Real-Time Systems

Part 8: Model-Driven Design

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- Model-driven design of real-time systems
- Dynamic models
- Models of computation
- Tools
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  - Esterel
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Literature

- Sastry et al: Scanning the issue – special issue on modeling and design of embedded software, Proceedings of the IEEE, vol.91, no.1, pp. 3-10, Jan 2003
- Thomas Stahl, Markus Völter: Model-Driven Software Development, Wiley, 2006
- Chapter 2-6 in Lee and Seshia, Introduction to Embedded Systems – A Cyber-Physical Systems Approach, 1st Edition, 2011, LeeSheshia.org
- Ptolemy: Software and Documentation http://ptolemy.eecs.berkeley.edu/ptolemyII/index.htm
- Benveniste et al.: The Synchronous Languages, 12 Years Later, Proceedings of the IEEE, vol.91, no.1, pp. 64-83, Jan 2003
- Publications on Esterel, Lustre, Safe State Machines: http://www.esterel-technologies.com/technology/scientific-papers/

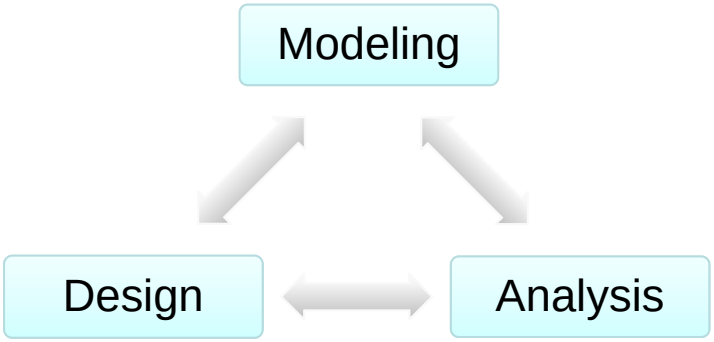
Publications of IEEE, Springer, ACM can be downloaded inside the university network through the TUM Informatics Proxy (proxy.in.tum.de)

Model

- **Britannica**:
  Scientific modeling, the generation of a physical, conceptual, or mathematical representation of a real phenomenon that is difficult to observe directly. Scientific models are used to explain and predict the behaviour of real objects or systems and are used in a variety of scientific disciplines, […]

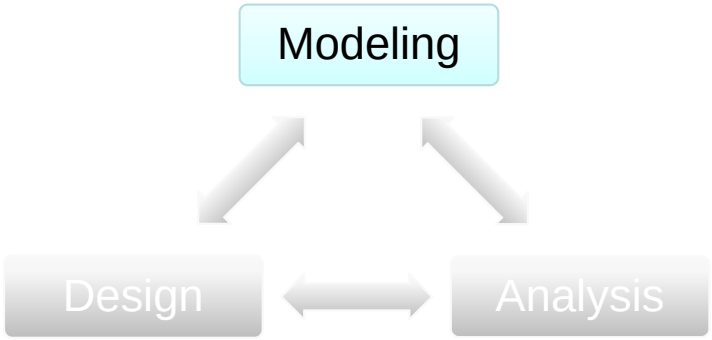
- **Wikipedia**:
  In the most general sense, a model is anything used in any way to represent anything else. […] a conceptual model is a model that exists only in the mind. Conceptual models are used to help us know and understand the subject matter they represent.

Modeling, Design and Analysis



- Modeling:
  - Model is a **representation of reality** (usually limited to the essentials)
  - Mirroring system properties
  - ***What*** the system is doing
- Design:
  - Implementation
  - Hardware/Software
  - ***How*** the system is producing the required results
- Analysis:
  - Understanding the system
  - ***Why*** the system is doing what it is supposed to

Modeling



- Continuous Dynamics
- Discrete Dynamics
- Hybrid Systems
- State Machines
- Concurrent Models of Computation

Modeling

➢ *As simple as possible, as complex as necessary!*
(Occam's Razor)

- Models can be built for:
  - The ***environment***
    for a better understanding of the processes to be controlled
  - The underlying (electronic) ***hardware***
    to understand exact timing issues
  - The ***software*** to be developed
    to refine specification & generate code

Model-driven design of Real-time systems

- Development of Real-time systems calls for:
  - ***Guaranteed*** performance
  - ***Fault-tolerant*** systems
  - ***Verification*** against a model

➢ Models of hardware, software and the environment are necessary!

- Only a model makes formal verification possible!
- A ***functional model*** is an executable description.

Model-driven design of Real-time systems

- Models can take different roles along the development process:
  - Design
  - Simulation
  - Code generation
  - Analysis

- Some tools can cover the whole process, turning the development process into a graphical programming approach

Model-driven design – Advantages

- Advantages:
  - Models are often easier to understand than programming code (graphical representation, higher level of abstraction)
  - Systems can be simulated, evaluating different designs
  - Code generation can reduce the time to implement changes
    This is only true if the process is fully automatic (inconsistensies!)
  - Formal methods can be applied to test the code against the models

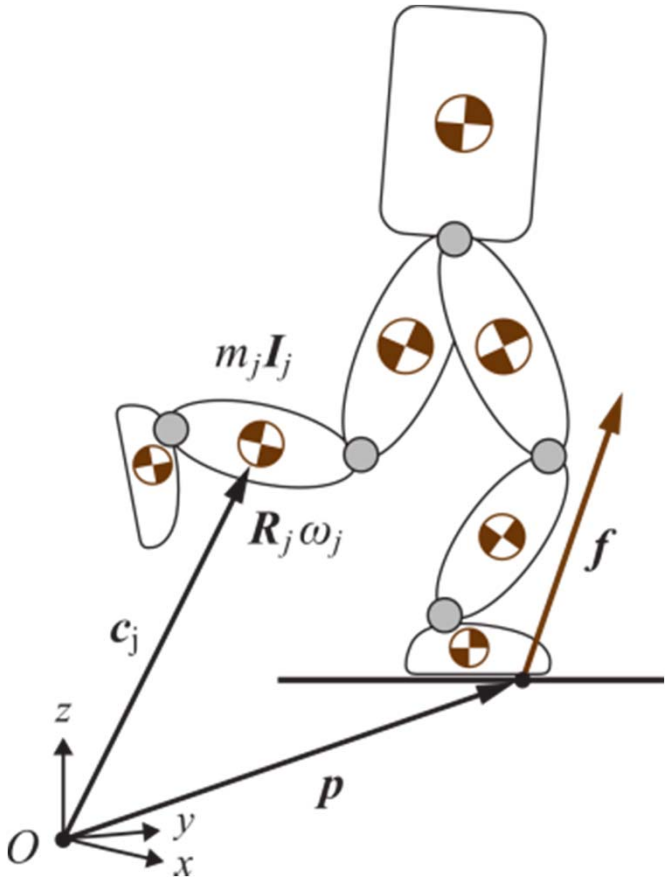
- Disadvantages:
  - Underlying processes are less understood and can still lead to unwanted behavior

Continuous Dynamics

- Modeling physical systems
  - Mechanics (motion dynamics)
  - Electrical systems
  - Thermodynamics
- System of first-order ordinary differential equations (ODE)

$$\dot{\underline{x}} = f(\underline{x}, \underline{u})$$

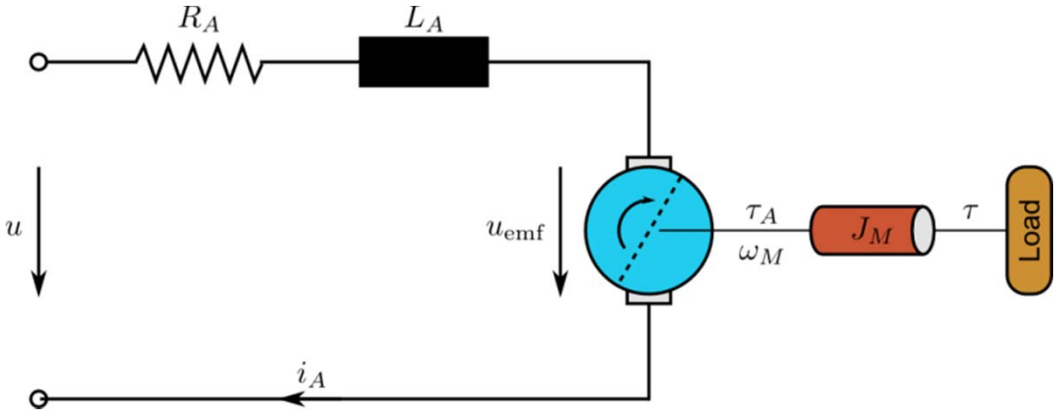
- Usage:
  - Simulation of environment
  - Controller development



Springer Handbook of Robotics, 2008

Continuous Dynamics – Example

- Motor Dynamics:



$$u = R_A i_A + L_A \frac{di_A}{dt} + u_{emf}$$

$$u_{emf} = c_M \omega_M$$

$$\tau_A = c_M i_A$$

$$\tau_A = J_M \dot{\omega}_M + \tau$$

- Direct integration of ODEs is used to simulate motor dynamics
- Any system of ODEs can be expressed in e.g. MATLAB/Simulink for simulation and controller development

Dynamic Models – Discrete Dynamics

- Discrete dynamical systems are discrete in time
- Any continuous system, expressed as a system of ODEs, can be discretized with a timestep T
- The new state vector $\underline{x}_k$ is expressed as a function of the previous states $\underline{x}_{k-1} - \underline{x}_{k-n}$ and the current input u_k

$$\underline{x}_k = f(\underline{x}_{k-1}, \underline{x}_{k-2}, \dots, \underline{x}_{k-n}, \underline{u}_k)$$

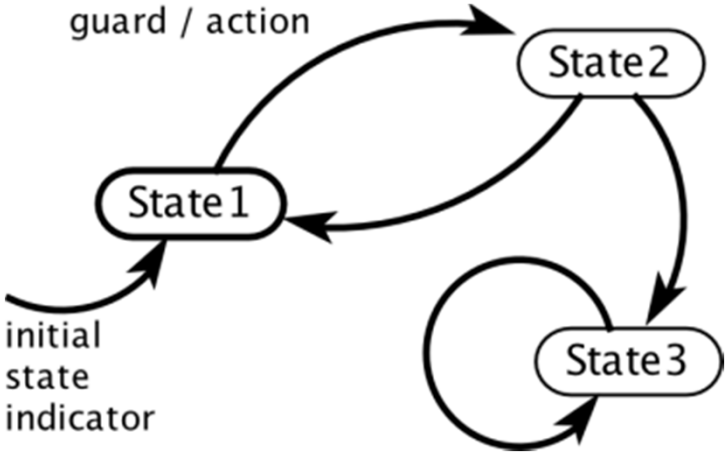
- Example – Discrete Integrator:

$$x_k = x_{k-1} + Tu_k$$

- Usage:
  - Digital control design

Finite State Machines (FSM)

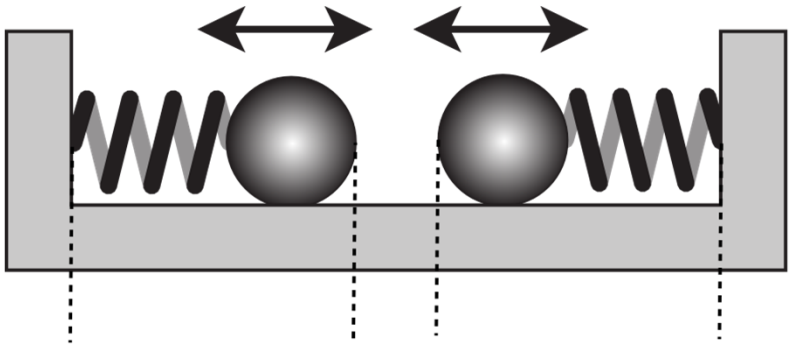
- Discrete in states (time is irrelevant)
- Defined as a (finite) set of ***states*** $S = \{s_1, s_2, \dots, s_n\}$ and ***transitions*** which are activated by a ***guard*** expression
- Each transition leads to an ***action***
- Description of a logical sequence
- Purpose in software engineering:
  - Code generation
  - Verification

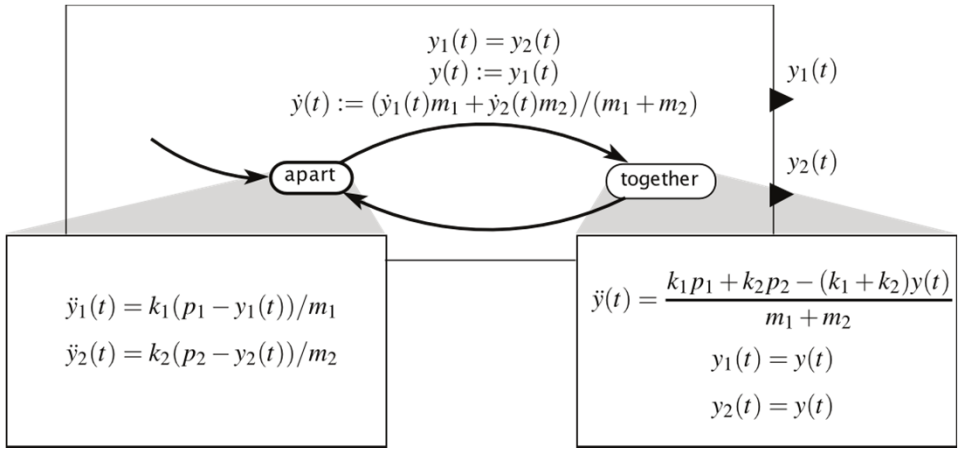


Lee, Seshia, 2011

Hybrid Systems

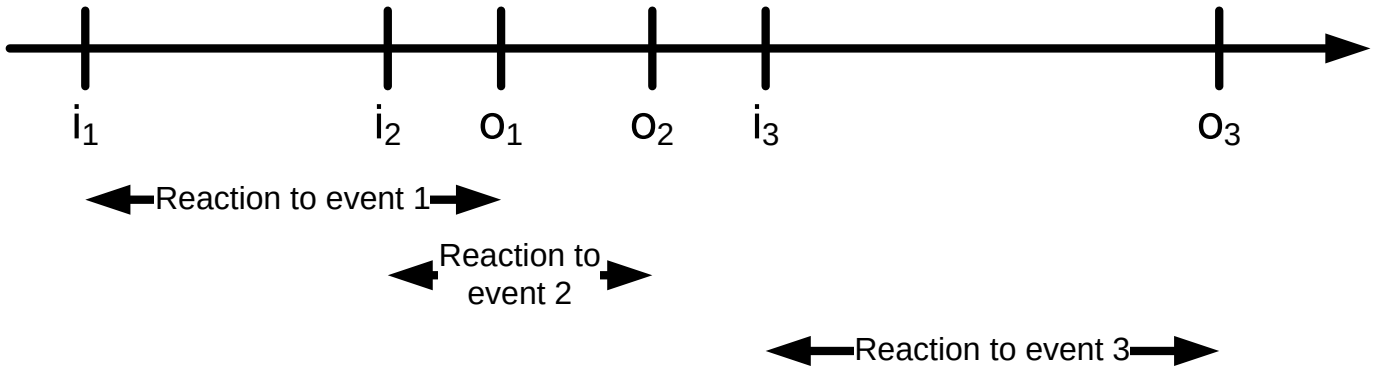
- Composite of FSMs with continuous systems
- The set of ODEs used to express the system is selected depending on the state of the FSM
- Usage: model physical systems





Models of Computation – Reactive Systems

- Reactive systems (also: reflex systems) produce an output o for each input event i
- Reactive systems are used e.g. in industrial process control or for control of airplanes and cars.
- Emphasis is placed on safety and determinism
- Execution of events can overlap



Models of Computation – Synchronous Reactive (SR) Systems

- The ***synchrony hypothesis*** assumes that the underlying physical machine is infinitely fast.

➢ Ideal assumption of a system producing outputs synchronously to changes of the inputs.

➢ Reaction intervals are reduced to reaction instants

- ***Justification***: This assumption is correct when the probability of a second event happening during the execution of a first event drops towards zero.

- Examples:
  - Esterel
  - SCADE/Lustre
  - SystemC

Concurrent Models of Computation

- Dataflow
  - Execution is driven by data
  - If one actor needs data produced by another actor, execution has to wait until data is ready
  - Usage: Execution of discrete dynamics
- Time-Triggered Execution
  - Execution is planned for each instant in time
  - Usage: Real-time control
  - Tools: Giotto, FTOS
- Component Interaction:
  - Composition of data and query driven execution
  - Example: Web Server

Concurrent Models of Computation

- Process Networks
  - Processes communicate through channels
  - Channels store messages in a queue (asynchronous messages)
  - Usage: distributed systems

- Rendezvous
  - Processes communicate via synchronous messages (Processes wait until both sender and receiver is ready)
  - Examples: CSP, CCS, Ada

Tools – UML

- Unified Modeling Language (UML)
- Inherent part of the software development process

- Problems:
  - Heterogeneous models
  - No model of computation, therefore no code generation (except FSM)
  - Inconsistencies between model and code

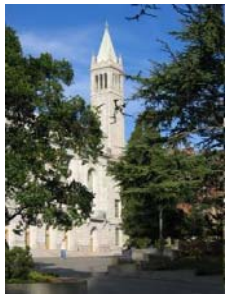
Tools – UML

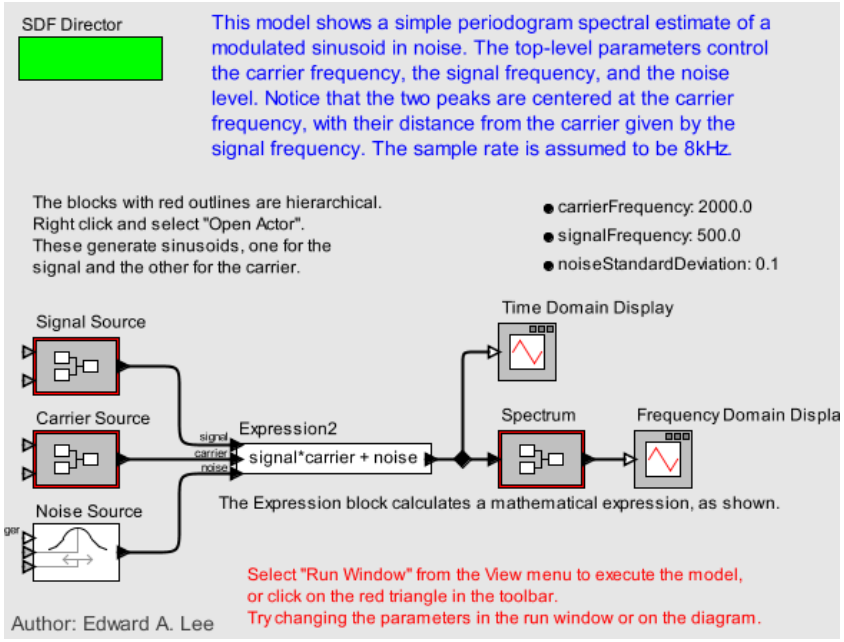
- Useful executable modeling languages impose *constraints* on the designer.

- The constraints may come with benefits:
  - Model is constrained to the fundamental part
  - Models may be (partly) verifyable
  - Code generation

We have to stop thinking of constraints as a universal negative!!!

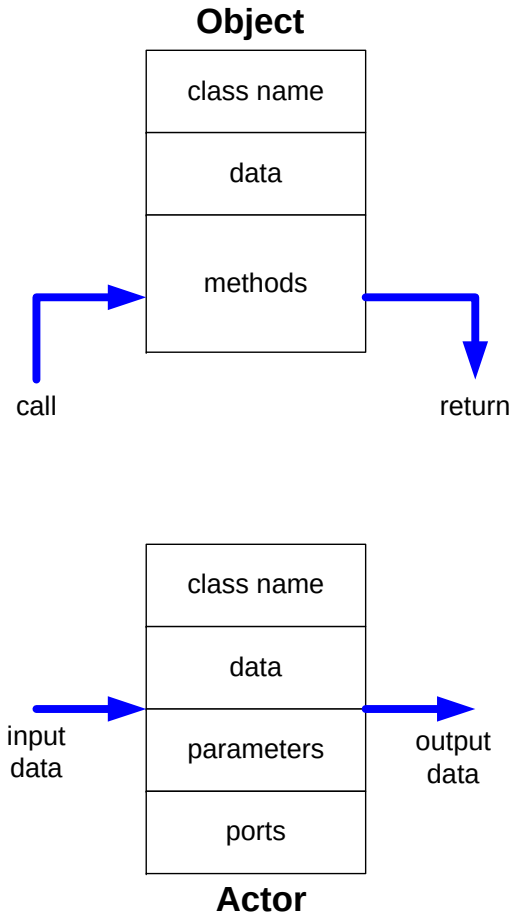
Tools – Ptolemy





- Ptolemy-Project at UC Berkeley
- Named after **Claudius Ptolemaeus**
- Support of several different models of computation
- Ptolemy supports:
  - Modeling
  - Simulation
  - Code generation
  - Formal verification (to some extent)
- Information and download: http://ptolemy.eecs.berkeley.edu/

Tools – Ptolemy: Actor Oriented Design



- Ptolemy models use actors instead of objects
- Objects:
  - Focus on control flow
  - System manipulates objects
- Actors
  - Focus on data flow
  - Actors manipulate the system
- Both paradigms increase reusability by dividing the system into subsystems
- Actors can be used to represent parallelism of actions

Tools – Ptolemy: Actor Oriented Design

- Ptolemy implements several models of computations
- User can define the model of computation used by choosing a so called *director.*

➢ Seperation of the logical and temporal design by separating the director choice from the actor connections

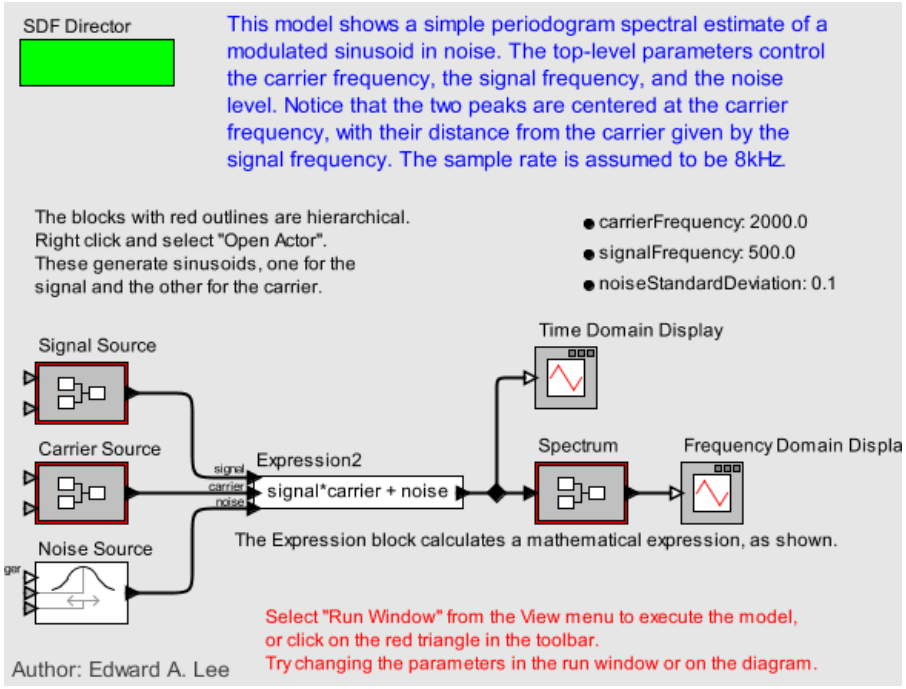
- Which model of computation to choose, depends on the use case
- Subsystems can be represented with different directors

➢ Representation of different domains in a single model:

  – Environment
  – Hardware
  – Software

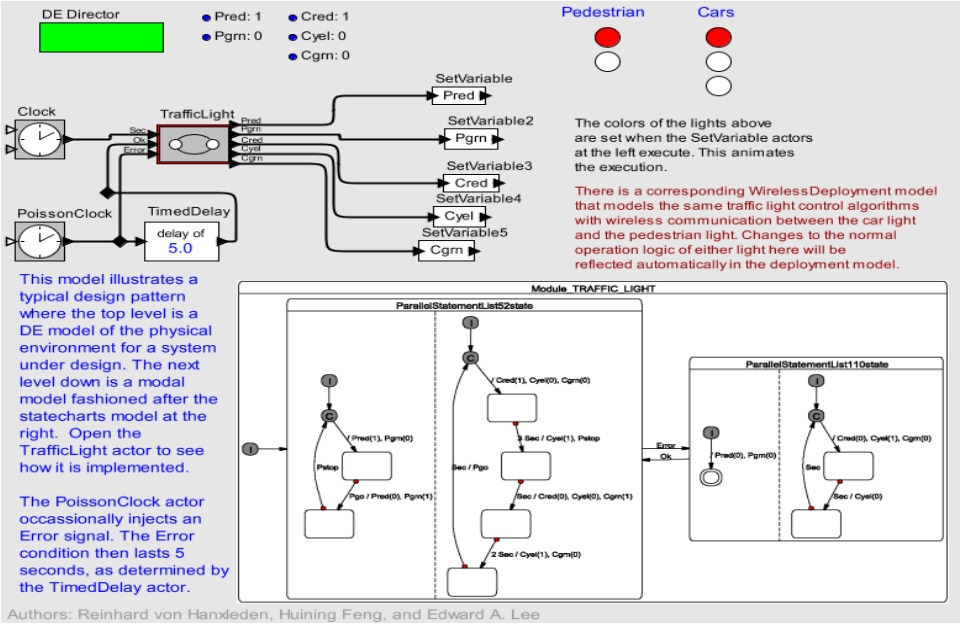
Example Ptolemy Model of Computation: Synchronuous Dataflow

- General principle:
  - Assumption: infinitely fast machine
  - Data is processed periodically
  - Data flow is executed once per period
- Advantages:
  - Static memory allocation
  - Static schedule
  - Dead locks are detectable
  - Runtime can be calculated
- Tools:
  - Matlab
  - Labview
  - **EasyLab**



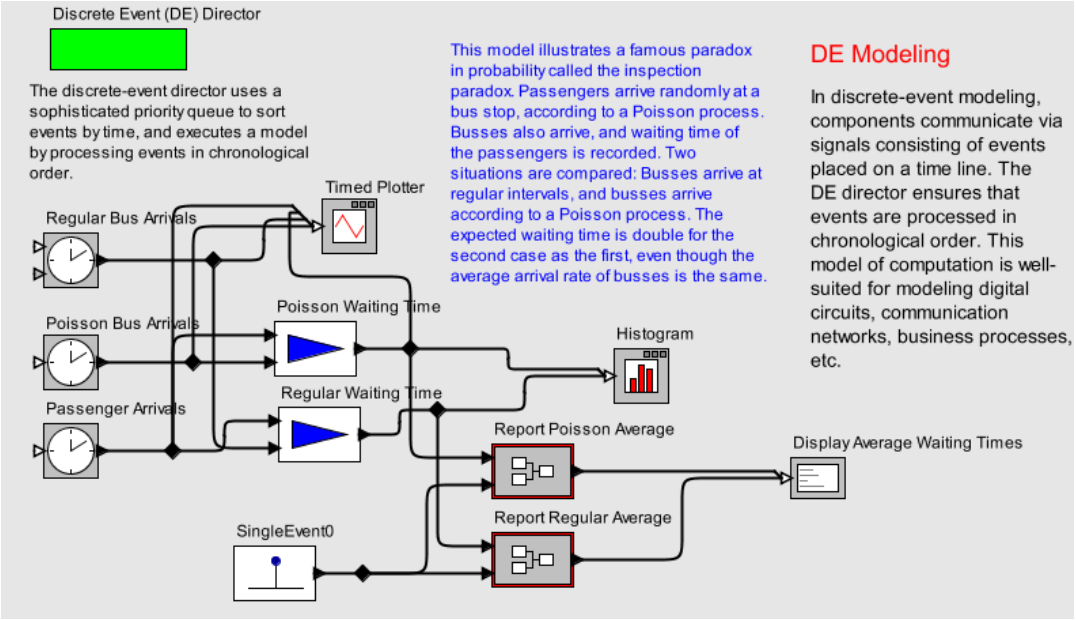
Example Ptolemy Model of Computation: Synchronous Reactive

- General principle:
  - Assumption: infinitely fast machine
  - Discrete Events (DE) are used periodically (Events do not have to occur each period)
  - One reaction per round
  - Often used with Finite State Machines
- Advantages:
  - Easy formal verification
- Tools:
  - Esterel Studio
  - SCADE/Lustre



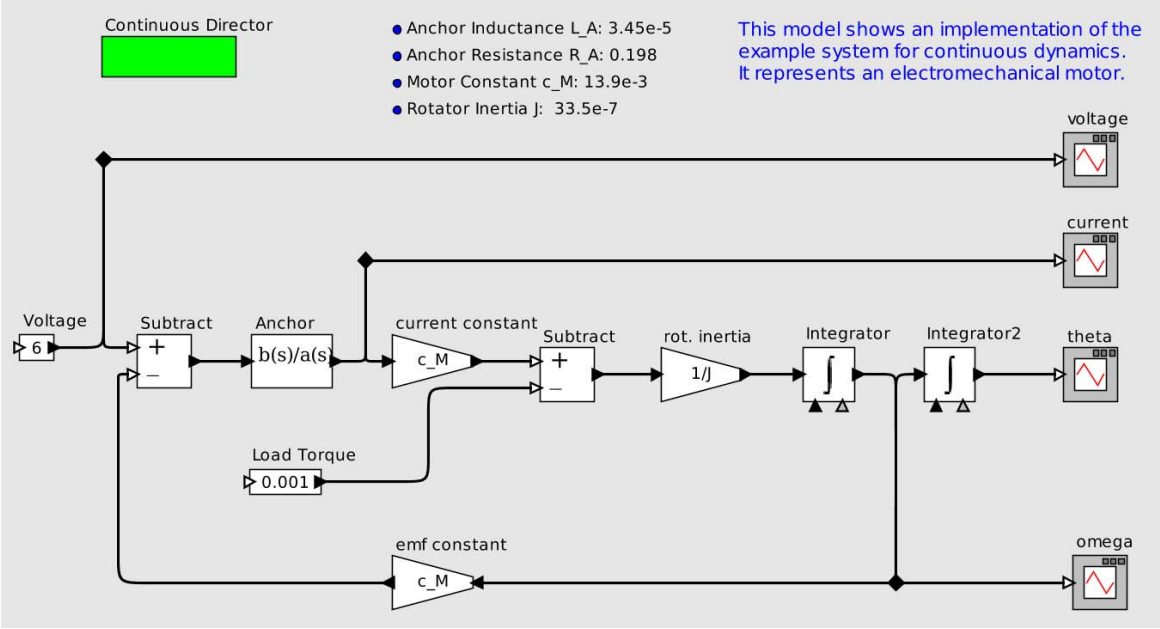
Example Ptolemy Model of Computation: Discrete Event

- General principle:
  - Communication through events
  - Each event has a time stamp and a value
- Usage:
  - Digital Hardware
  - Telecommunication
- Tools:
  - VHDL
  - Verilog



Example Ptolemy Model of Computation: Continuous Time

- General principle:
  - Continuous signals (actors represent ODEs)
- Usage:
  - Simulation
- Tools:
  - MATLAB/Simulink
  - Labview

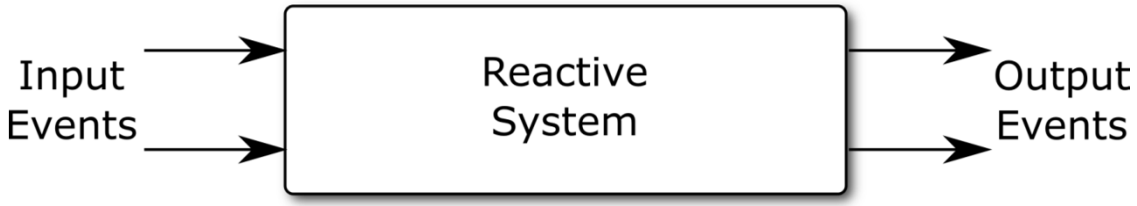


Tools – Esterel

- Esterel is actually more a programming language than a modeling language, however it uses the *Synchronous Reactive* model of computation
- Esterel was developed by Jean-Paul Marmorat and Jean-Paul Rigault to meet the challenges of real-time systems:
  - Expression of parallelism and preemption
  - Strict concept of timing
- G. Berry developed the formal semantics of Esterel
- There are code generators to generate e.g. sequential C, C++ Code:
  - In Esterel (parallel) programs are transformed into a ***single*** finite state machine
  - The FSM is converted into a program with a ***single*** process
  - ➢ Deterministic execution can be proven despite a parallel model
- Example: SCADE (a commercial tool that uses Esterel) was used to develop components for the Airbus A380.
- An Esterel compiler is freely available at http://www-sop.inria.fr/esterel.org/files/

Introduction to Esterel

- Esterel is a ***synchronous language***.
  These languages were developed to program reactive systems
  Other Examples:
  - Lustre
  - Signal
  - Statecharts
- ***Reactive Systems*** directly generate ***output reactions*** for ***input events***
  - ***Interactions*** with the environment are the main building blocks of the system
  - Physical time is replaced by a ***notion of order*** (of the occuring events)
  - Interactions with the environment (**macro steps)** consist of sub steps (micro steps).



Tools – Esterel – Determinism

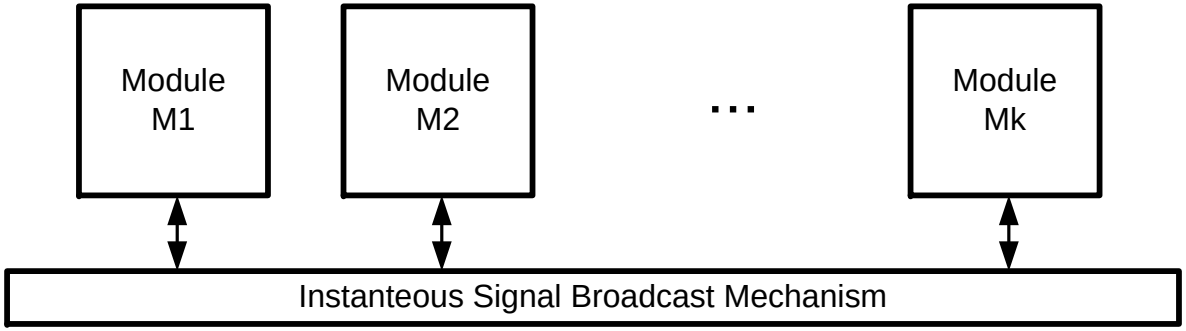
- Esterel is deterministic: a sequence of input events (even simultaneous ones) will always produce the same sequenc of output events

- Each Esterel instruction and construct is guaranteed to be deterministic. This is achieved by
  - the constraints the language puts on the designer
  - the compiler that is proven to produce deterministic code

- Determinism of the language majorly simplifies the verification of applications

Tools – Esterel – Basics

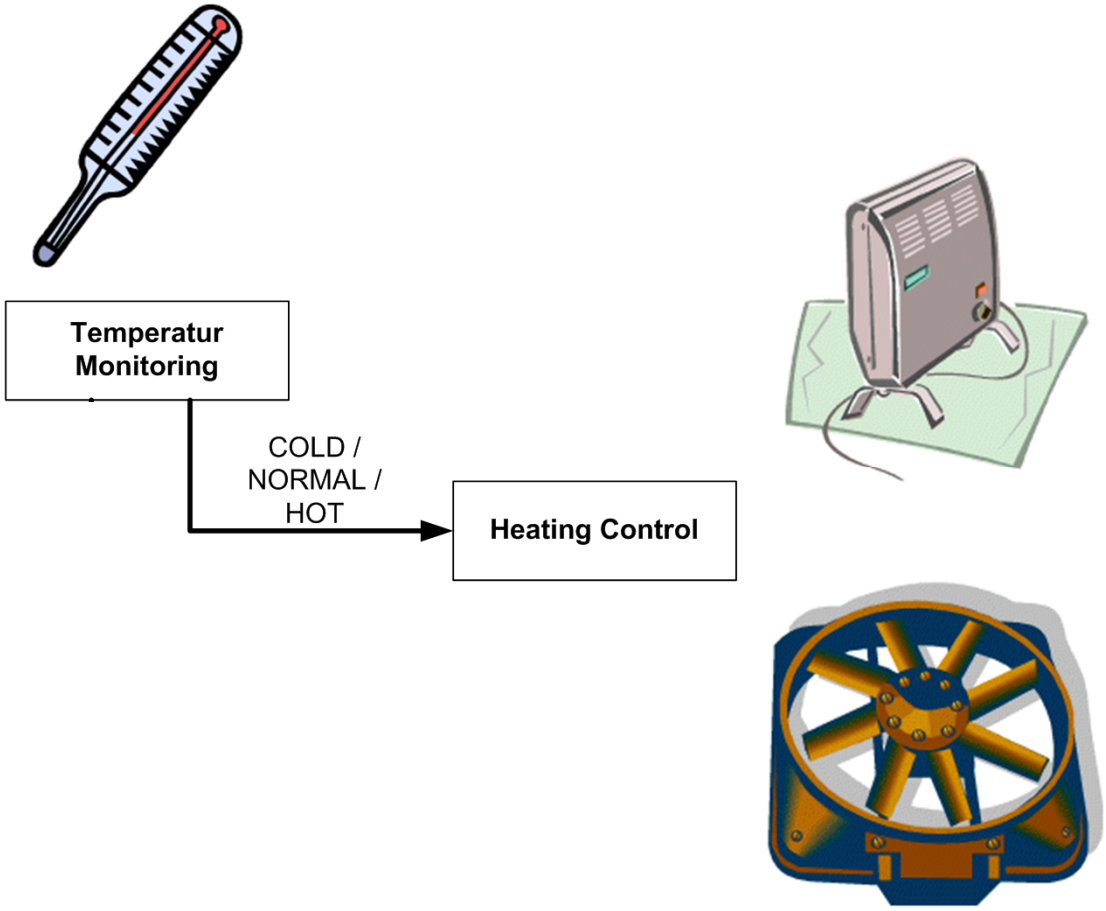
- Communication is achieved through signals and sensors
  - Sensors provide measurements; They always provide a value (independent of changes)
  - Signals fire whenever there is an event; This can be used for I/O operations
- There are two kinds of signals
  - *Non-valued* signals (signal is either present or not)
  - *Valued* signals (signal contains a value that can be used by the consumer)
- Esterel programs can be divided into modules
- Communication between modules is achieved through a broadcast mechanism



Tools – Esterel – Basics

- Signal statements
  - ***emit***: Sends a signal
  - ***await***: Waits until the specified signal is present
  - ***present***: Tests if a signal is present
- Execution of a module can be aborted by calling `abort`:
  - Syntax: `abort Body when Exit_Condition`
- Periodic execution can be achieved by the `every` statement:
  - Syntax: `every Occurrence do Body end every`
- Composition of instructions:
  - Blocks of commands (Modules) can be executed ***sequentially*** or in ***parallel***.
  - Blocks of commands (Modules) can be executed ***repeadtedly***.
  - Blocks of commands (Modules) can be ***interrupted***.

Tools – Esterel – Example: Temperature Control



Tools – Esterel – Example: Temperature Control

- Goal: Temperature control (operating range: $5 - 40°C$) with a simple controller
- Operating mode:
  - Whenever the temperature comes to be close to one of the limits, the heater or ventilation is turned on, respectively.
  - If the temperature stays high (or low), the ventilation (or heating) is set to strong mode
  - When control reaches the normal temperature range, the ventilation or heating is turned off
  - If the temperature leaves the operating range, the module sends an abortion signal

Tools – Esterel – Example: Temperature Control

```
module TemperatureController:
input TEMP: integer, SAMPLE_TIME, DELTA_T;
output HEATER_ON, HEATER_ON_STRONG,
       HEATER_OFF,VENTILATOR_ON, VENTILATOR_OFF,
       VENTILATOR_ON_STRONG, SIG_ABORT;

relation SAMPLE_TIME => TEMP;

  signal COLD, NORMAL, HOT in
    every SAMPLE_TIME do
      await immediate TEMP;
      if  ?TEMP<5 or ?TEMP>40 then emit SIG_ABORT
      elseif ?TEMP>=35 then emit HOT
      elseif ?TEMP<=10 then emit COLD
      else emit NORMAL
      end if
    end every
    ||
    loop
        await
          case COLD do
            emit HEATER_ON;
            abort
              await NORMAL;
              emit HEATER_OFF;
            when DELTA_T do
              emit HEATER_ON_STRONG;
              await NORMAL;
              emit HEATER_OFF;
            end abort
          case HOT do
              %...
        end await
    end loop
  end signal
end module
```

Tools – MATLAB/Simulink

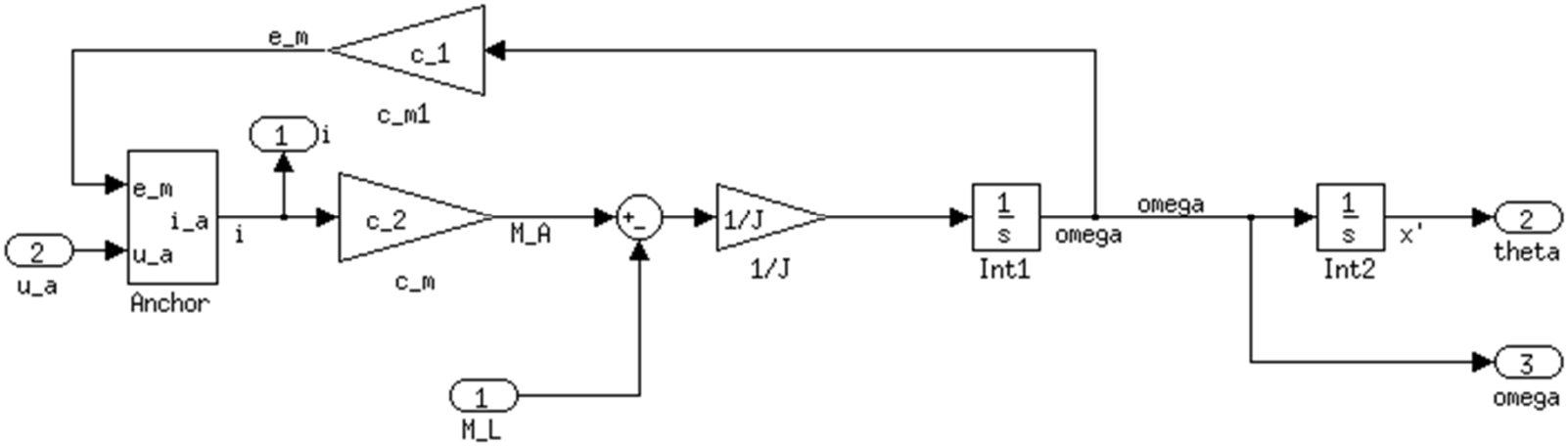
- Synchronous block diagram environment
- Models of computation:
  - Continuous dynamics
  - Discrete dynamics
  - Extensions through toolboxes available
- Features:
  - System-level design
  - Simulation
  - Extendable by MATLAB and C/C++ algorithms
  - Extendable multitarget Code generation

Tools – MATLAB/Simulink

- Usage:
  - Simulation of physical processes
  - Controller design
  - Prototyping (e.g. dSpace)
  - Code generation (Real-time workshop toolbox)
  - Verification and Validation (toolbox)
  - HIL/SIL

www.dspace.com

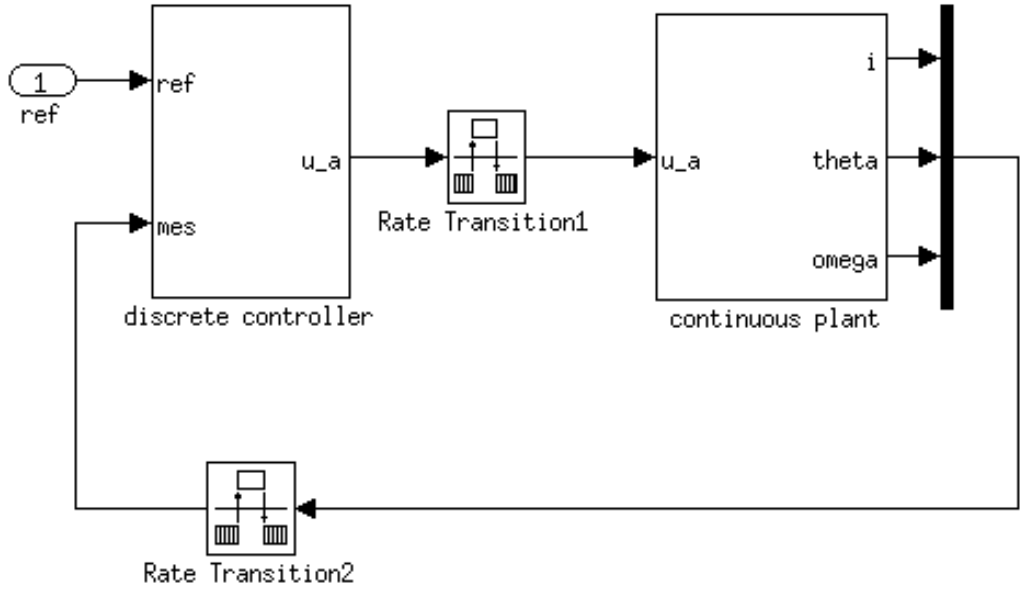
Tools – MATLAB/Simulink – Example



- Simulation of continuous dynamic systems (Example of the DC motor model),

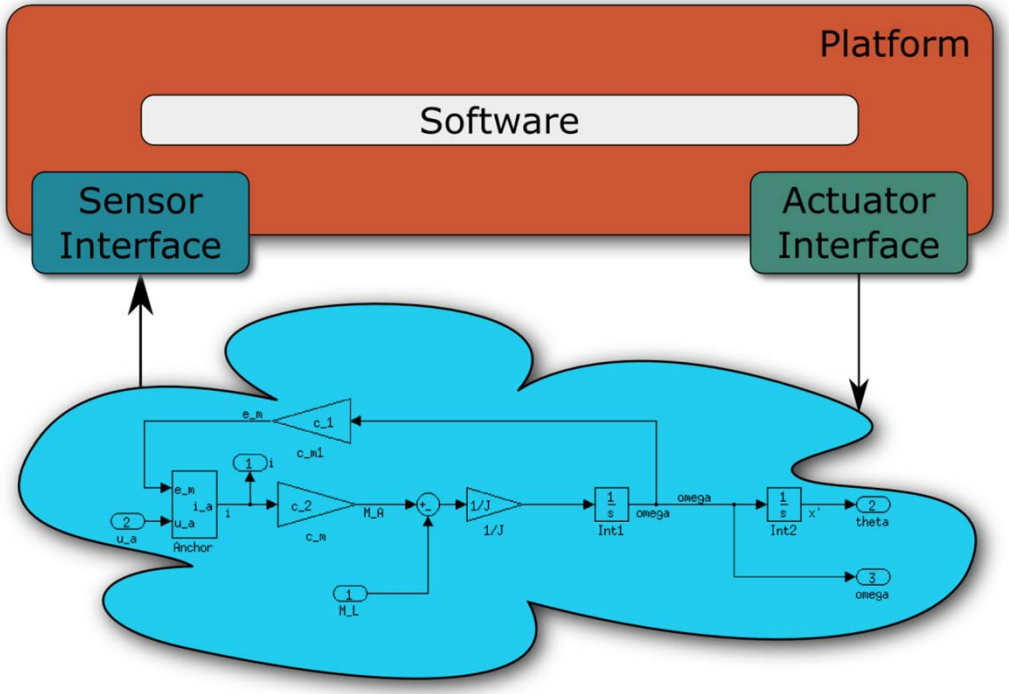
- Models can be built and extended quickly
- Simulation with different ODE solvers

Tools – MATLAB/Simulink – Example



- Controller design & test
- Code generation of controller part for different platforms

Tools – MATLAB/Simulink – HIL/SIL



- Hardware in the Loop (HIL)
- Software in the Loop (SIL)

➢ Embedding the embedded system (hardware or software) into a simulation for testing purposes