# The Ptolemy Project


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## Modeling and Design of Reactive Systems


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# Abstract

Ptolemy is a research project and software environment focused on the design and modeling of reactive systems, providing high-level support for signal processing, communication, and real-time control. The key underlying principle in the project is the use of multiple models of computation in a hierarchical heterogeneous design and modeling environment. This talk gives an overview of some of the models of computation of interest, with a focus on their concurrency, thier ability to model and specify real-time systems, and their ability to mix control logic with signal processing.



 

# Organizational

## Staff

Diane Chang, administrative assistant
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Edward A. Lee, professor and PI
Mary Stewart, programmer analyst

## Postdocs

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## Key Outside Collaborators

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Soonhoi Ha (Seoul N. Univ.)
Tom Lane (SSS)
Thomas M. Parks (Lincoln Labs)
José Luis Pino (Hewlett Packard)

## Sponsors

DARPA
MICRO
The Alta Group of Cadence
Hewlett Packard
Hitachi
Hughes
LG Electronics
NEC
Philips
Rockwell
SRC

# Types of Computational Systems

## Transformational

- transform a body of input data into a body of output data

## Interactive

- interact with the environment at their own speed

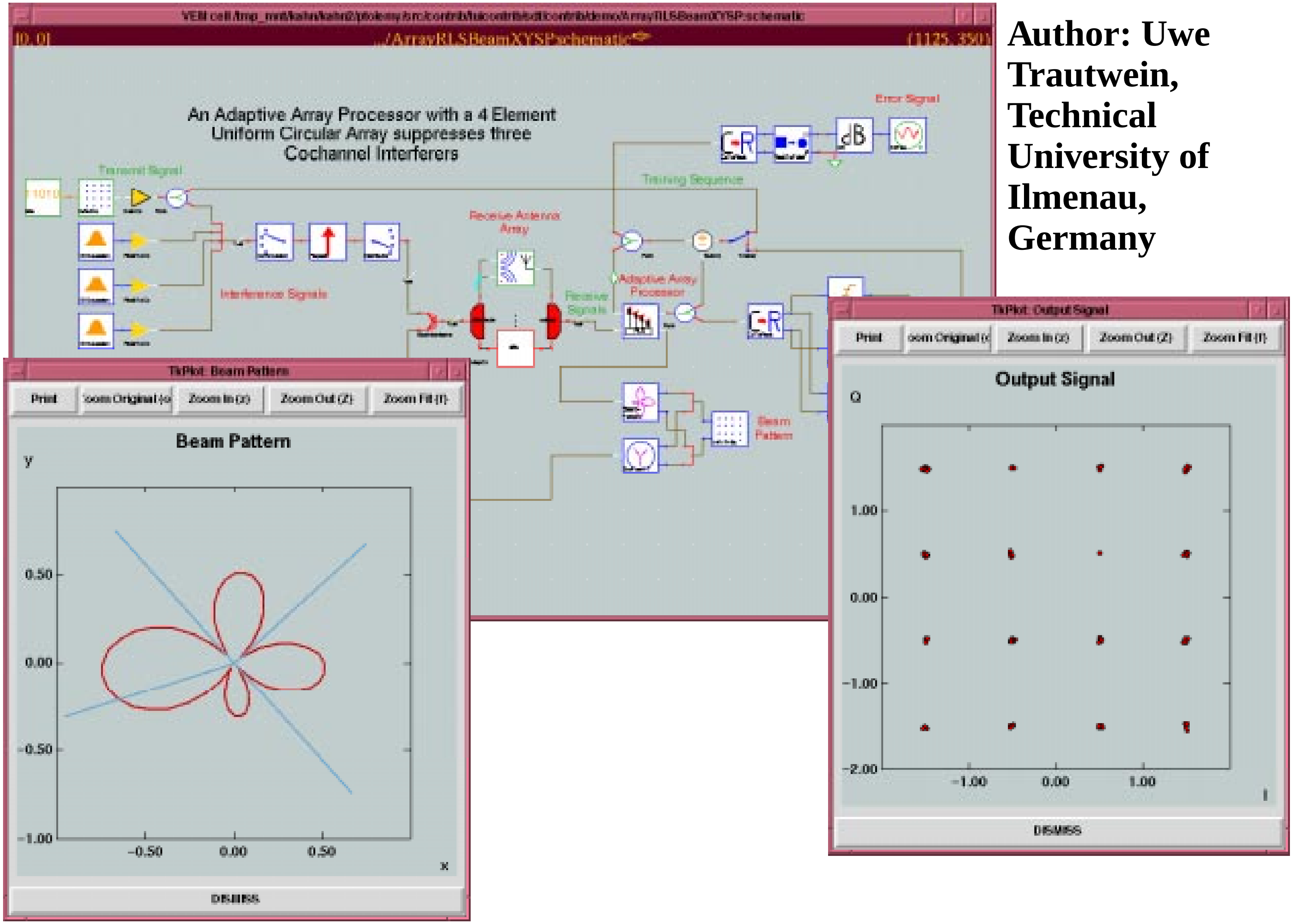
## Reactive

- react continuously at the speed of the environment

*This project focuses on design of reactive systems*

- real-time
- embedded
- concurrent
- network-aware
- adaptive
- heterogeneous

# Interactive, High-Level Simulation and Specification



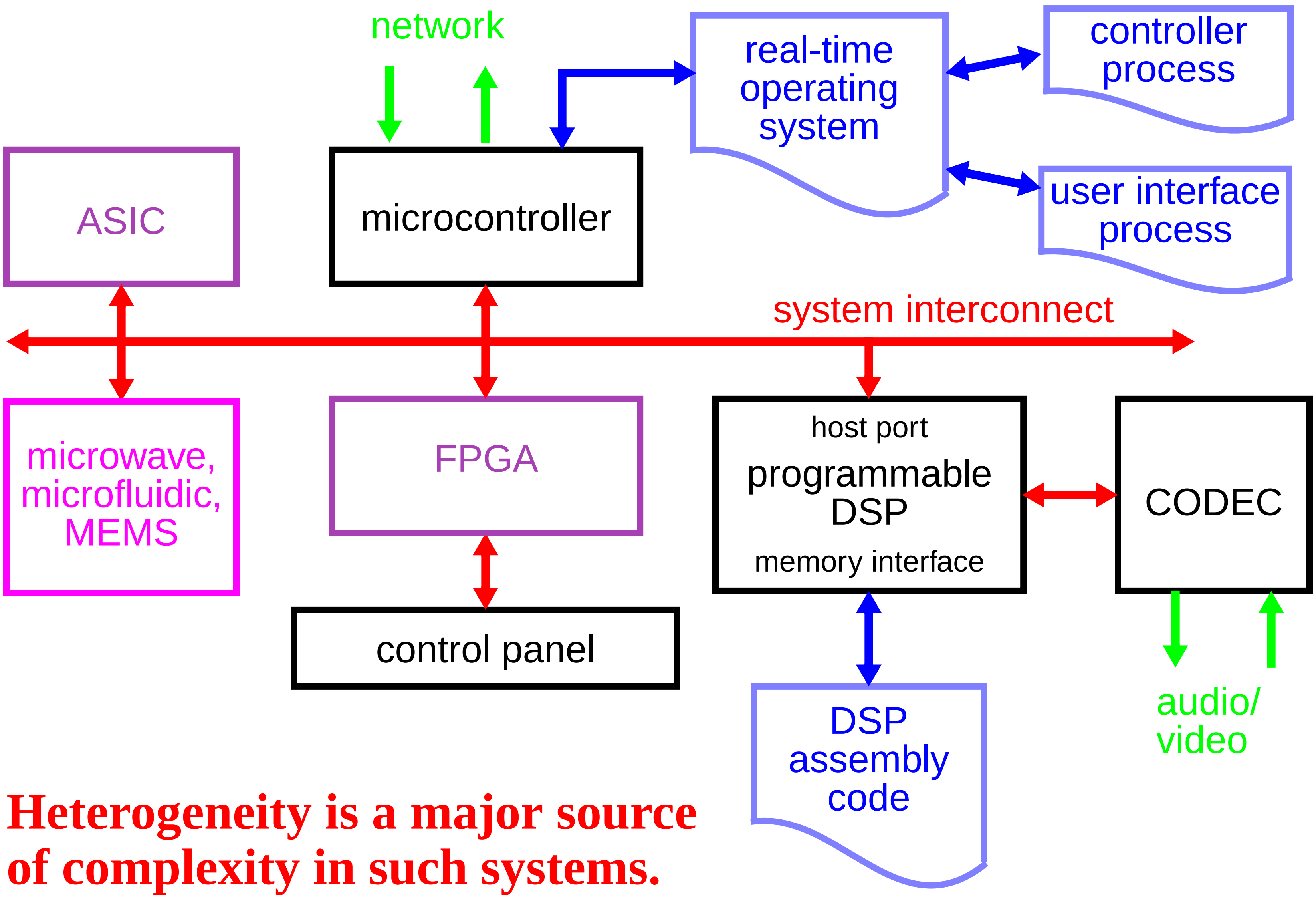


Author: Uwe Trautwein, Technical University of Ilmenau, Germany

# Properties of Such Specifications

- **Modular**
  - Large designs are composed of smaller designs
  - Modules encapsulate specialized expertise
- **Hierarchical**
  - Composite designs themselves become modules
  - Modules may be very complicated
- **Concurrent**
  - Modules logically operate simultaneously
  - Implementations may be sequential or parallel or distributed
- **Abstract**
  - The interaction of modules occurs within a “model of computation”
  - Many interesting and useful MoCs have emerged
- **Domain Specific**
  - Expertise encapsulated in MoCs and libraries of modules.

# Heterogeneous Implementation Architectures




**Heterogeneity is a major source of complexity in such systems.**

# Two Approaches to the Design of Such Systems

- **The grand-unified approach**
  - **Find a common representation language for all components**
  - **Develop techniques to synthesize diverse implementations from this**
- **The heterogeneous approach**
  - **Find domain-specific *models of computation* (MoC)**
  - **Hierarchically mix and match MoCs to define a system**
  - **Retargetable synthesis techniques from MoCs to diverse implementations**

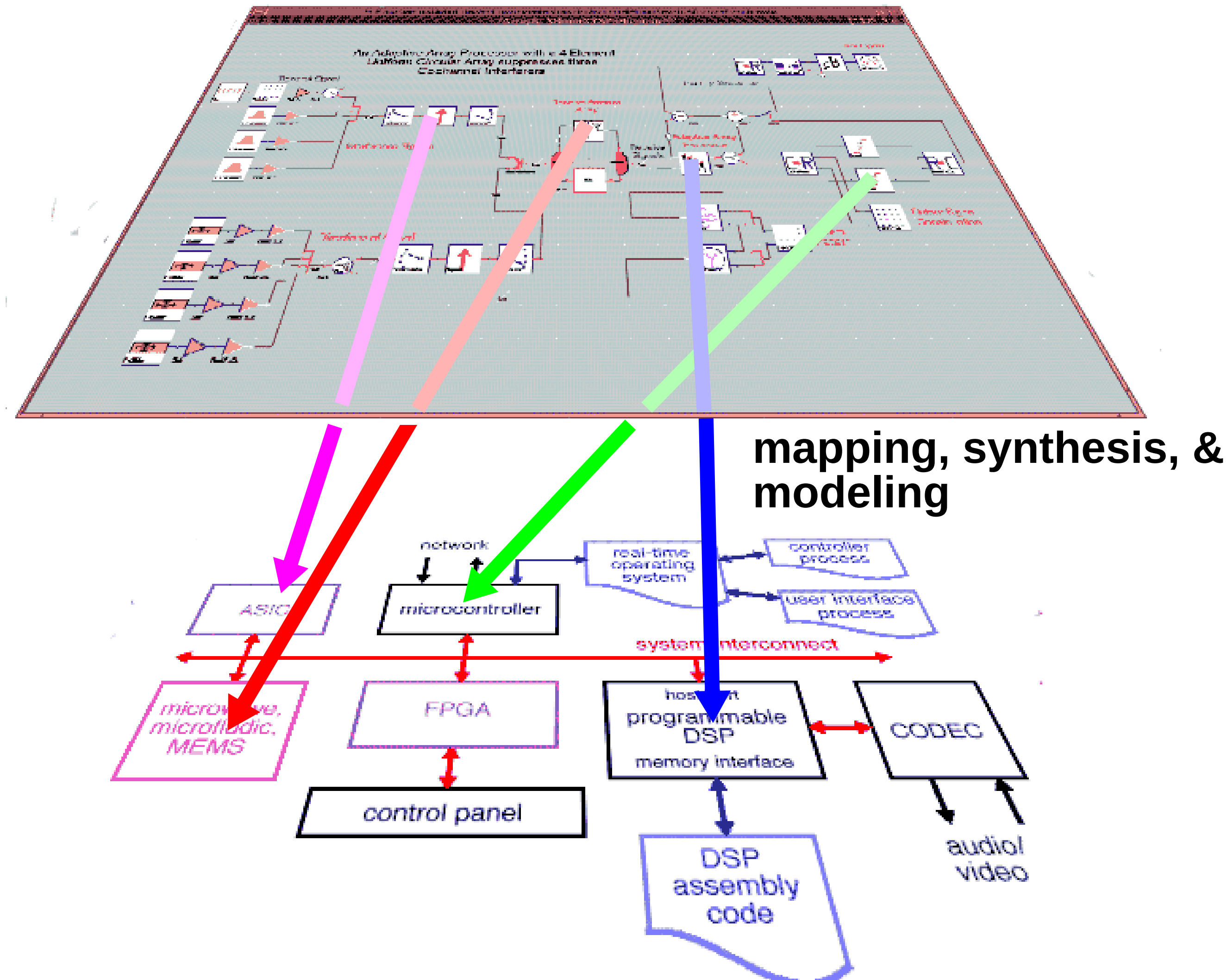
## The Ptolemy project is pursuing the latter approach

- **Domain specific MoCs match the applications better**
- **Choice of MoC can profoundly affect system architecture**
- **Choice of MoC can limit implementation options**
- **Synthesis from specialized MoCs is easier than from GULs.**

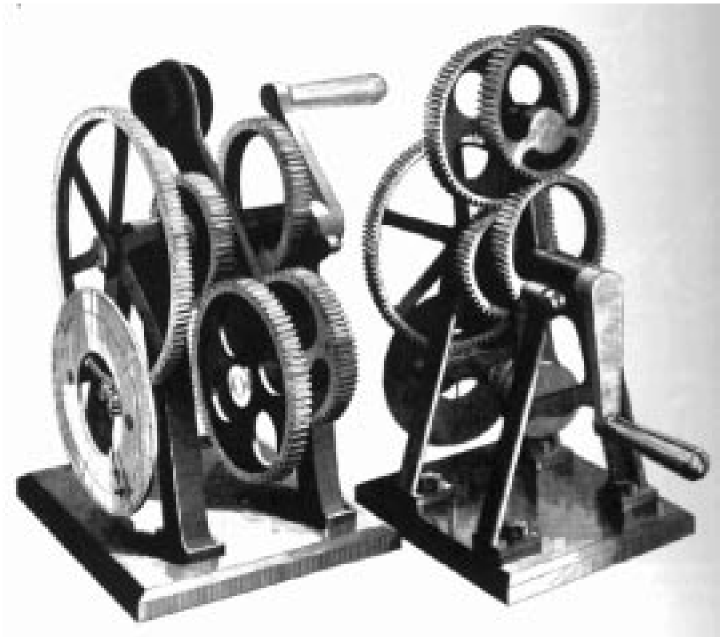
# Heterogeneous System-Level Specification & Modeling

problem level (heterogeneous models of computation)




implementation level (heterogeneous implementation technologies)

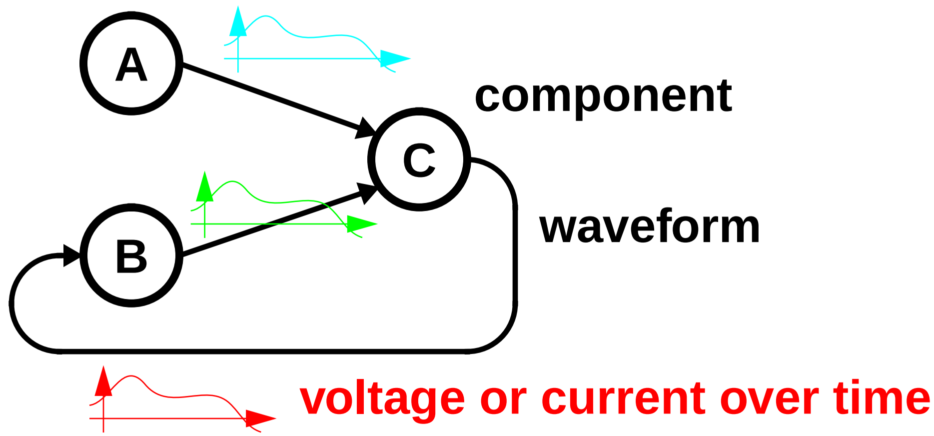
# Some Problem-Level Models of Computation



- Gears
- Differential equations
- Difference equations
- Discrete-events
- Petri nets
- Dataflow
- Process networks
- Actors
- Threads
- Synchronous/reactive languages
- Communicating sequential processes
- Hierarchical communicating finite state machines

# Example — Analog Circuit Modeling




## Strengths:

- Accurate model for many physical systems
- Declarative
- Determinate

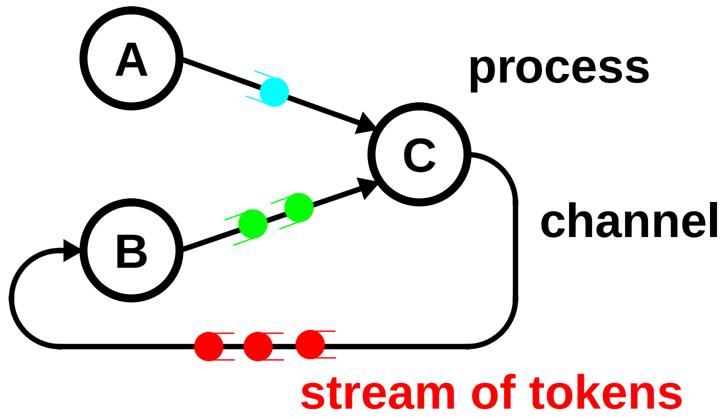
## Weaknesses:

- Tightly bound to an implementation
- Expensive to simulate
- Difficult to implement in software

# Example — Process Networks

Note: Dataflow is
a special case.




## Strengths:

- Good match for signal processing
- Loose synchronization (distributable)
- Determinate
- Maps easily to threads
- Dataflow special cases map well to hardware and embedded software

## Weakness:

- Control-intensive systems are hard to specify

# Our Contributions to Dataflow Modeling

**— the most mature parts of Ptolemy —**

- **Compile-time scheduling of *synchronous dataflow* graphs with optimized partitioning and memory utilization.**
- **Specification of the *Boolean dataflow (BDF) model*, which is Turing complete.**
- **Proof that the existence of a finite complete cycle and a bounded memory implementation for BDF is *undecidable*.**
- ***Heuristics* for constructing finite complete cycles and bounded memory schedules most of the time.**
- ***Multidimensional* generalization to dataflow models.**
- ***Process network* model generalization to dataflow.**
- ***Visual programming* formulation and use of *higher-order functions*.**

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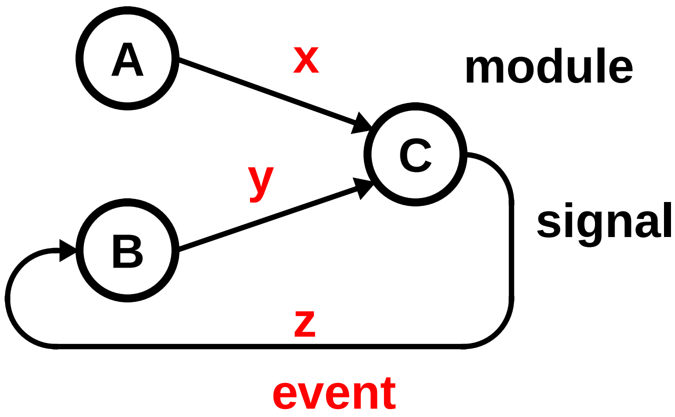
# Example — Synchronous/Reactive Models




A discrete model of time progresses as a sequence of "ticks." At a tick, the signals are defined by a fixed point equation:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} f_{A,\,t}(1) \\ f_{B,\,t}(z) \\ f_{C,\,t}(x,\,y) \end{bmatrix}$$

## Strengths:

- Good match for control-intensive systems
- Tightly synchronized
- Determinate
- Maps well to hardware and software

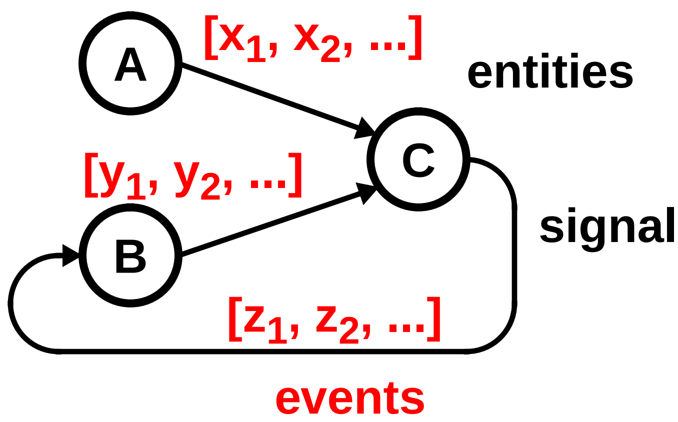
## Weaknesses:

- Computation-intensive systems are overspecified
- Modularity is compromised



# Example — Discrete-Event Models




**Events occur at discrete points on a time line that is usually a continuum. The entities react to events in chronological order.**

## Strengths:

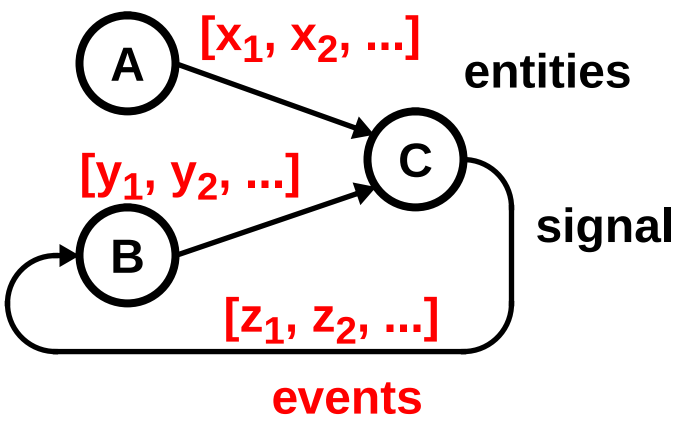
- **Natural description of digital hardware**
- **Global synchronization**
- **Can be made determinate (often is not, however)**

## Weaknesses:

- **Expensive to implement in software**
- **May over-specify and/or over-model systems (global time)**

# Rendezvous Models




Events represent rendezvous of a sender and a receiver. Communication is unbuffered and instantaneous. Examples include CSP and CCS.

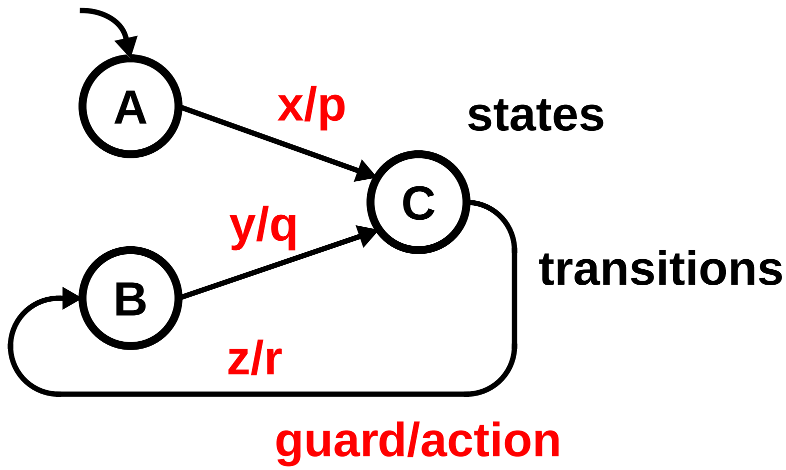
## Strengths:

- Models resource sharing well.
- Partial-order synchronization.
- Supports naturally nondeterminate interactions.

## Weaknesses:

- Oversynchronizes some systems.

# Sequential Example — Finite State Machines




**Guards determine when a transition may be made from one state to another, in terms of events that are visible, and outputs assert other events.**

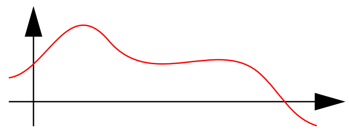
## Strengths:

- Natural description of sequential control
- Behavior is decidable
- Can be made determinate (often is not, however)
- Good match to hardware or software implementation

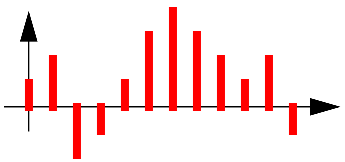
## Weaknesses:

- Awkward to specify numeric computation
- Size of the state space can get large

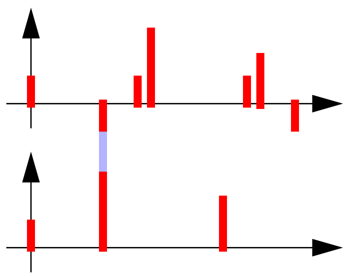
# Essential Differences — Models of Time



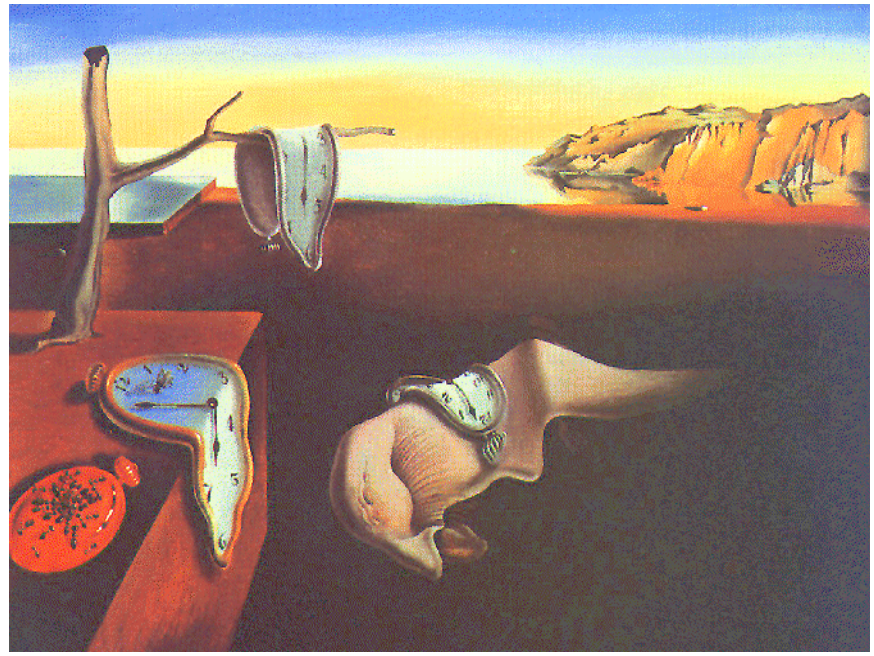
continuous time



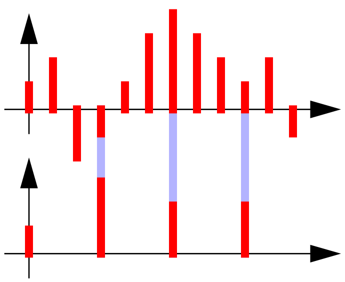
discrete time



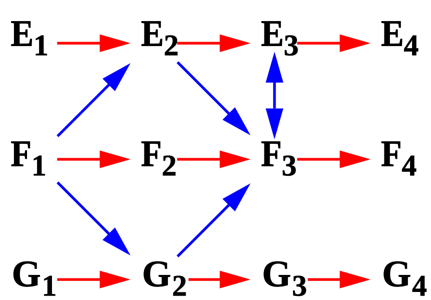
totally-ordered discrete events



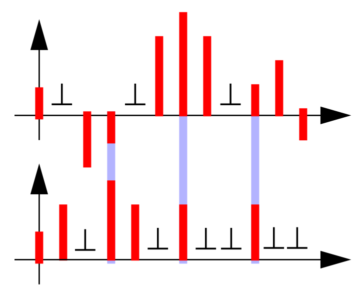
Salvador Dali, ***The Persistence of Memory***, **1931**



multirate discrete time




partially-ordered discrete events




synchronous/reactive

# Key Issues in these Models of Computation

- **Maintaining determinacy.**
- **Supporting nondeterminacy.**
- **Bounding the queueing on channels.**
- **Scheduling processes.**
- **Synthesis: mapping to hardware/software implementations.**
- **Providing scalable visual syntaxes.**
- **Resolving circular dependencies.**
- **Modeling causality.**
- **Achieving fast simulations.**
- **Supporting modularity.**
- **Composing multiple models of computation.**

## Validation methods

- **By construction**
  - property is inherent.
- **By verification**
  - property is provable syntactically.
- **By simulation**
  - check behavior for all inputs.
- **By testing**
  - observation of a prototype.
- **By intuition**
  - property is true, I think.
- **By assertion**
  - property is true. That’s an order.

Meret Oppenheim, *Object*, 1936

**It is generally better to be higher in this list**

# Usefulness of Modeling Frameworks

**The following objectives are at odds with one another:**

- **Expressiveness**
- **Generality**

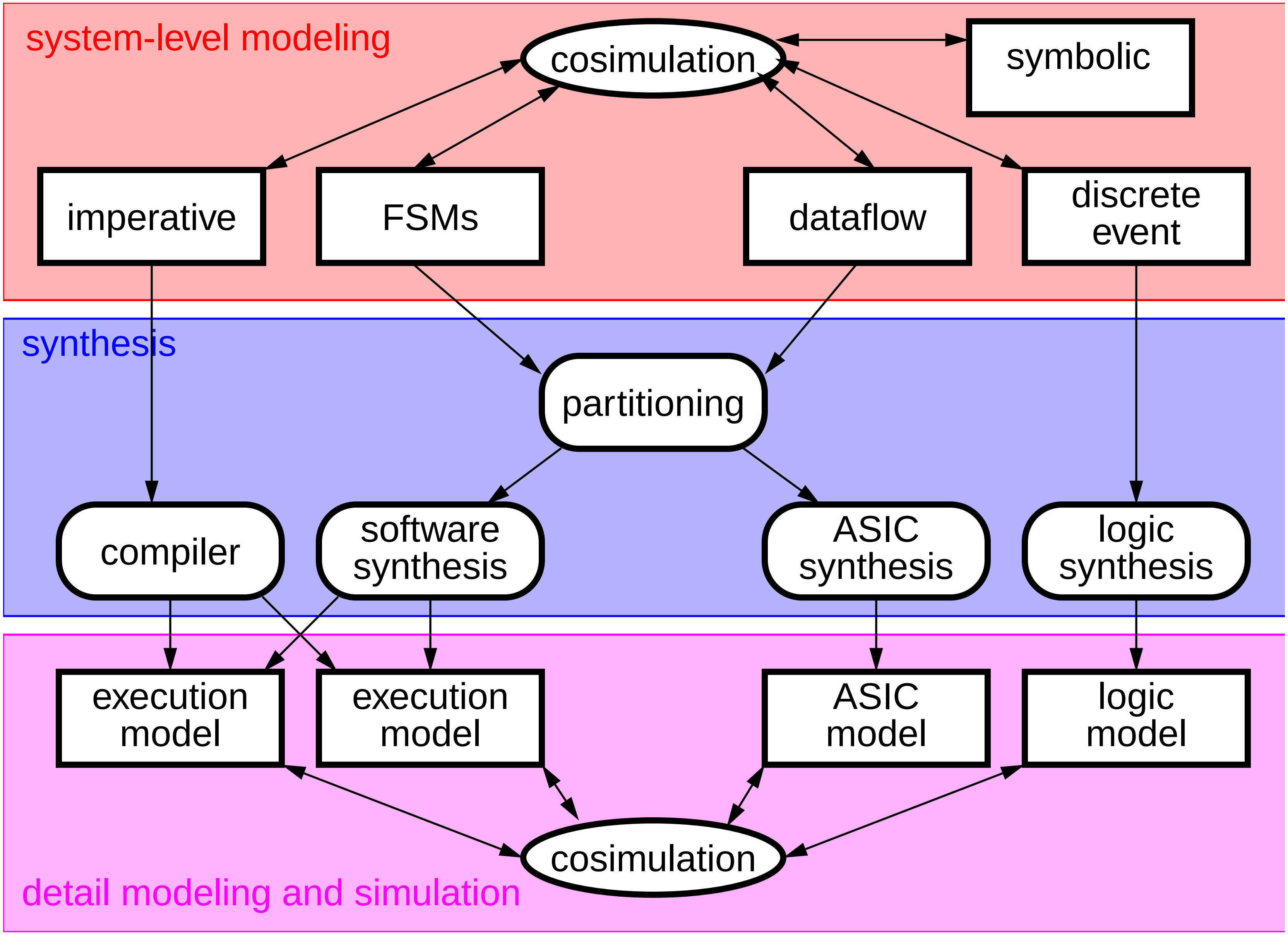
**vs.**

- **Verifiability**
- **Compilability/Synthesizability**

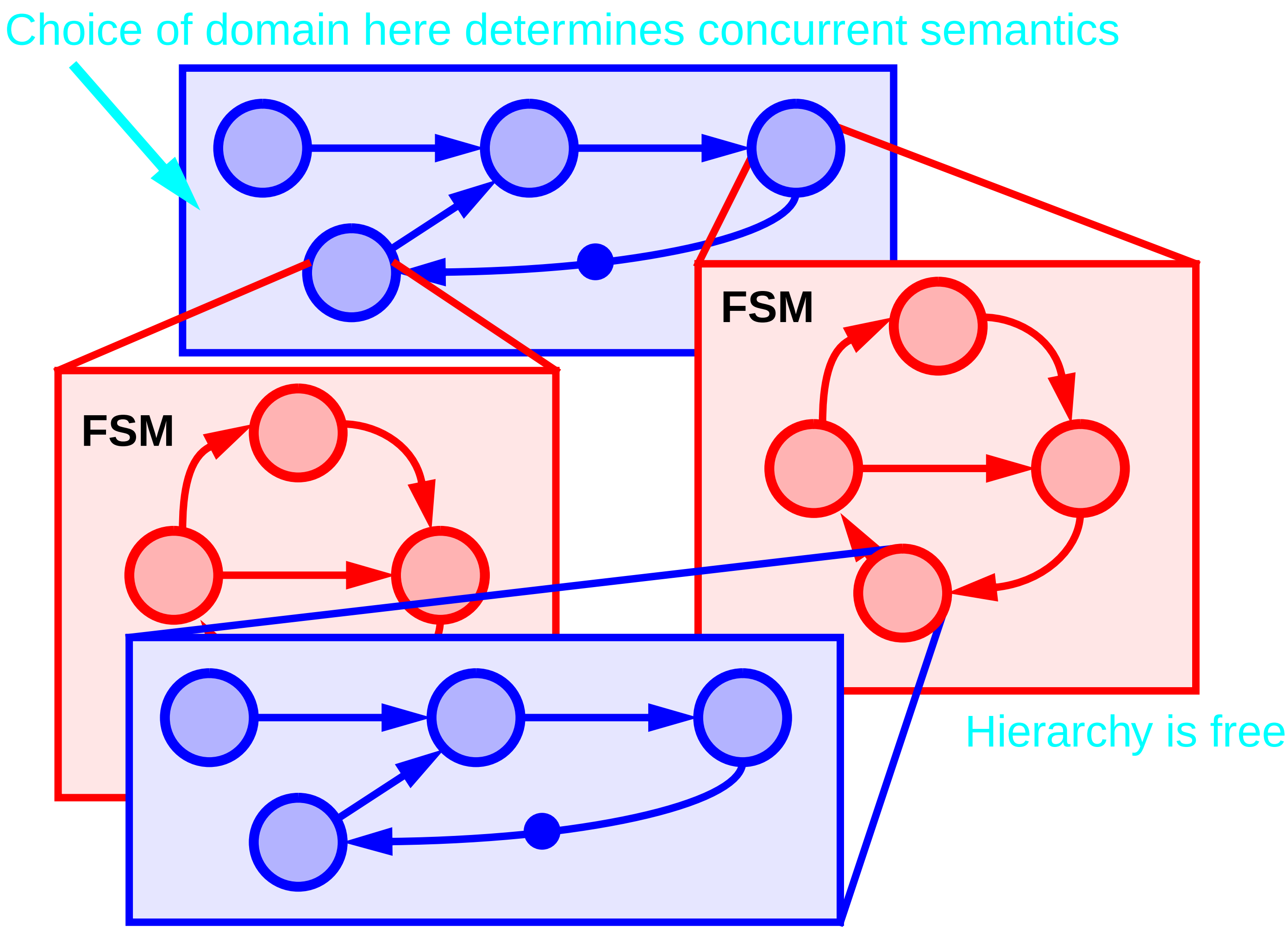
**The Conclusion?**

**Heterogeneous modeling.**

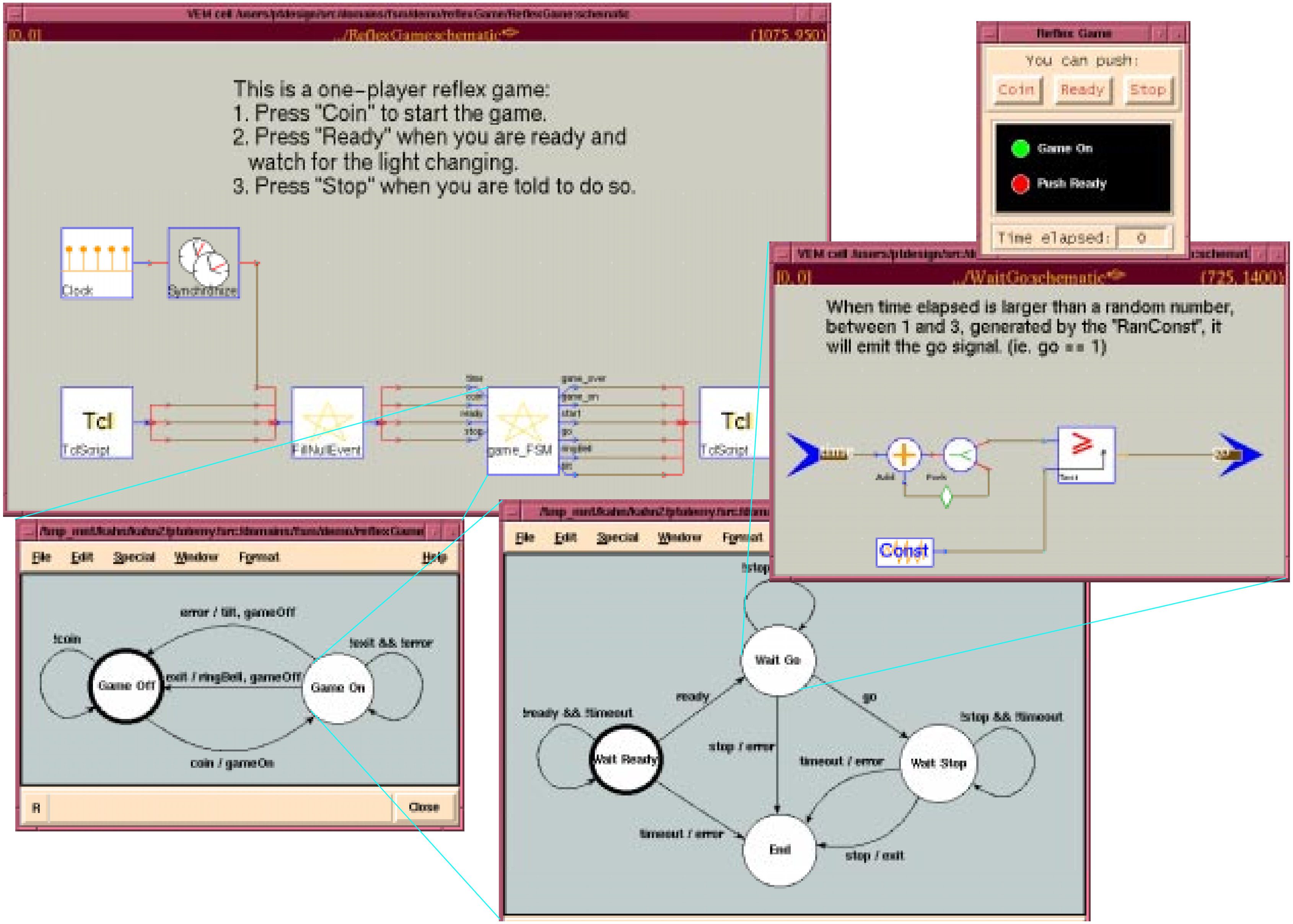
# A Mixed Design Flow



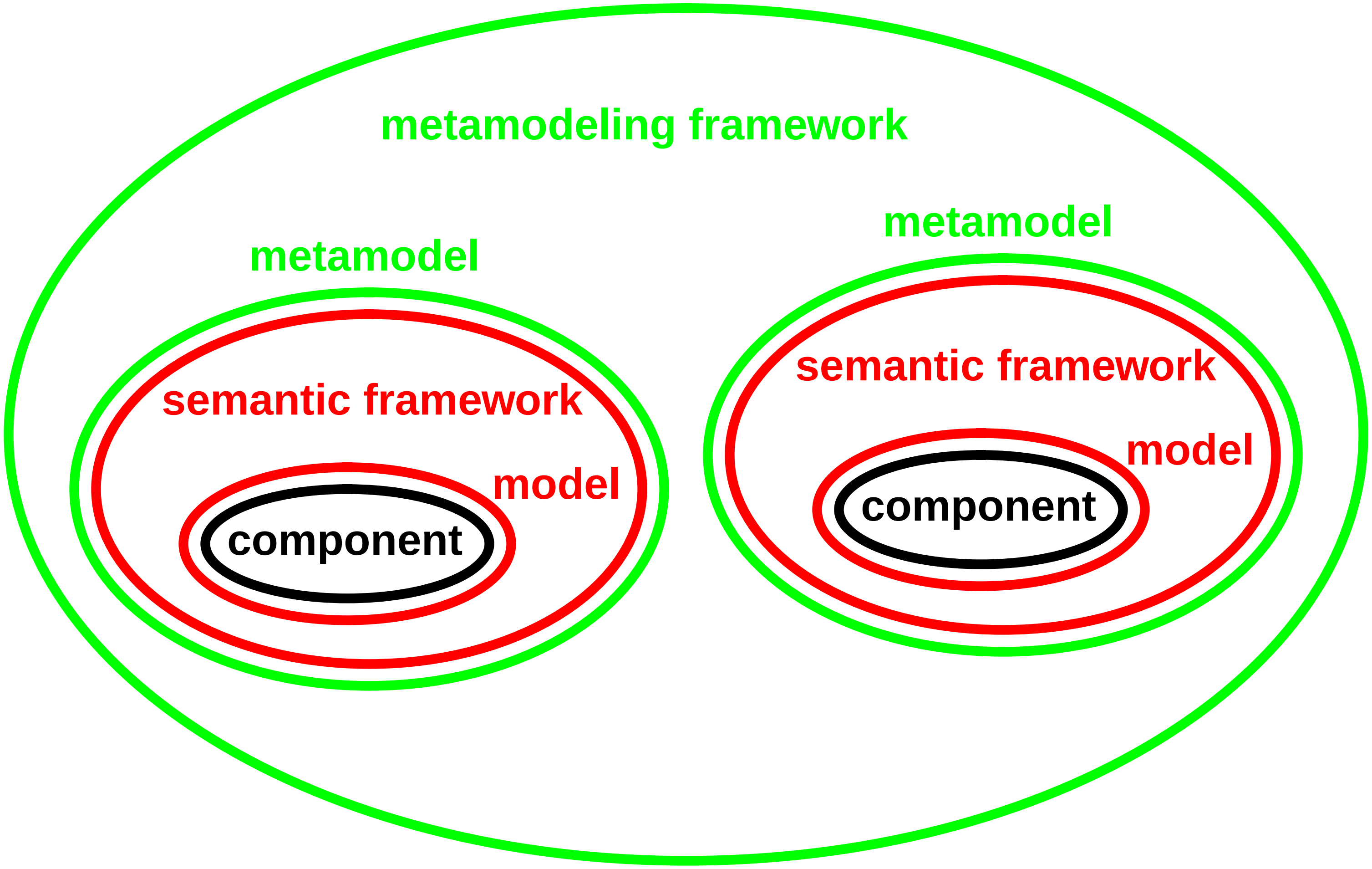
# Mixing Control and Signal Processing — *Charts



# Example: DE, Dataflow, and FSMs



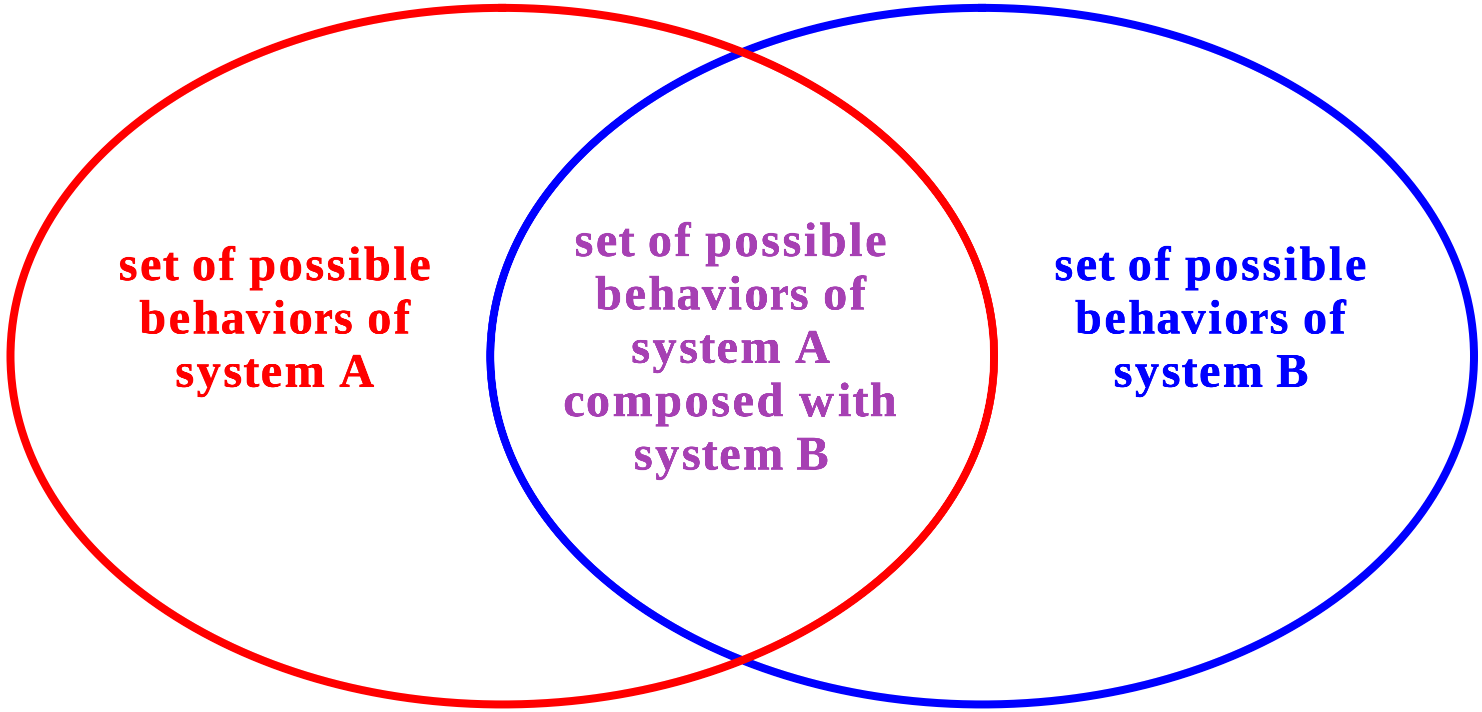
# Metamodeling





# Constraint-Based Metamodeling Frameworks




**These sets might be deterministic or random, exact or approximate.**

# Uses for Metamodeling

- **Heterogeneous mixtures of semantic frameworks**
  - **heterogeneous systems**
  - **multiple views of the same system**
- **Design analysis**
  - **check aspects of correctness**
  - **discover opportunities for optimization**
- **Design refinement**
  - **the set of all possible design refinements gives the concretization operator**
- **Run-time modeling**
  - **reflection**
  - **model discovery and adaptation**
  - **model-driven control**

# Milestones in the Ptolemy Project

- **1990 — started with seed support from DARPA VLSI program. Focus on embedded DSP software and communication networks.**
- **1993 — joined DARPA RASSP program. Focus on high-throughput embedded real-time signal processing systems.**
- **1995 — The Alta Group at Cadence announces software using Ptolemy dataflow and mixed dataflow/discrete-event technology (SPW).**
- **1997 — joined DARPA Composite CAD program. Focus on distributed adaptive reactive systems with mixed implementation technologies and modeling techniques.**
- **1997 — Hewlett-Packard (EEsof) announces “HP Ptolemy,” an integration of Ptolemy dataflow technology with analog RF and microwave design and modeling tools.**

# Ptolemy Software as a Tool and as a Laboratory

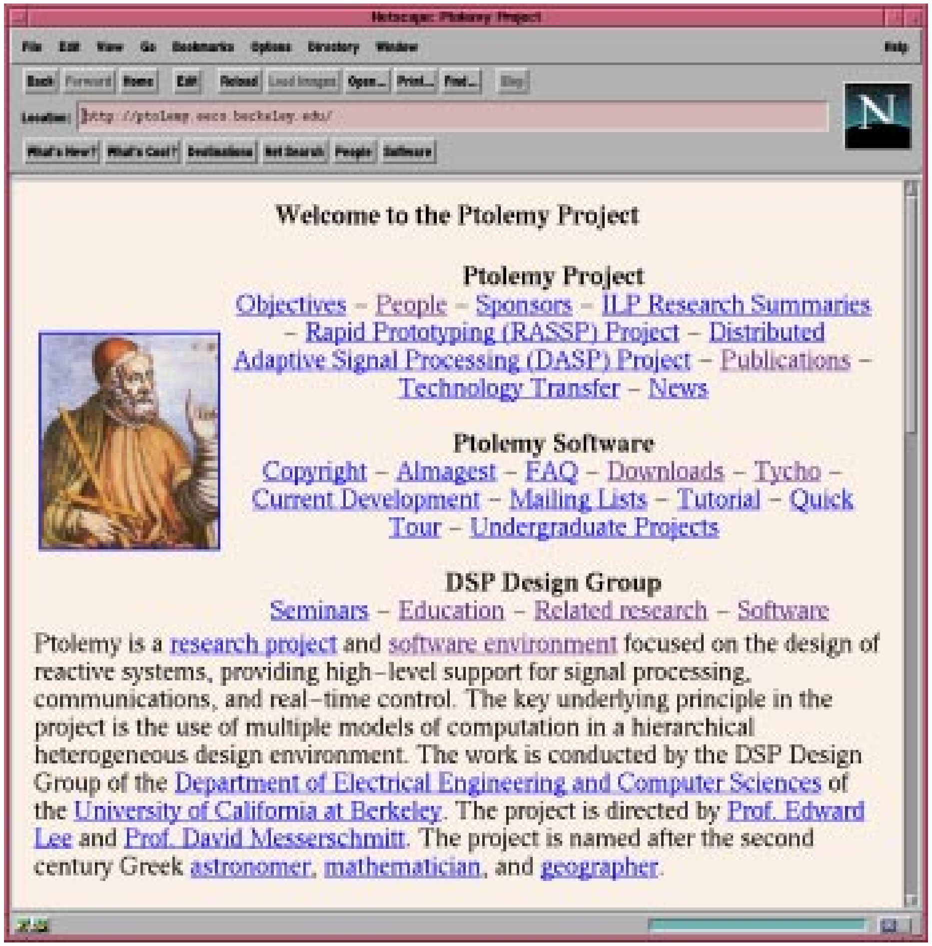
**Ptolemy software is**

- **Extensible**
- **Publicly available**
- **An open architecture**
- **Object-oriented**

**Allows for experiments with:**

- **Models of computation**
- **Heterogeneous design**
- **Domain-specific tools**
- **Design methodology**
- **Software synthesis**
- **Hardware synthesis**
- **Cosimulation**
- **Cosynthesis**
- **Visual syntaxes (Tycho)**

# Further Information




- Software distributions
- Small demonstration versions
- Project overview
- *The Almagest* (software manual)
- Current projects summary
- Project publications
- Keyword searching
- Project participants
- Sponsors
- Copy of the FAQh
- Newsgroup info
- Mailing lists info

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