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, their ability to model and specify real-time systems, and their ability to mix control logic with signal processing.
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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
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

Note: Dataflow is a special case.

Example — Process Networks

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.

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

- **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

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.

Essential Differences — Models of Time

- **Synchronous/reactive**
- **Continuous time**
- **Discrete time**
- **Totally-ordered discrete events**
- **Multirate discrete time**
- **Partially-ordered discrete events**
- **Synchronous/reactive**

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

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

Meret Oppenheim, *Object*, 1936
Usefulness of Modeling Frameworks

The following objectives are at odds with one another:

- Expressiveness
- Generality
- 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

Detail modeling and simulation
- execution model
- execution model
- ASIC model
- logic model
- cosimulation
Mixing Control and Signal Processing — *Charts

Choice of domain here determines concurrent semantics

Hierarchy is free

Example: DE, Dataflow, and FSMs
Metamodelling

Constraint-Based Metamodelling Frameworks

These sets might be deterministic or random, exact or approximate.
Uses for Metamodelling

- 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 FAQ
- Newsgroup info
- Mailing lists info

http://ptolemy.eecs.berkeley.edu