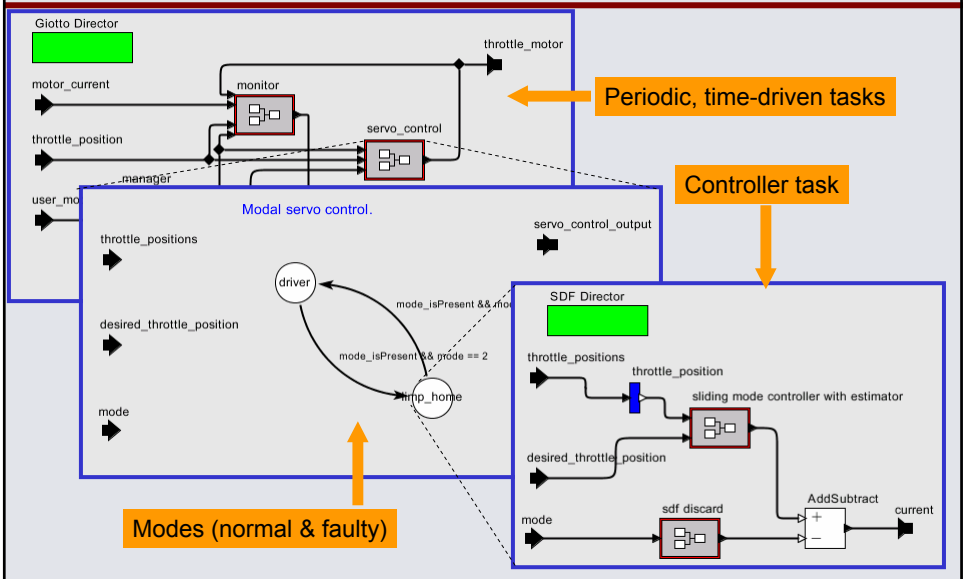
by Paul Griffiths, Christoph Kirsch, Tunc Simsek, Jason S
Last updated January 15, 2002



Domain-polymorphic component.

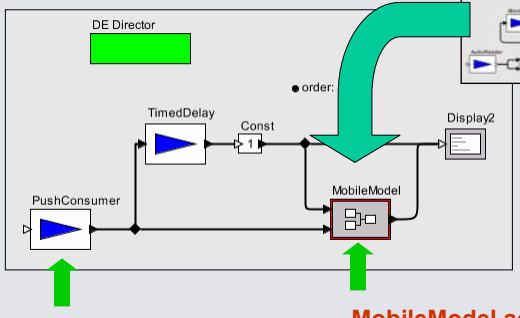
Domains can be nested and mixed.

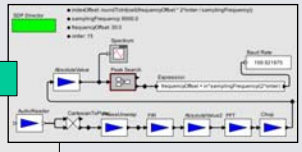
Enabled by Behavioral Polymorphism (3): Modal Models



Enabled by Behavioral Polymorphism (4): Mobile Models

Model-based distributed task management:





Authors:
Yang Zhao
Steve Neuendorffer
Xiaojun Liu

PushConsumer actor receives pushed data provided via CORBA, where the data is an XML model of a signal analysis algorithm.

MobileModel actor accepts a StringToken containing an XML description of a model. It then executes that model on a stream of input data.

Data *and* behavioral type safety will help make such models secure

… And More

- Refinement of communication between actors
  - supporting hardware/software codesign
  - using fault tolerant bus protocols
  - synthesizing custom hardware
  - using middleware for distributed systems
- We are also working on expressing temporal properties in behavioral types
  - execution time dependencies on state
  - schedulability analysis

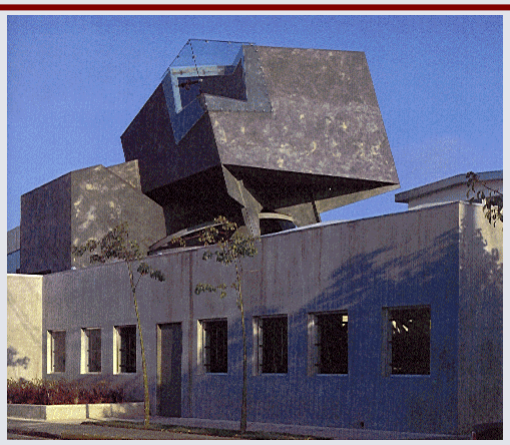
Will Model-Based Design Yield Better Designs?

Not necessarily.

"Why isn't the answer XML, or UML, or IP, or something like that?"

Direct quote from a high-ranking decision maker at a large embedded systems company with global reach.

"New" is not better than "good"



The Box, Eric Owen Moss

Source: *Contemporary California Architects*, P. Jodidio, Taschen, 1995

Mandating use of the wrong platform is far worse than tolerating the use of multiple platforms.

Better Architecture is Enabled but not Guaranteed by Model-Based Design

- Understandable concurrency
- More re-usable component libraries
- Systematic heterogeneity
- Models of computation with time

Conclusion – What to Remember

- Model-based design
  - specification using platforms with useful modeling properties
- Actor-oriented design
  - concurrent components interacting via ports
- Models of computation
  - principles of component interaction
- Understandable concurrency
  - compositional models
- Behavioral types
  - a practical approach to verification and interface definition
- Behavioral polymorphism
  - defining components for use in multiple contexts

http://ptolemy.eecs.berkeley.edu
http://chess.eecs.berkeley.edu

Desirable Modeling Properties in Actor-Oriented Design

For at least some models of computation:

- Closer to the application level
- Compatibility of components with each other
- Compatibility of components with the framework
- Analyzable concurrency
  - Deadlock detection
  - Load balancing
  - No semaphores or mutexes
- Memory requirements
- Schedulability analysis
  - Timing properties
  - Throughput analysis
  - Latency analysis