# The Ptolemy Project

## Modeling and Design of Reactive Systems

**Presenter:**

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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.

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# Organizational

**Staff**
Diane Chang, administrative assistant
Kevin Chang, programmer
Christopher Hylands, programmer analyst
Edward A. Lee, professor and PI
Mary Stewart, programmer analyst

**Postdocs**
Praveen Murthy
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**Students**
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**Undergraduate Students**
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Luis Gutierrez

**Key Outside Collaborators**
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Joseph T. Buck (Synopsys)
Brian L. Evans (UT Austin)
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

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# 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

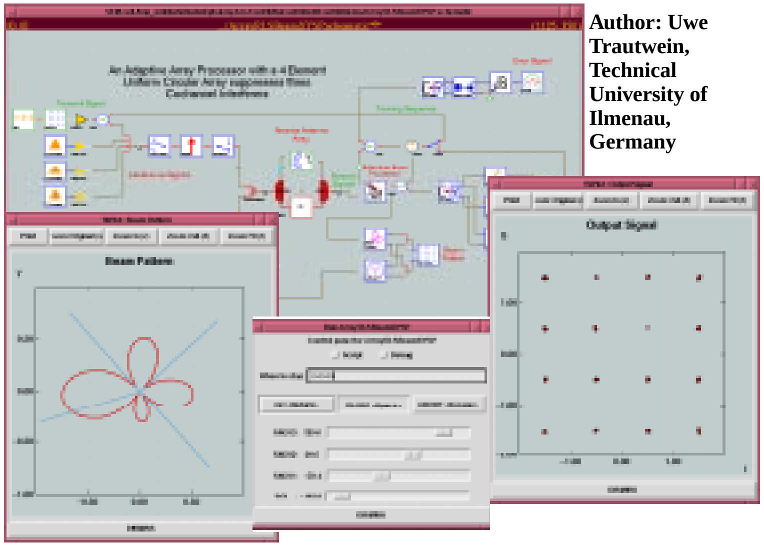
## Reactive

- 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**

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# 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.

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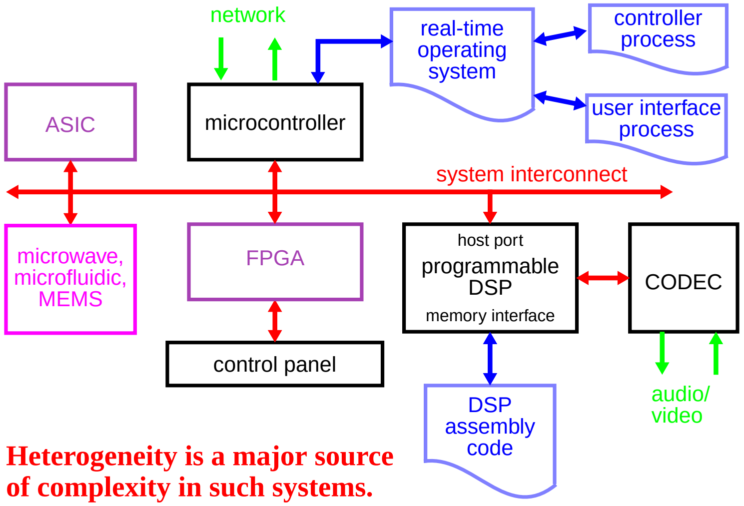
# Heterogeneous Implementation Architectures



Heterogeneity is a major source of complexity in such systems.

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# Two Approaches to the Design of Such Systems

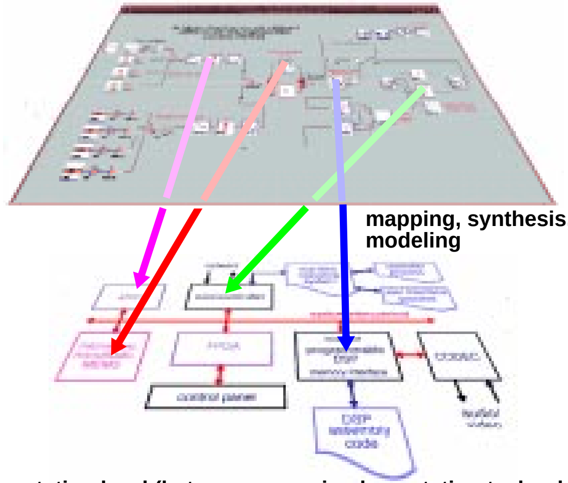
- The grand-unified approach
  - Find a common representation language for all components
  - Develop techniques to synthesize diverse implementations from this
- The heterogeneous approach
  - Find domain-specific *models of computation* (MoC)
  - Hierarchically mix and match MoCs to define a system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



mapping, synthesis, & modeling

implementation level (heterogeneous implementation technologies)

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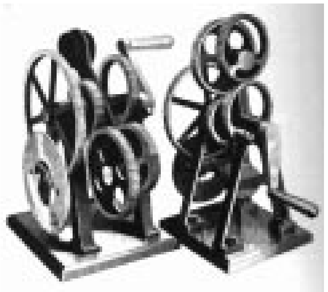
## Some Problem-Level Models of Computation

- 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



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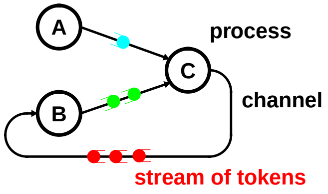
## Example — Process Networks

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

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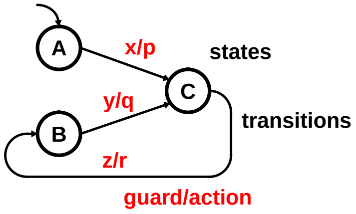
## Sequential Example — Finite State Machines



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.

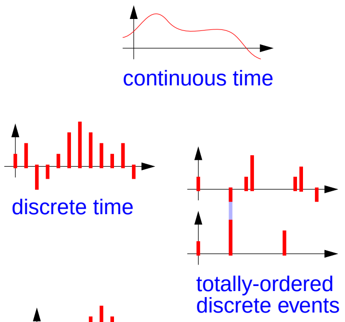
### Strengths:

- 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

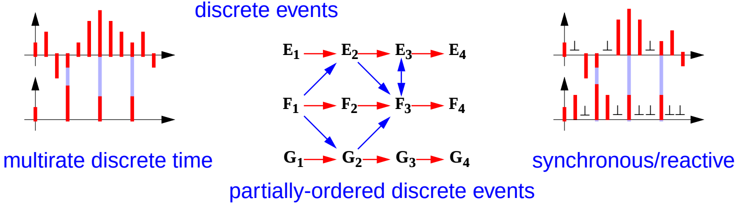
# Essential Differences — Models of Time


continuous time

discrete time

totally-ordered discrete events


Salvador Dali, *The Persistence of Memory*, 1931



multirate discrete time

synchronous/reactive

partially-ordered discrete events

# 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.**

# Choosing 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**

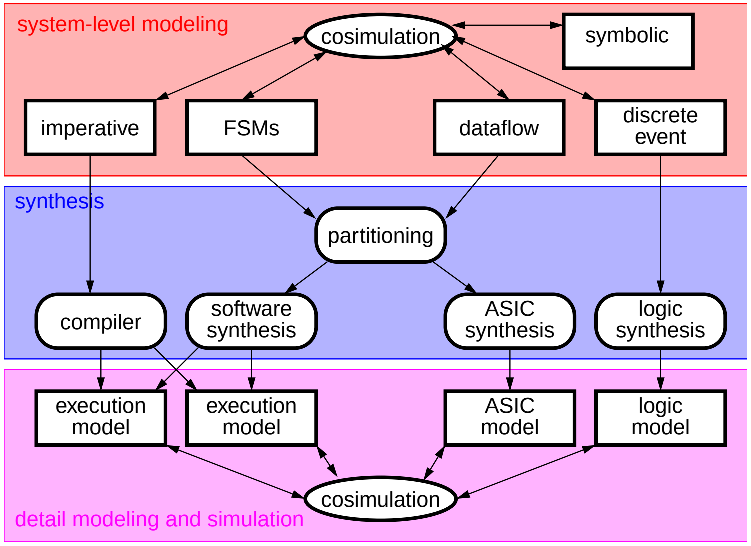
**vs.**

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

**The Conclusion?**

**Heterogeneous modeling.**

## A Mixed Design Flow



system-level modeling

cosimulation

symbolic

imperative

FSMs

dataflow

discrete event

synthesis

partitioning

compiler

software synthesis

ASIC synthesis

logic synthesis

execution model

execution model

ASIC model

logic model

cosimulation

detail modeling and simulation

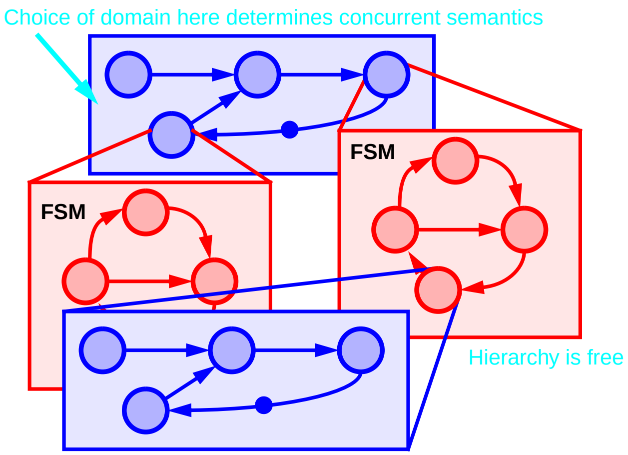
## Major Contributions under RASSP

- Static scheduling of synchronous dataflow (SDF) graphs for optimum memory utilization, for partitioning into mixed hardware/software implementations, and for synthesis of VHDL.
- Mixed modeling and design of hardware, embedded software, and the test environment.
- Integrated symbolic processing with numeric and demonstrated heterogeneous design tools that leverage commercial tools such as Matlab, Mathematica, and VHDL simulators.
- Generalizations of dataflow to multidimensional streams and to process networks.
- Robust dynamic dataflow scheduling for bounded memory.
- Visual programming and use of higher-order functions.
- Optimized synchronization for multiprocessors.

## Contributions (contd.)

- A synchronous-reactive modeling technique that is modular and can be combined with dataflow, finite-state machines, and discrete-event modeling.
- A hierarchical finite-state machine model of computation that can be combined with dataflow, discrete-event, and synchronous reactive modeling.
- A mathematical semantic framework for comparing models of computation, and analysis within this framework of the discrete-event semantics of VHDL and the formal semantics of dataflow.
- Public distribution of three major versions of the Ptolemy software and two versions of the Tycho user-interface framework. This software serves as our laboratory and as a major vehicle for technology transfer.

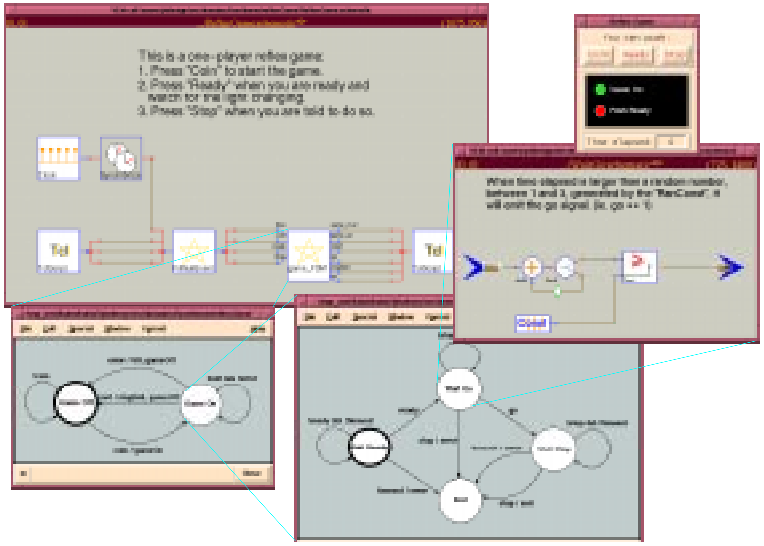
## Mixing Control and Signal Processing — *Charts



Choice of domain here determines concurrent semantics

Hierarchy is free

## Example: DE, Dataflow, and FSMs


This is a one-player reflex game.
1. Press "Coin" to start the game.
2. Press "Ready" when you are ready and watch for the light changing.
3. Press "Stop" when you are told to do so.

When time elapsed is larger than a random number, between 1 and 3, generated by the "RanConst", it will emit the go signal (ie, go == 1)

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## Technology Transfer

**Our policy of free and open software distribution has proven to be a very effective facilitator for technology transfer.**

- **1995 — The Alta Group at Cadence announces software using Ptolemy dataflow and mixed dataflow/discrete-event technology (SPW 3.5).**
- **1995 — DQDT uses and extends Ptolemy VHDL generation for ASIC designs.**
- **1995 — BDTI uses the Ptolemy kernel to integrate commercial tools (SPW and Bones from Alta).**
- **1996 — Lockheed/Martin develops architecural tradeoff analysis tool based on Ptolemy.**
- **1997 — Hewlett-Packard (EEsof) announces "HP Ptolemy," an integration of Ptolemy dataflow technology with analog RF and microwave design and modeling tools.**
- **1997 — BNED, Technologies Lyre, White Eagle Systems, ...**

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## 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)**

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## 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**