Hybrid Systems:
From Models to Code

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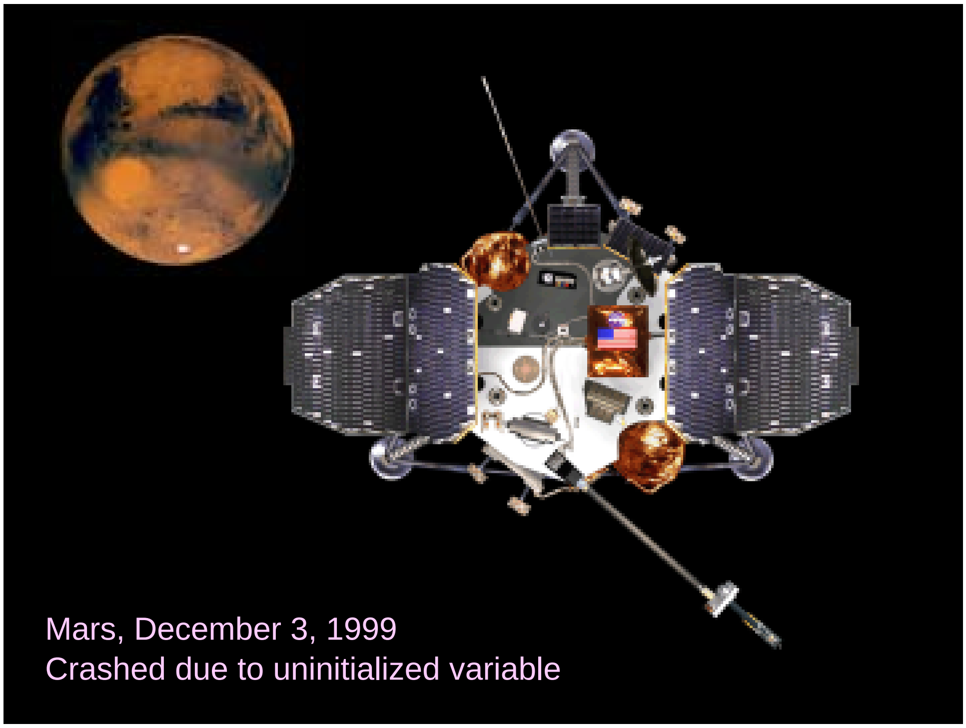
UC Berkeley: Chess
Vanderbilt University: ISIS
University of Memphis: MSI

Foundations of Hybrid and Embedded Software Systems


Mars, December 3, 1999
Crashed due to uninitialized variable


BOEING 777-300
$4 billion development effort
40-50% system integration & validation cost

Sources of Complexity

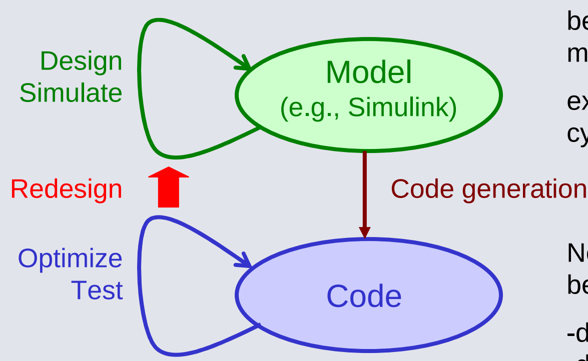
-concurrency

-real time

-heterogeneity

A **hybrid system** consists of multiple continuous (physical) and discrete (computational) components that interact with each other in real time.

Embedded Software Design: Current State



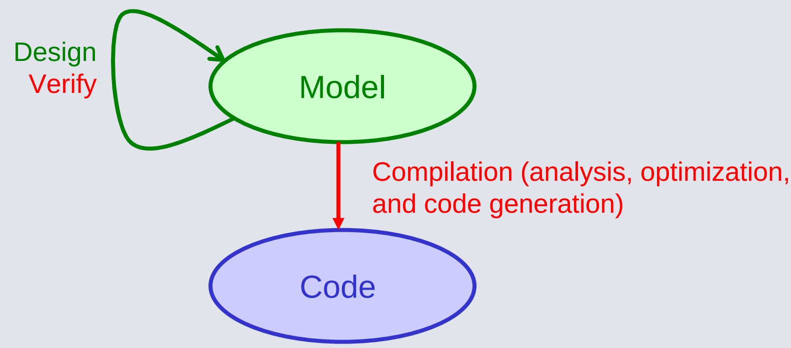
No formal connection between requirements, model, and resources:

expensive development cycle iterates all stages

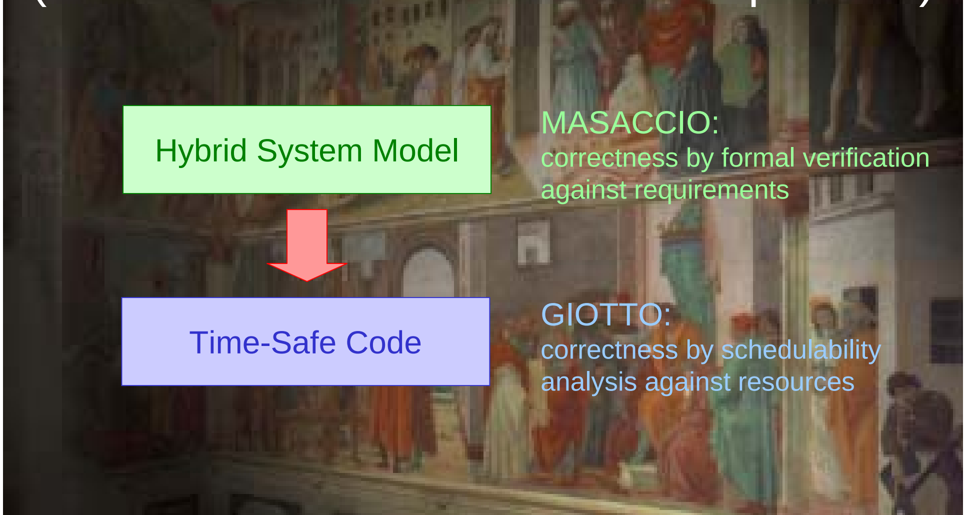
No exact correspondence between model and code:

-difficult to upgrade code
-difficult to reuse code

Embedded Software Design: Our Vision

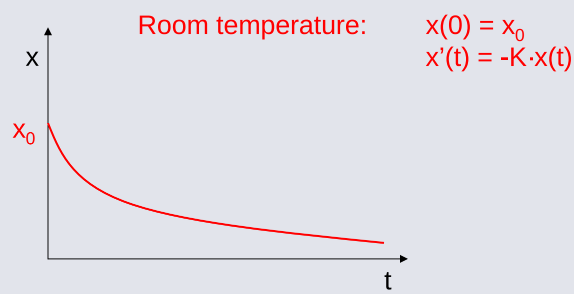


The FRESCO Project
(Formal Real-Time Software Components)



Continuous (Euclidean) Systems

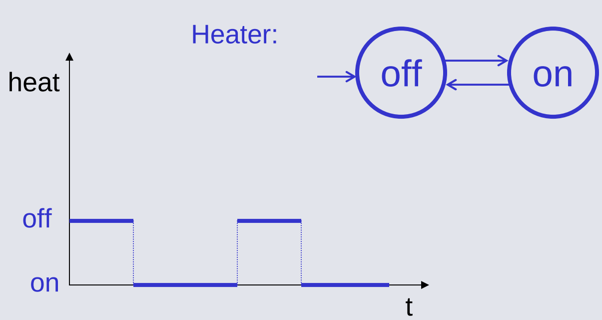
State space: R^n
Dynamics: initial condition + differential equations



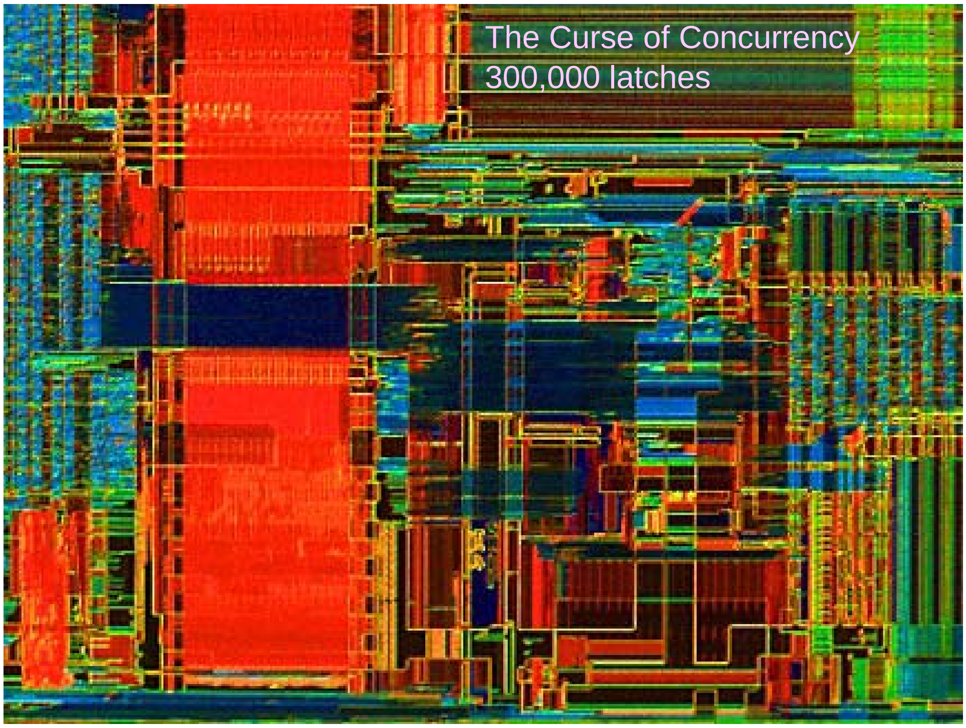
Analytic complexity.

Discrete (Boolean) Systems

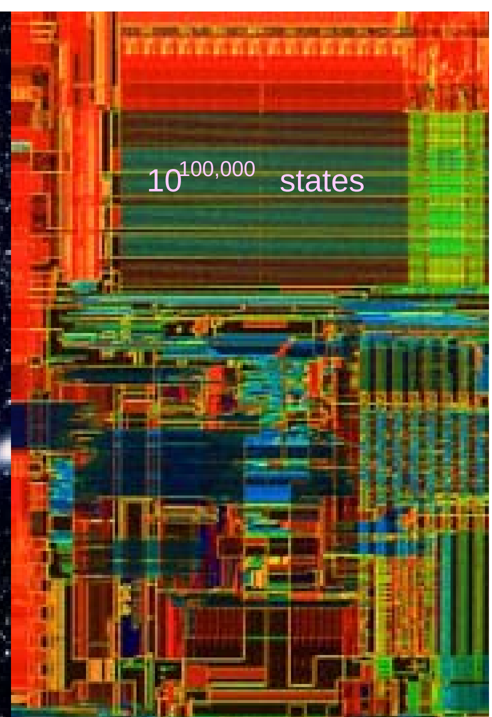
State space: B^m
Dynamics: initial condition + transition relation



Combinatorial complexity.


The Curse of Concurrency
300,000 latches

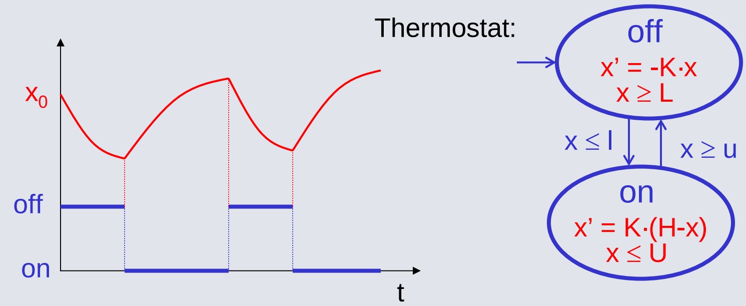

10^{11} stars


$10^{100,000}$ states

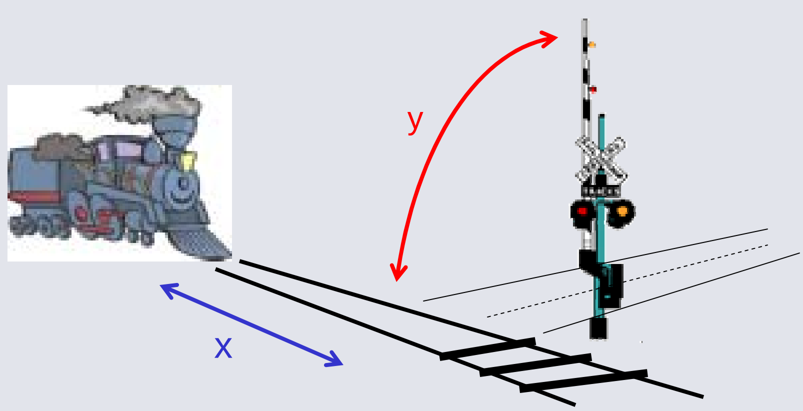
Hybrid Systems

State space: $B^m \times R^n$

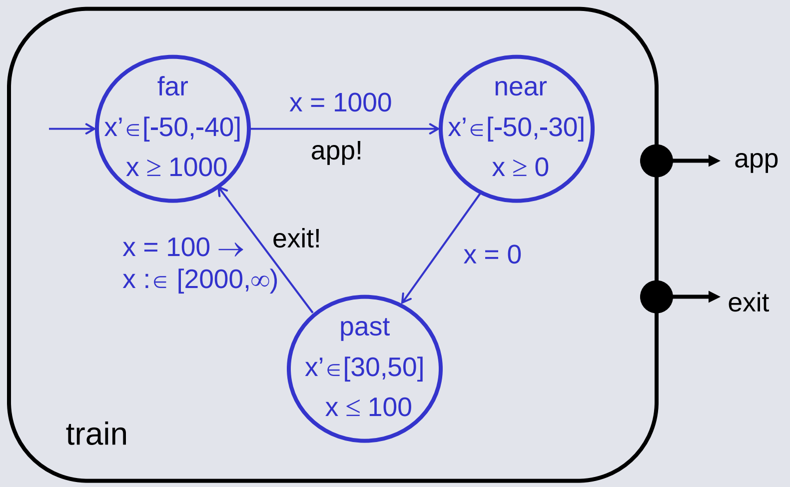
Dynamics: initial condition + transition relation + differential equations



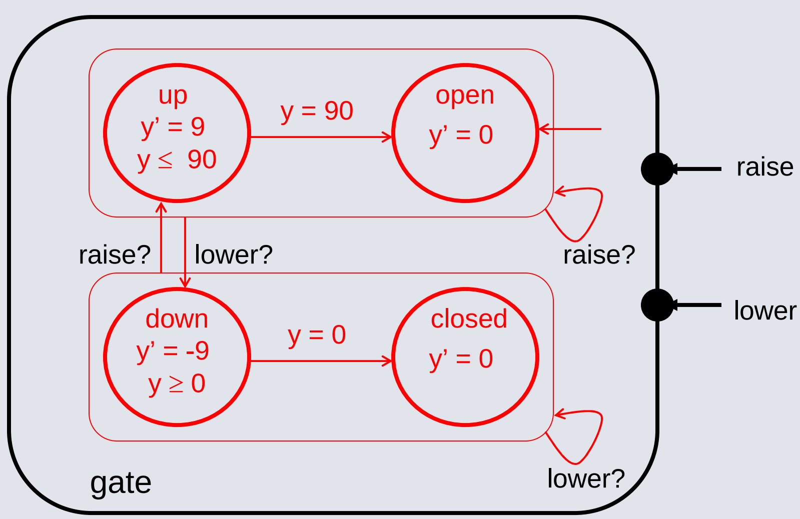
Hybrid Automata



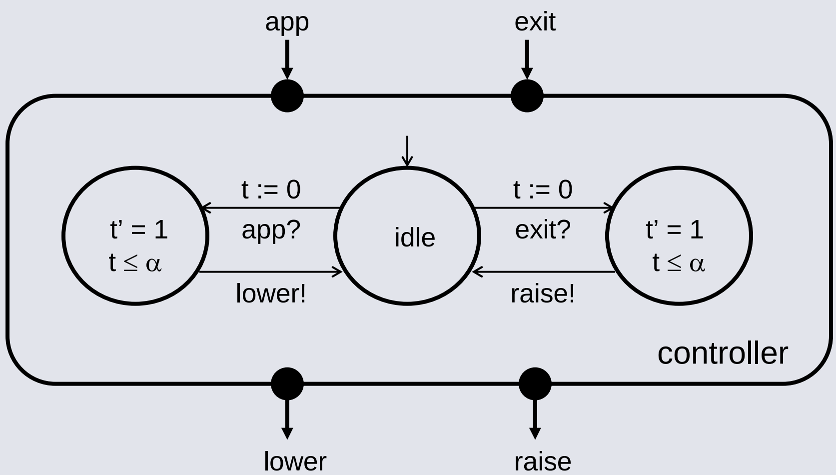
Hybrid Automata



Hybrid Automata



Hybrid Automata



Requirements

Safety: $\forall\Box\ (x \leq 10 \Rightarrow loc[gate] = closed)$

Liveness: $\forall\Box\ \forall\Diamond\ (loc[gate] = open)$

Real time: $\forall\Box\ z := 0.\ (z' = 1 \Rightarrow$
$\forall\Diamond\ (loc[gate] = open \wedge z \leq 60))$

Verification and failure analysis by model checking (e.g., HyTech).

Two Problems with Hybrid Automata

1. Scalability

Possible solutions:

- hierarchy (MASACCIO)
- assume-guarantee decomposition (interfaces)

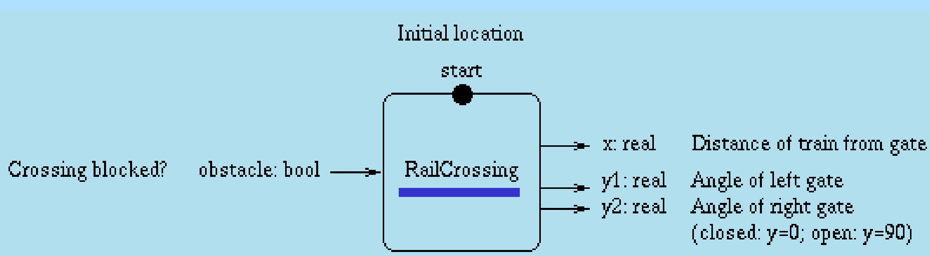
2. Robustness

Possible solutions:

- ε-variability
- discounted future

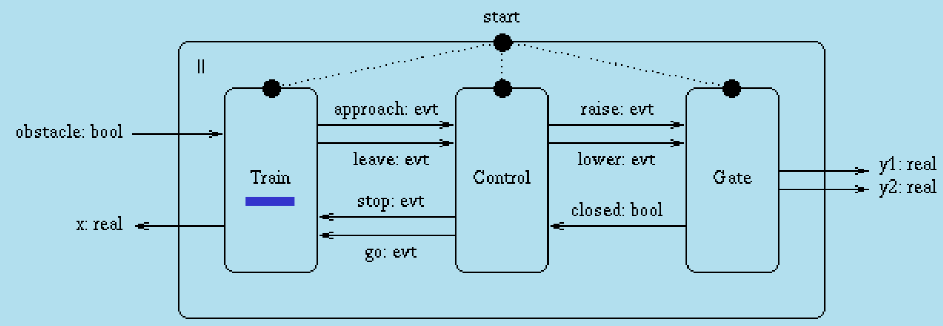
MASACCIO

Hierarchical Hybrid Automata



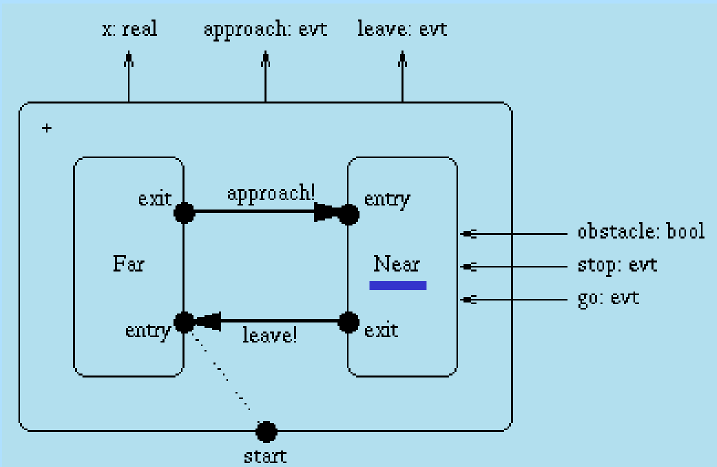
MASACCIO

Hierarchical Hybrid Automata



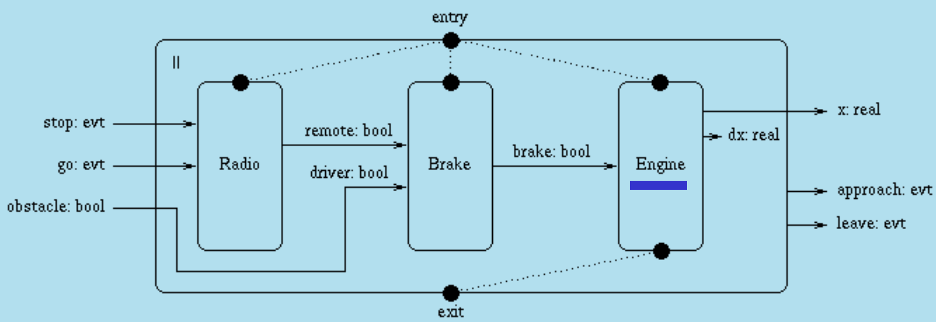
MASACCIO

Hierarchical Hybrid Automata

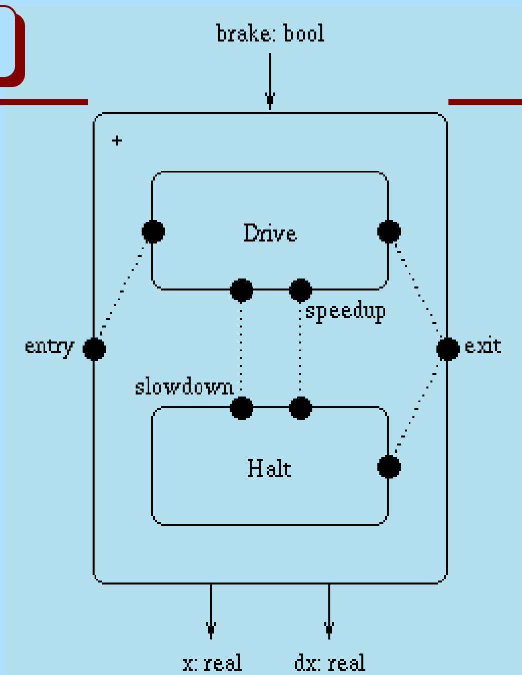


MASACCIO

Hierarchical Hybrid Automata



MASACCIO



Two Problems with Hybrid Automata

1. Scalability

   Possible solutions:
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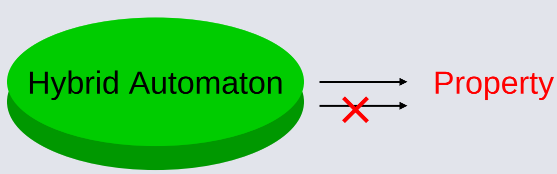
   - assume-guarantee decomposition (interfaces)

2. Robustness

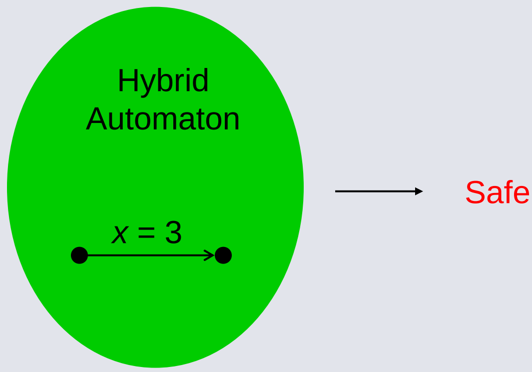
   Possible solutions:
   - ε-variability
   - discounted future

The Robustness Problem

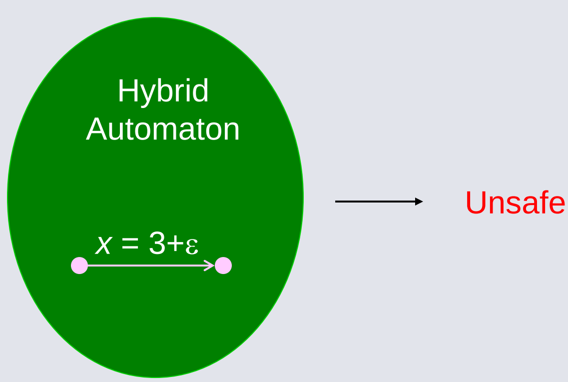


slightly perturbed automaton

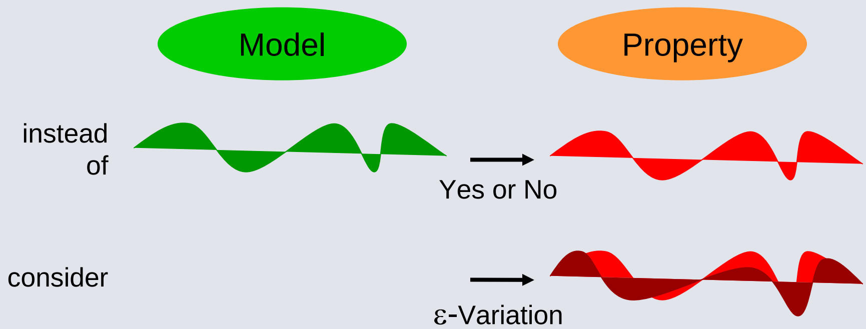
The Robustness Problem



The Robustness Problem



A Possible Solution of the Robustness Problem: Metrics on Traces



A More Radical Solution of the Robustness Problem: Discounting the Future

value(Model,Property): States → {Yes, No}

⇓

value(Model,Property): States → R

A More Radical Solution of the Robustness Problem: Discounting the Future

value(Model,Property): States $\rightarrow$ {Yes, No}

value(m,$\Diamond T$) = $\mu X.\ (T \vee \mathrm{pre}(X))$

discountedValue(Model,Property): States $\rightarrow$ R

discountedValue(m,$\Diamond T$) = $\mu X.\ \max(T, \lambda\cdot\mathrm{pre}(X))$

discount factor $0<\lambda<1$

A More Radical Solution of the Robustness Problem: Discounting the Future

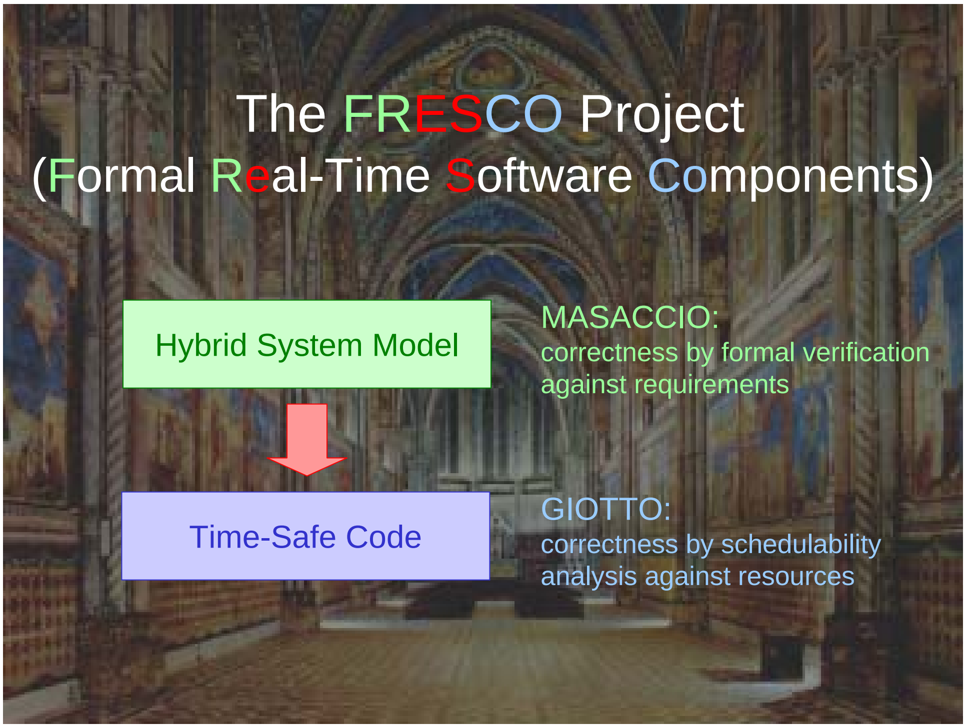
Robustness Theorem:

If discountedBisimilarity(m_1,m_2) > 1 - ε,
then |discountedValue(m_1,p) - discountedValue(m_2,p)| < $f(\varepsilon)$.

Further Advantages of Discounting:

-approximability because of geometric convergence (avoids non-termination of verification algorithms)

-applies also to probabilistic systems and to games (enables reasoning under uncertainty and control)



The History of Computer Science: Lifting the Level of Abstraction

High-level languages: Programming to the application — Requirements focused code

↓ Compilation

The "assembly age": Programming to the platform — Resource focused code

-Traditional high-level languages abstract time.

-This abstraction is unsuitable for real-time applications, which are still programmed in terms of platform time ("priority tweaking").

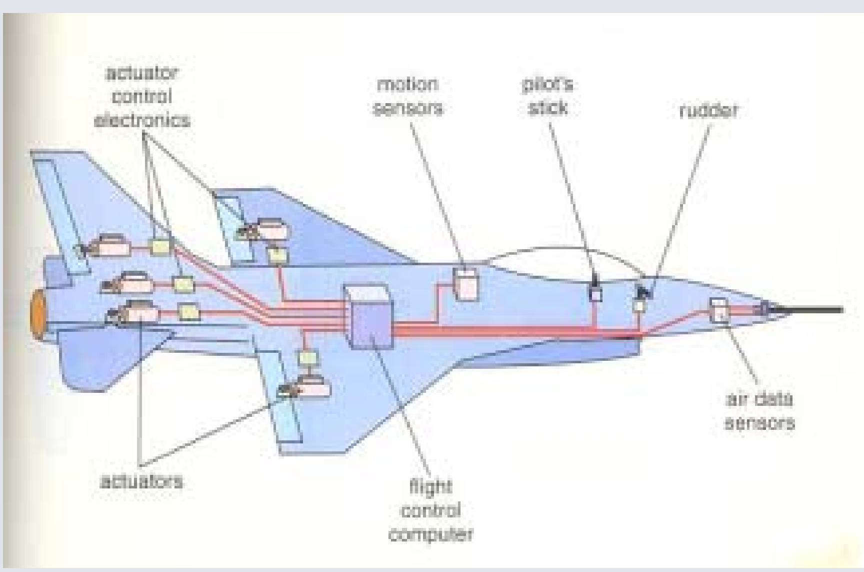
-GIOTTO: Real-time programming in terms of application time.

GIOTTO

Time-Triggered Programming

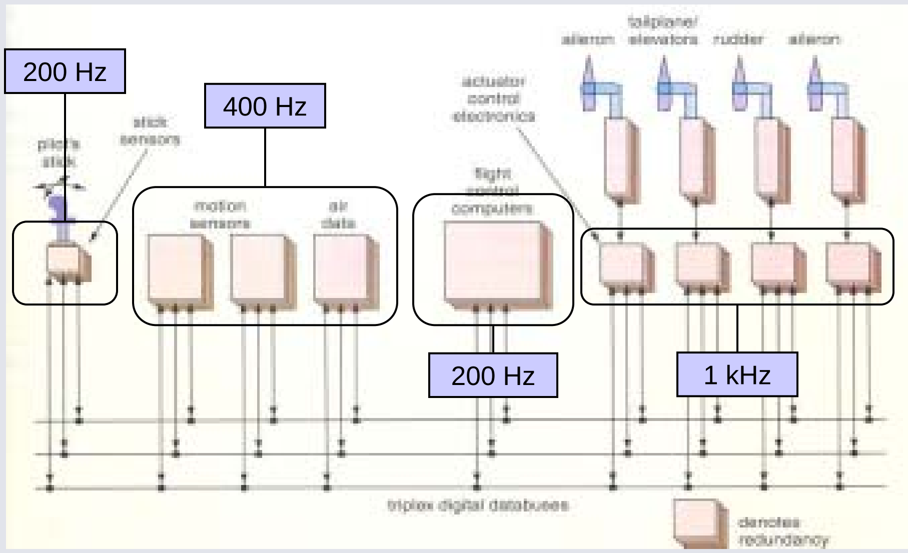
GIOTTO

Time-Triggered Programming



GIOTTO

Time-Triggered Programming



GIOTTO

Time-Triggered Programming

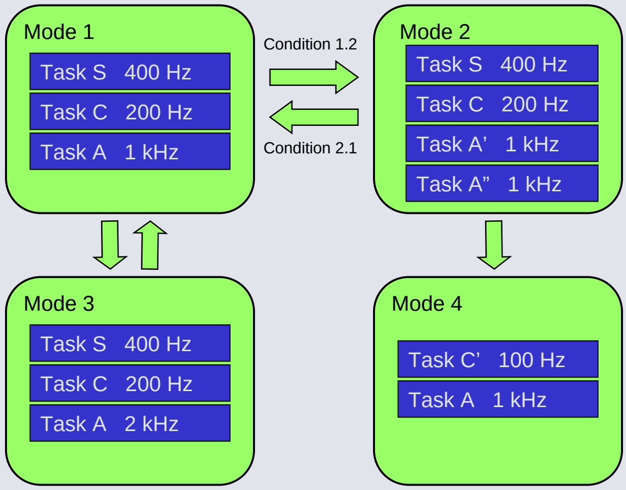
1. Concurrent Periodic Tasks:

-sensing
-control law computation
-actuating

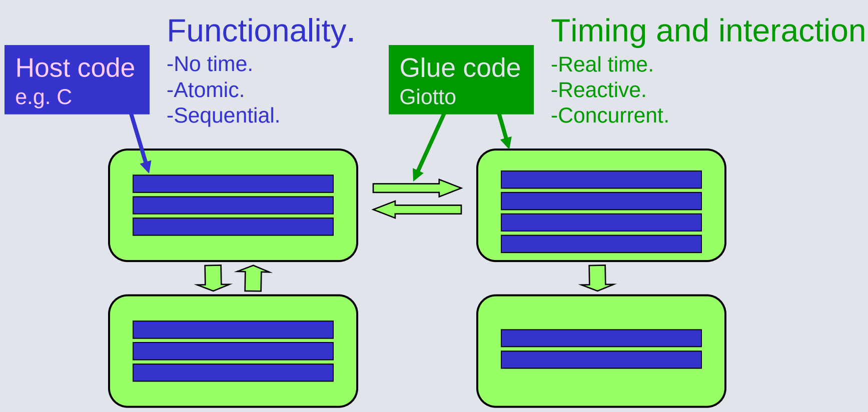
2. Multiple Modes of Operation:

-navigational modes (autopilot, manual, etc.)
-maneuver modes (taxi, takeoff, cruise, etc.)
-degraded modes (sensor, actuator, CPU failures)

Time-Triggered Programming



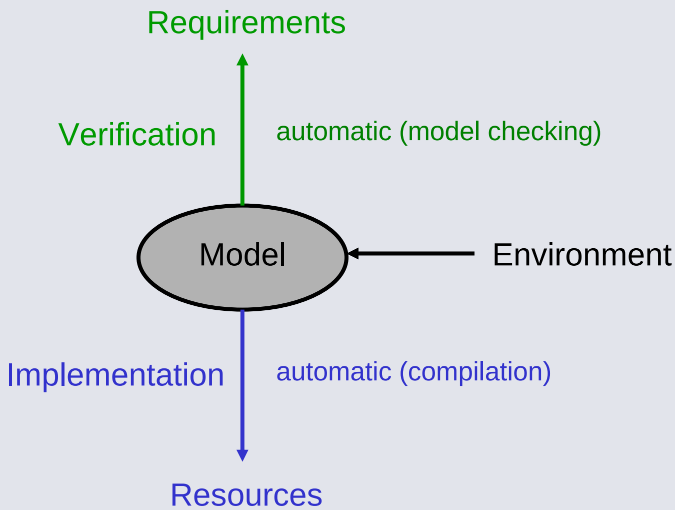
Separation of Concerns



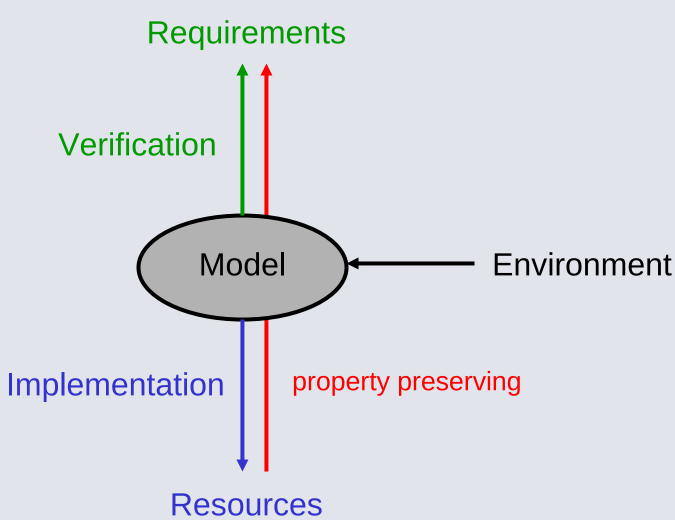
This kind of software is reasonably well understood.

The software complexity lies in the glue code.

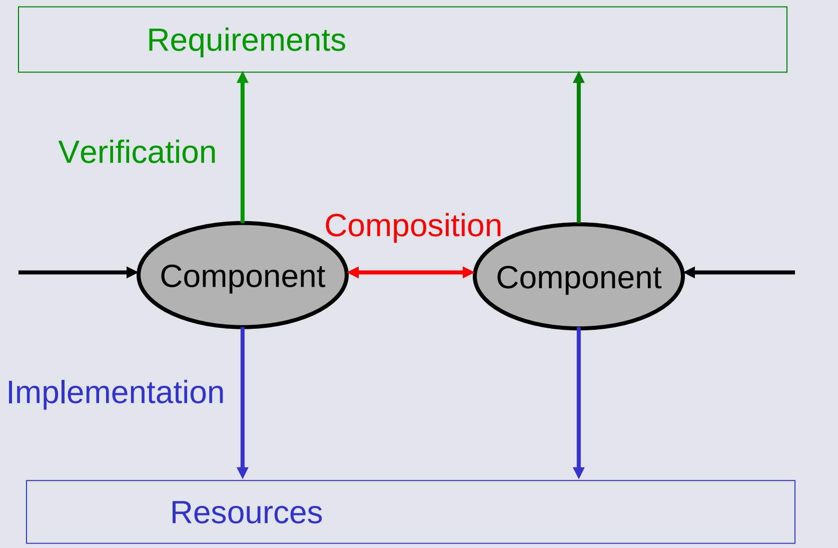
Two Opposing Forces



Two Opposing Forces



Two Opposing Forces



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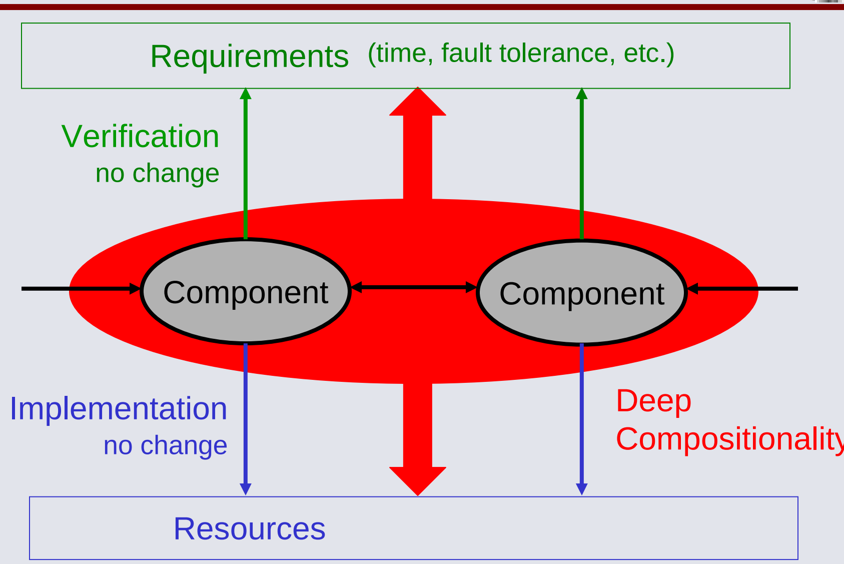
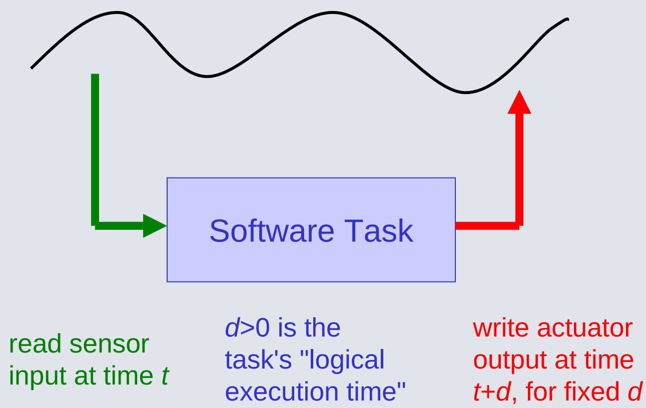


Achieving Verifiability and Compositionality in GIOTTO: The FLET (Fixed Logical Execution Time) Assumption

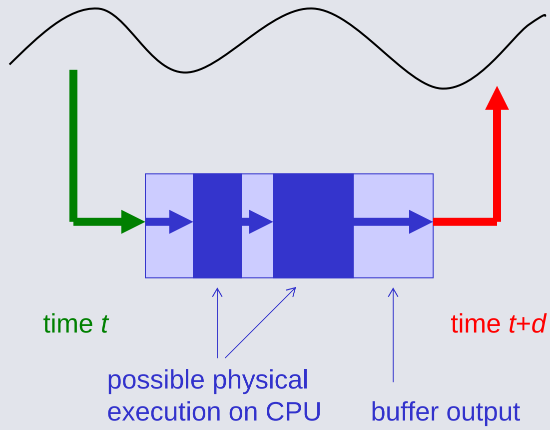


Embedded Programming in GIOTTO

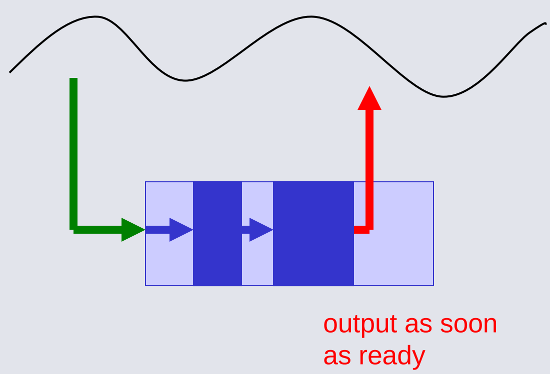
The programmer specifies sample rate *d* and jitter *j* to solve the control problem at hand.

The compiler ensures that *d* and *j* are met on a given platform (hardware resources and performance); otherwise it rejects the program.

Implementing the FLET Assumption



Contrast the FLET with Standard Practice



Advantages of the FLET and GIOTTO

-predictable timing and value behavior
(no internal race conditions, minimal jitter)

-portable, composable code (as long as the platform offers sufficient performance)

Research Agenda

From Hybrid Models

-robust hybrid models (tube topologies, discounting)

-model checking for hierarchical and stochastic hybrid models

-multi-aspect assume-guarantee decomposition of hybrid models (interface theories for time, resources, fault tolerance)

To Embedded Code

-distributed schedulability analysis and code generation

-on-line code modification and fault tolerance

Credits

Scalable and Robust Hybrid Systems: Luca de Alfaro, Arkadeb Ghosal, Marius Minea, Vinayak Prabhu, Marcin Jurdzinski, Rupak Majumdar

GIOTTO: Ben Horowitz, Christoph Kirsch, Rupak Majumdar, Slobodan Matic, Marco Sanvido

Collaborators of the FRESCO Project

-Alex Aiken on time-safety analysis of embedded code

-Karl Hedrick on Giotto implementation of electronic throttle control

-Edward Lee on Giotto modeling and code generation in Ptolemy

-Edward Lee on rich interface theories as type theories for component interaction

-George Necula on model checking device drivers

-George Necula on scheduler-carrying embedded code

-Alberto Sangiovanni-Vincentelli on synthesis of protocol converters from interfaces

-Alberto Sangiovanni-Vincentelli and Shankar Sastry on platform-based design of a helicopter flight control system using Giotto

-Shankar Sastry on hybrid automata