Component Architectures for Time-Sensitive Systems

Edward A. Lee

Robert S. Pepper Distinguished Professor and

Workshop on Foundations and Applications of Component-based Design (WFCD'2008)

With thanks to Thomas Huning Feng, Yang Zhao, and Ye (Rachel) Zhou

Atlanta, Georgia, USA

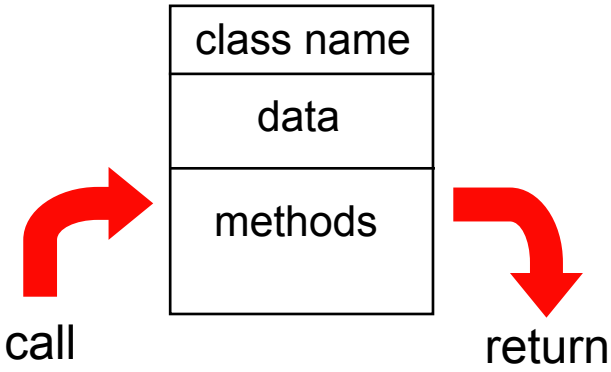
October 19, 2008

Abstract

Cyber-Physical Systems (CPS) are integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. The computational and networking elements of such systems require predictable and repeatable temporal behavior, something quite difficult to achieve reliably and portably with today's technology. Most critically, software systems speak about the passage of time only very indirectly and in non-compositional ways. This talk examines potential solutions that introduce temporal semantics in a software component architecture. We describe a model of computation called Ptides that facilitates the definition and construction of distributed time-sensitive systems.

Object Oriented vs. Actor Oriented

The established: Object-oriented:

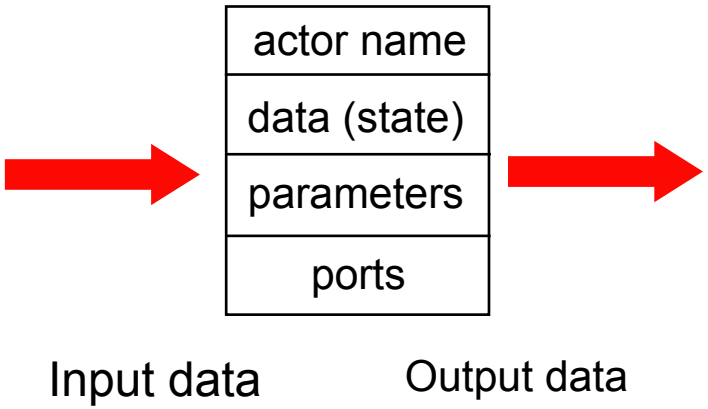


What flows through an object is sequential control

Things happen to objects

The alternative: Actor oriented:

Actors make things happen



What flows through an object is evolving data

Some Actor-Oriented Influences

- BIP [Basu, Bozga, Sifakis 2006]
- Colif [Jerraya et al. 2001]
- Esterel [Berry et al. 1992]
- ForSyDe [Sander, Jantsch 2004]
- FunState [Thiele, Ernst, Teich, et al. 2001]
- Giotto [Henzinger et al. 2001]
- HetSC [Herrera, Villar 2006]
- LabVIEW [Kodosky et al. 1986]
- Lustre [Halbwachs, Caspi et al. 1991]
- Metropolis [Goessler, Sangionvanni-Vincentelli et al. 2002]
- Model Integrated Computing [Sztipanovits, Karsai, et al. 1997]
- Ptolemy Classic [Buck, Ha, Messerschmitt, Lee et al. 1994]
- Ptolemy II [Eker, Janneck, Lee, et al. 2003]
- RTComposer [Alur, Weiss 2008]
- SCADE [Berry et al. 2003]
- SDL [Various, 1990s]
- Signal [Benveniste, Le Guernic 1990]
- Simulink [Ciolfi et al., 1990s]
- Statecharts [Harel 1987]

My Agenda

I will show a particular approach to the design of concurrent and distributed time-sensitive systems that is an actor-oriented component technology.

The approach is called PTIDES (pronounced “tides”), for Programming Temporally Integrated Distributed Embedded Systems.

[1] Y. Zhao, E. A. Lee, and J. Liu, "A Programming Model for Time-Synchronized Distributed Real-Time Systems," in Real-Time and Embedded Technology and Applications Symposium (RTAS), Bellevue, WA, USA, 2007.

[2] T. H. Feng, E. A. Lee, H. D. Patel, and J. Zou, "Toward an Effective Execution Policy for Distributed Real-Time Embedded Systems," in 14th IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), St. Louis, MO, USA, 2008.

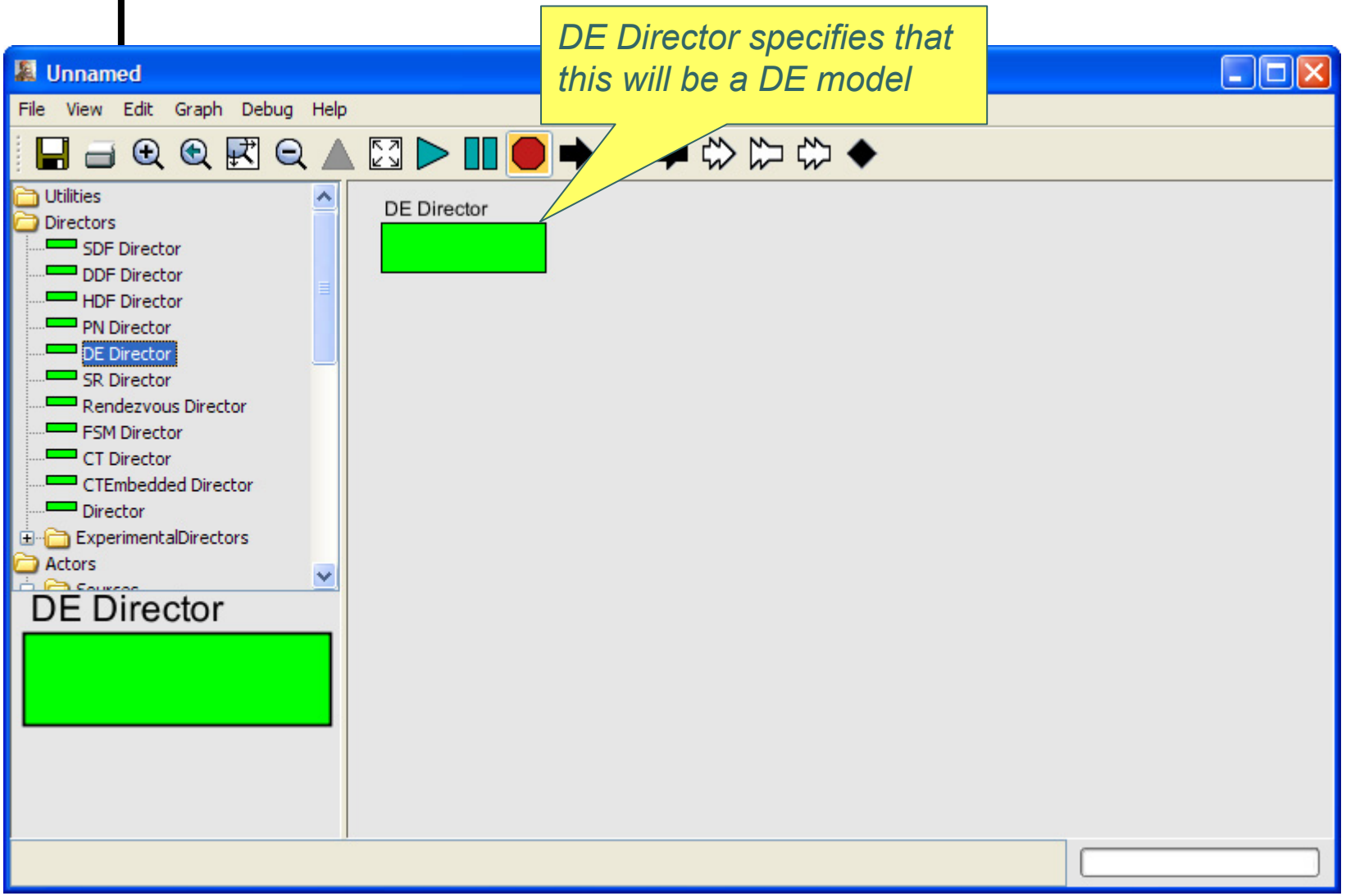
Our Approach is based on Discrete Events (DE)

- Concurrent actors
- Exchange time-stamped messages

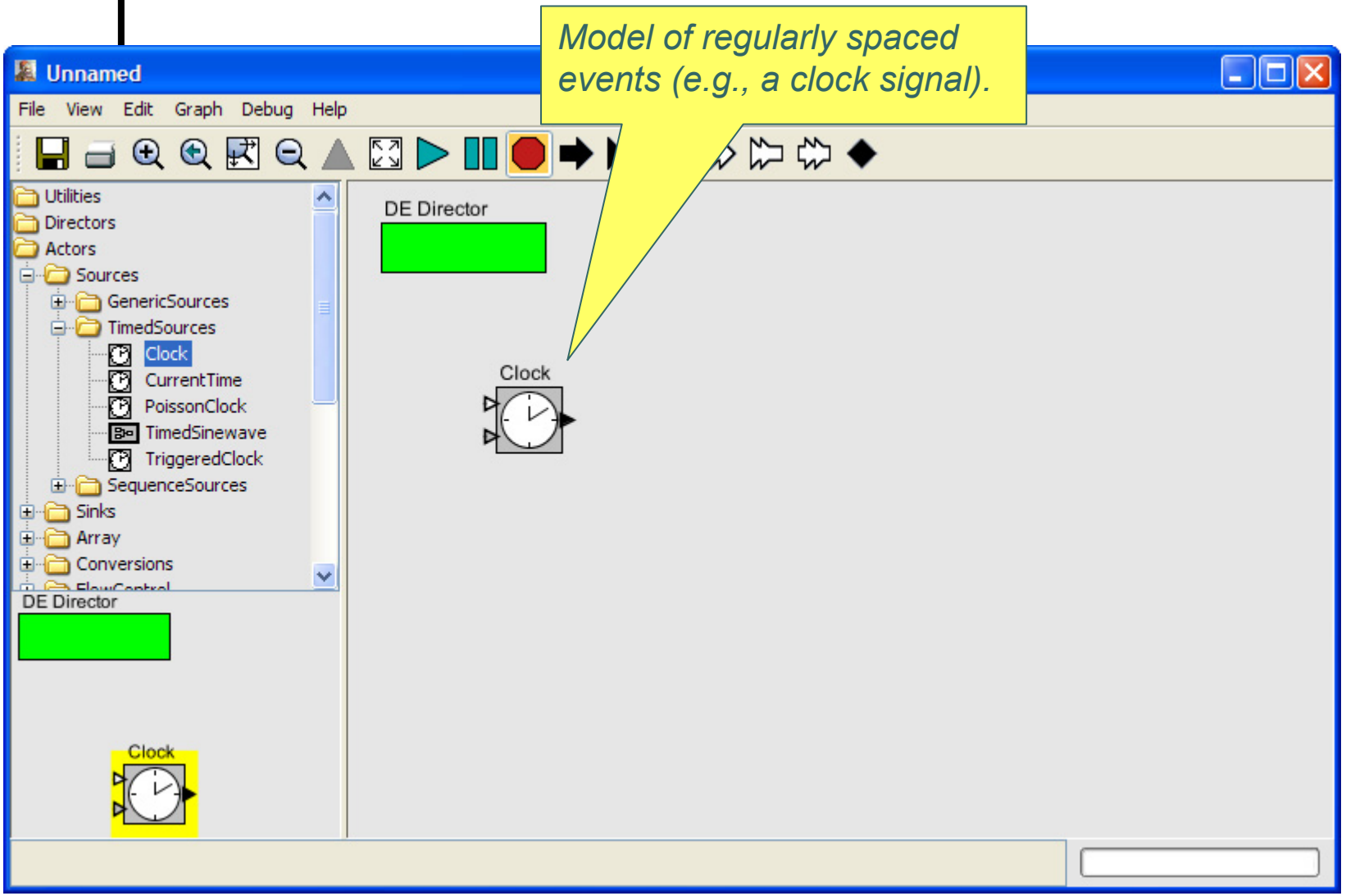
A correct execution is one where every actor reacts to input events in time-stamp order.

Time stamps are in “model time,” which typically bears no relationship to “real time” (wall-clock time).

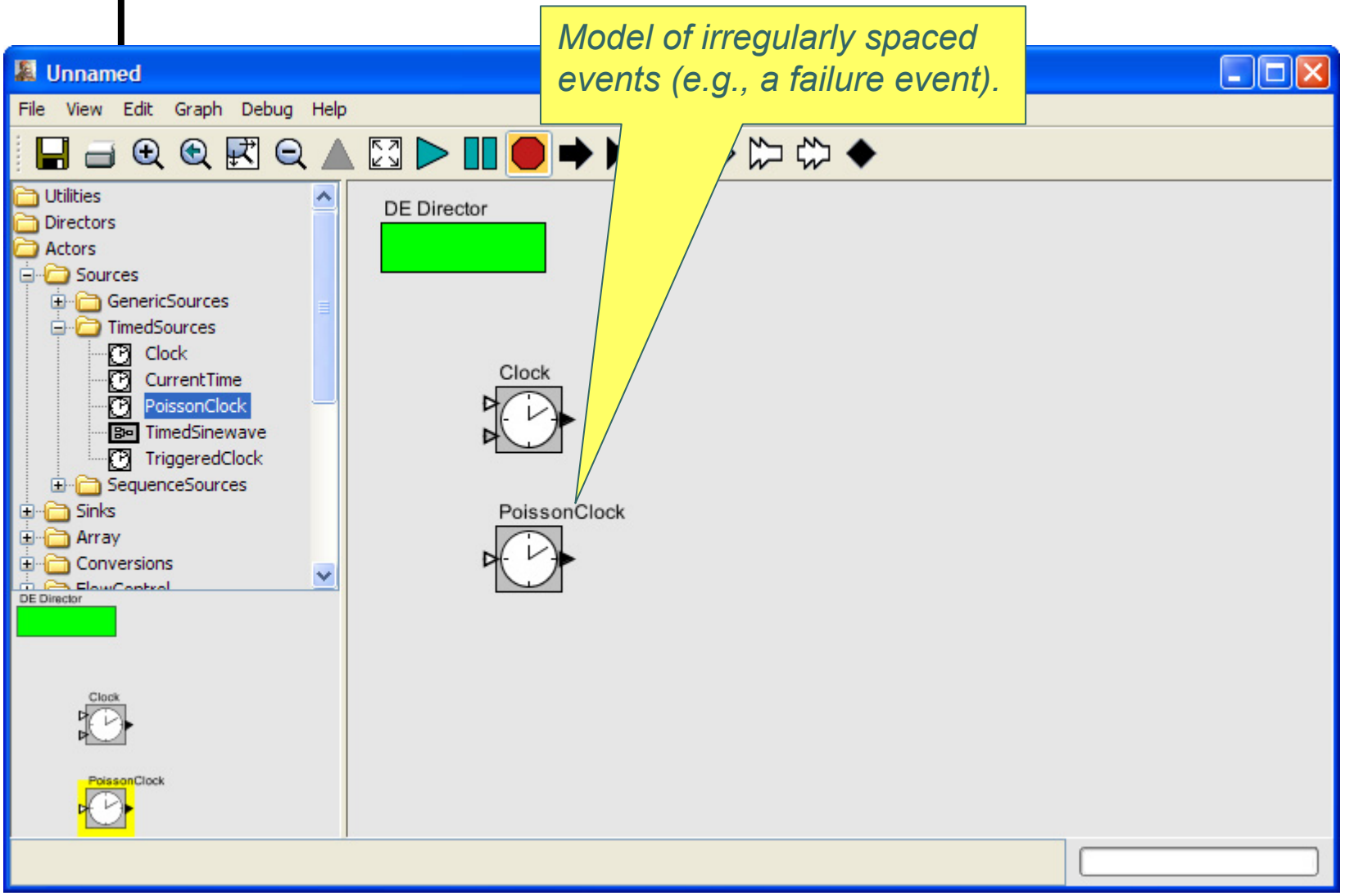
Example DE Model (in Ptolemy II)



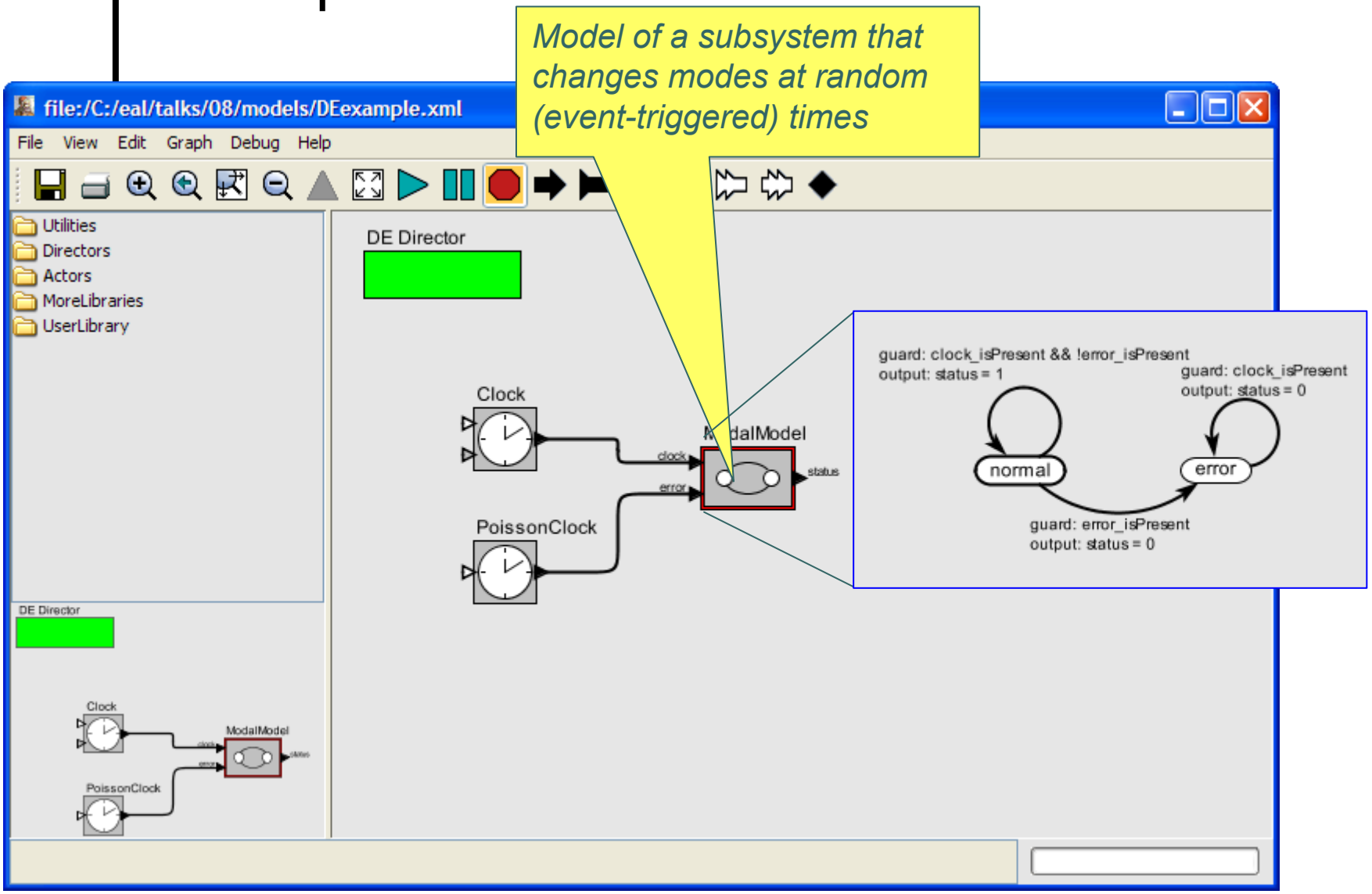
Example DE Model



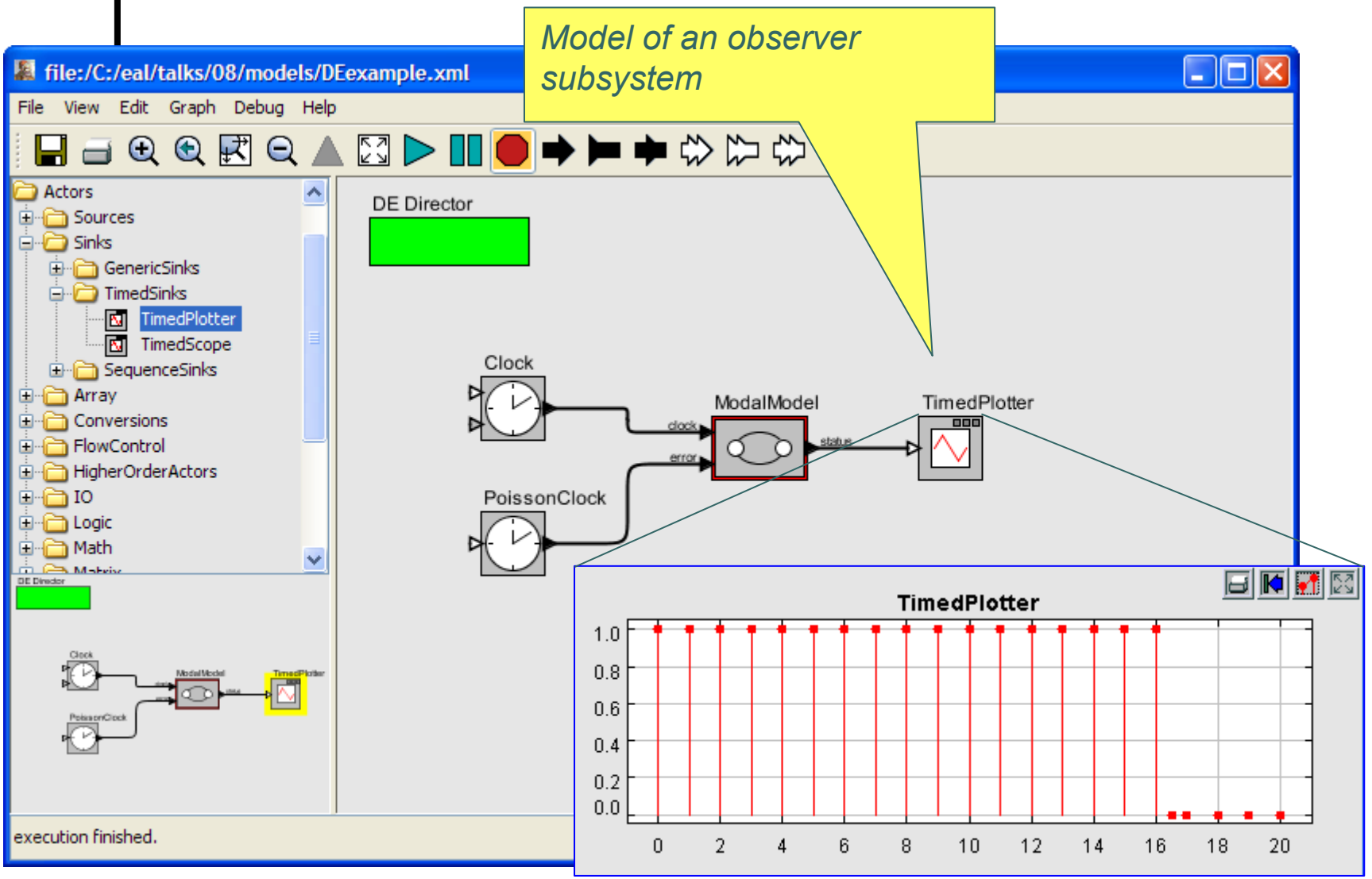
Example DE Model



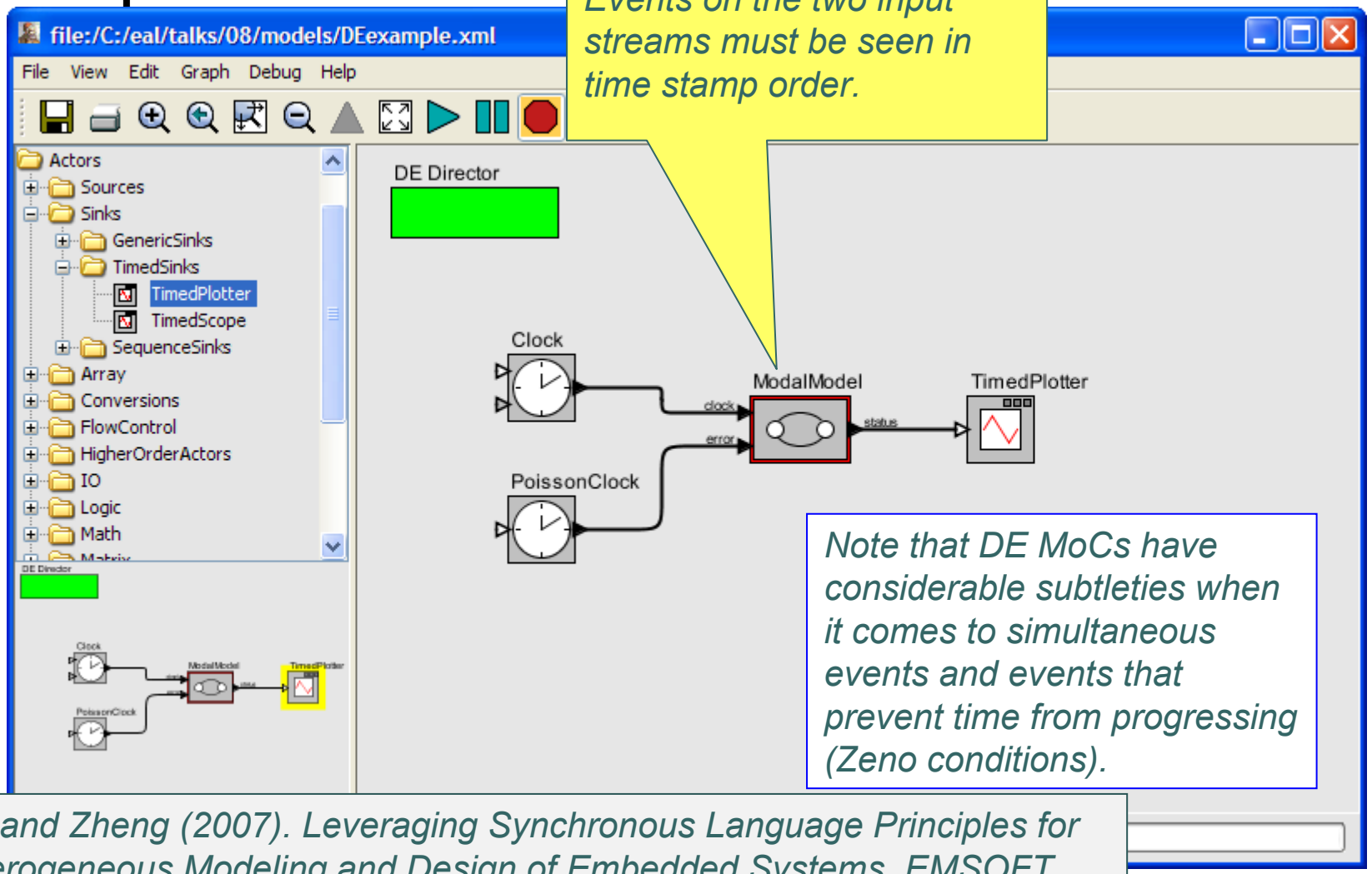
Example DE Model



Example DE Model

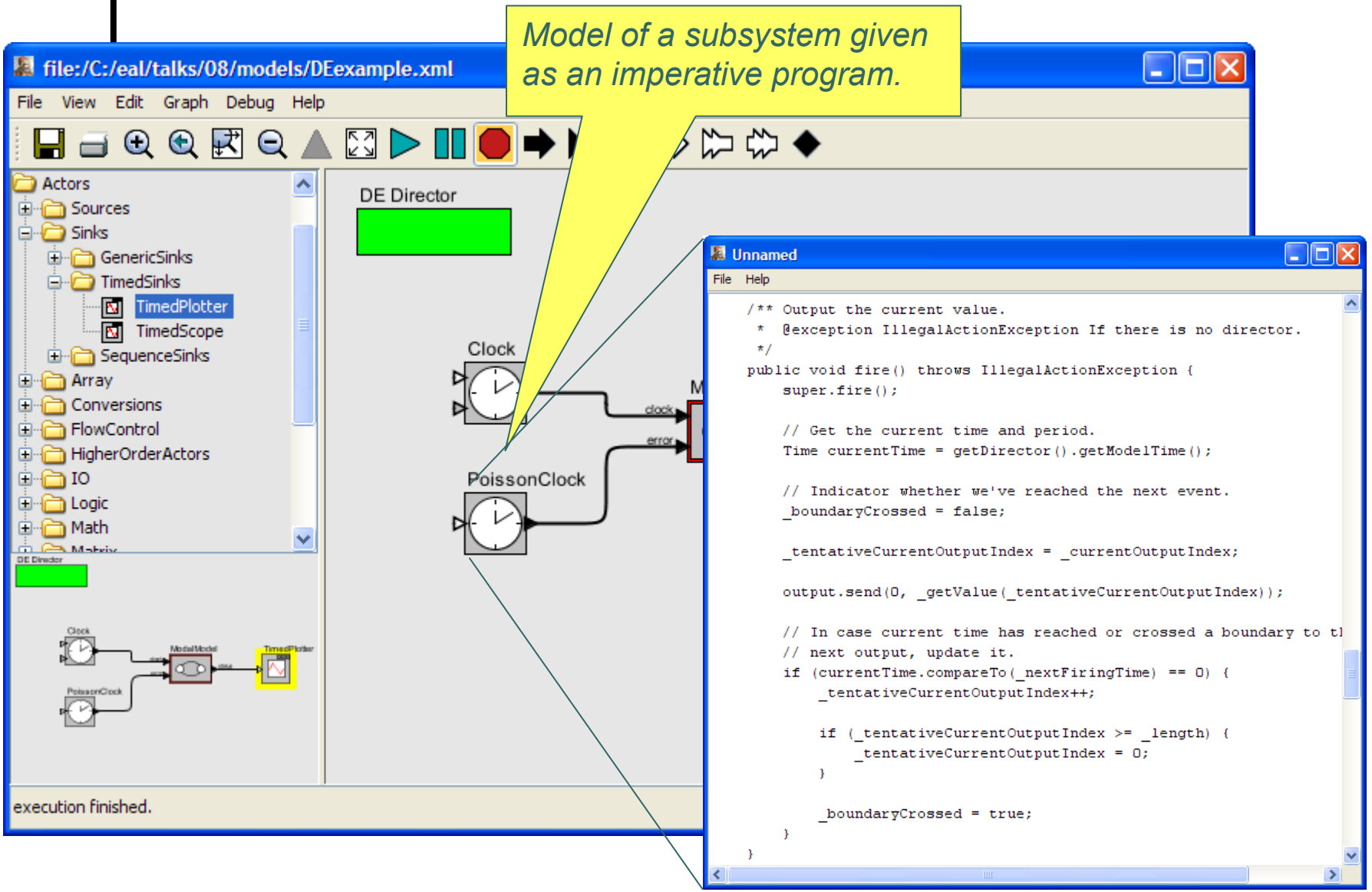


Example DE Model

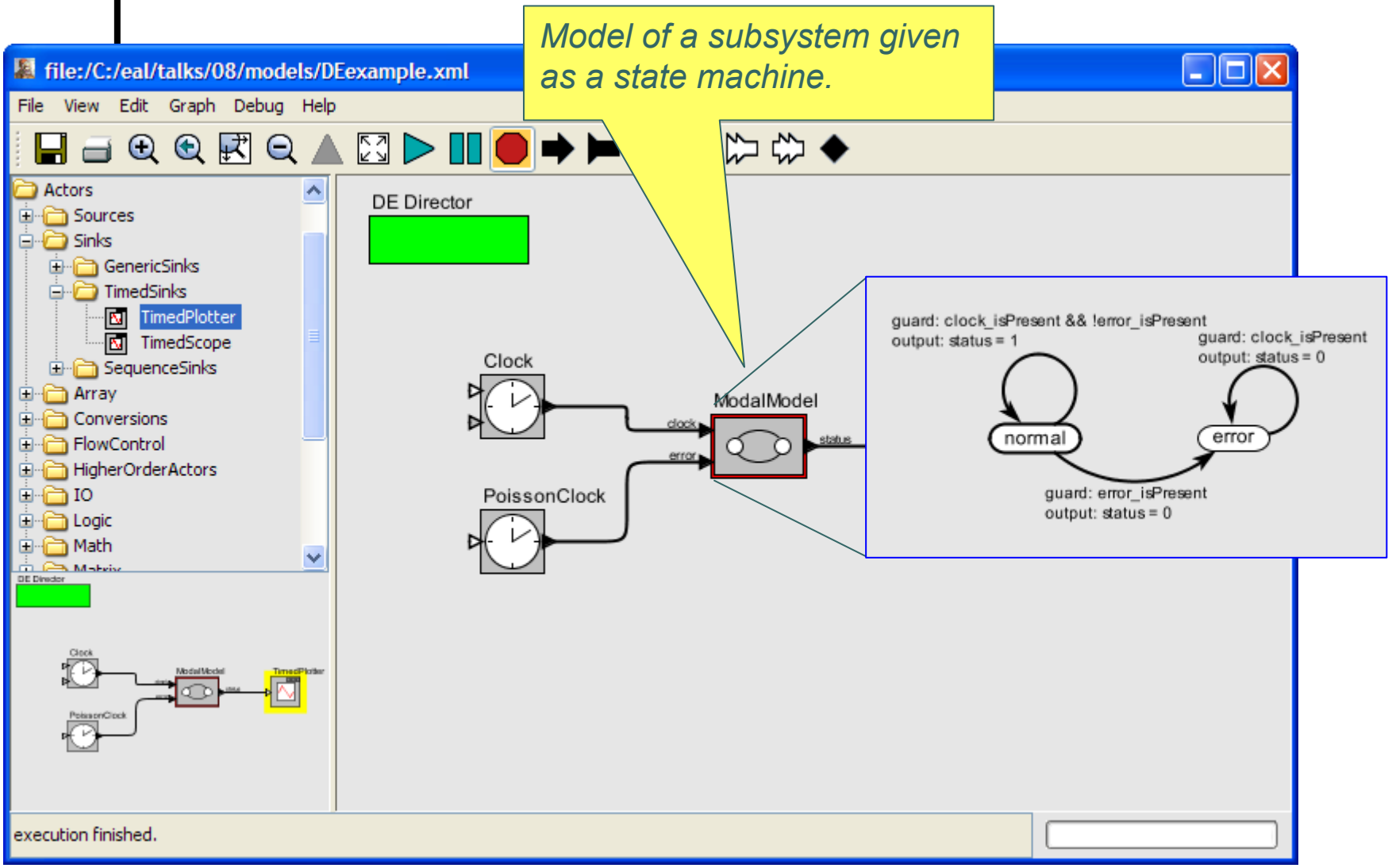


Lee and Zheng (2007). Leveraging Synchronous Language Principles for Heterogeneous Modeling and Design of Embedded Systems. EMSOFT.

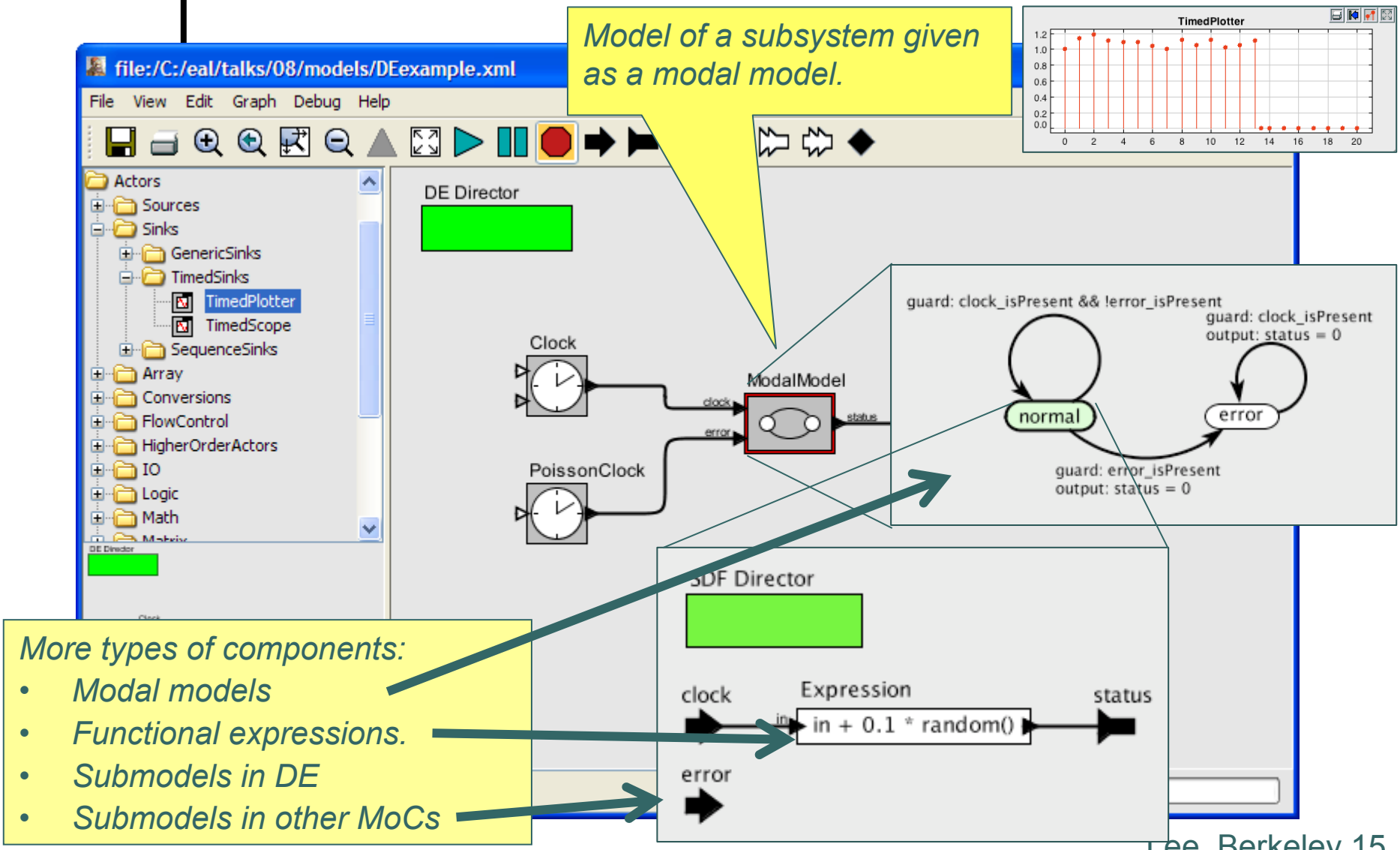
This is a Component Technology



This is a Component Technology



This is a Component Technology



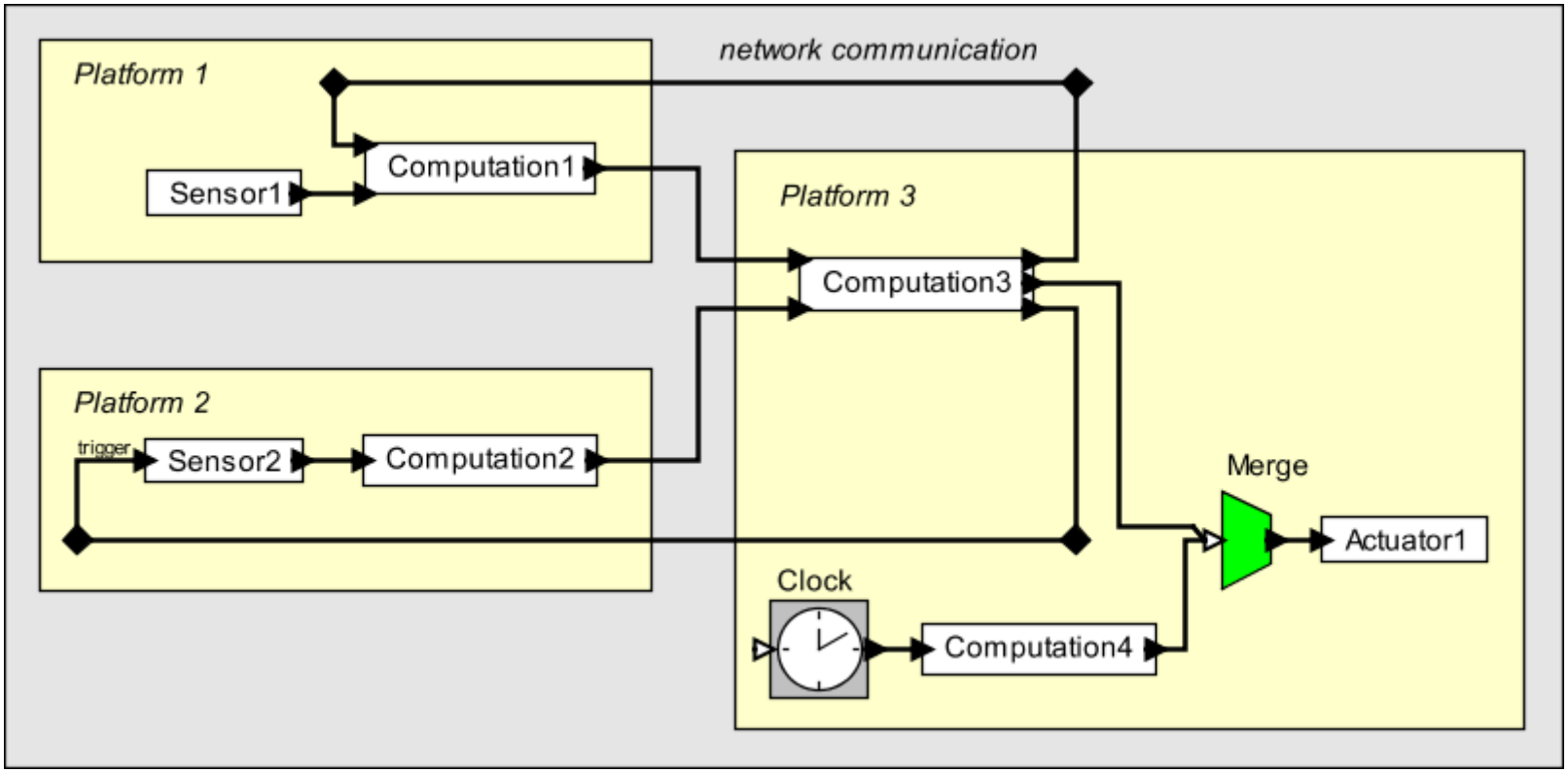
Using DE Semantics in Distributed Real-Time Systems

- DE is usually a simulation technology.
- Distributing DE is done for acceleration.
- Hardware design languages (e.g. VHDL) use DE where time stamps are literally interpreted as real time, or abstractly as ticks of a physical clock.

- We are using DE for distributed real-time software, binding time stamps to real time only where necessary.
- *PTIDES*: Programming Temporally Integrated Distributed Embedded Systems

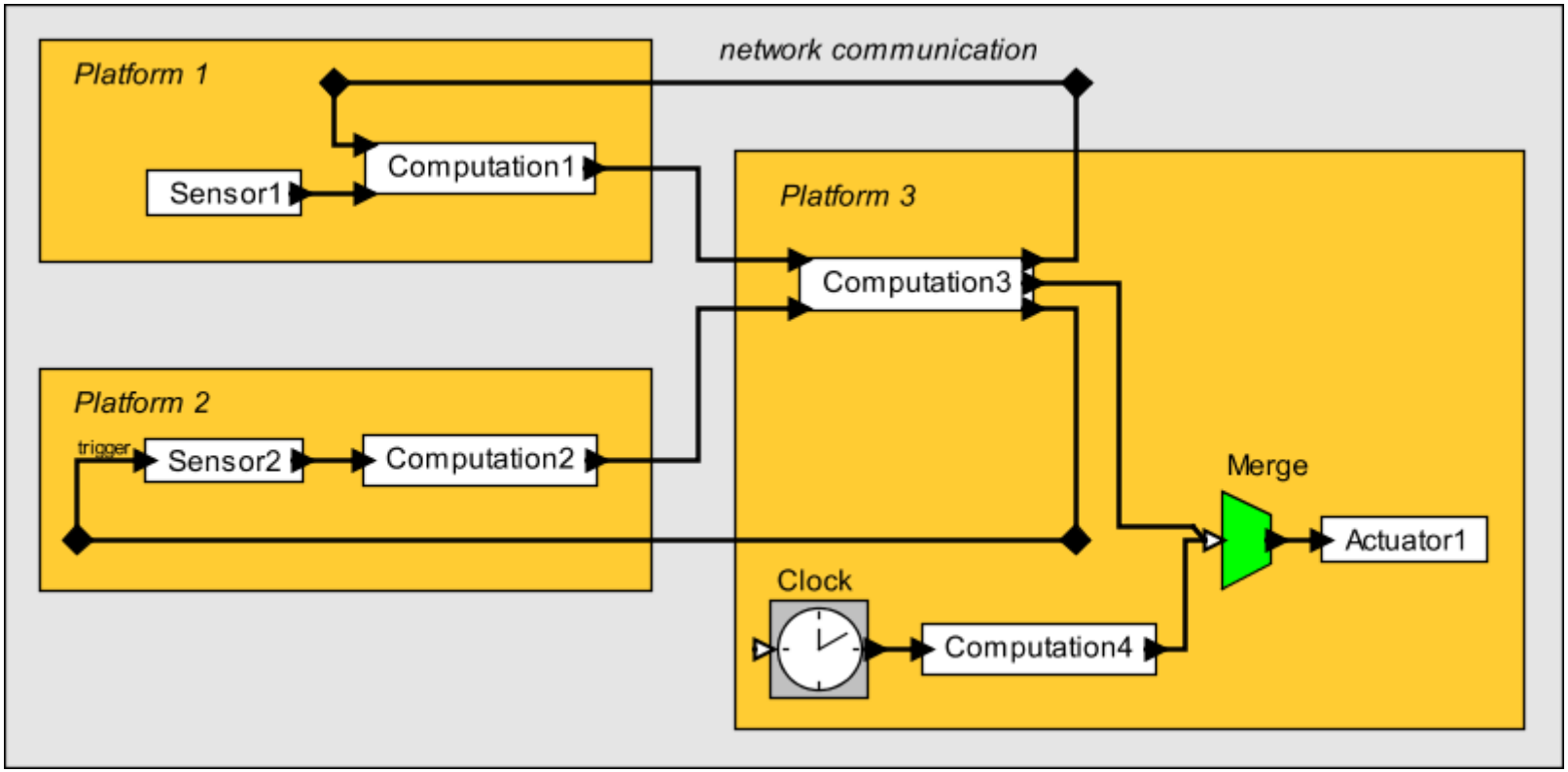
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

Consider a simple DE model of a distributed embedded system:



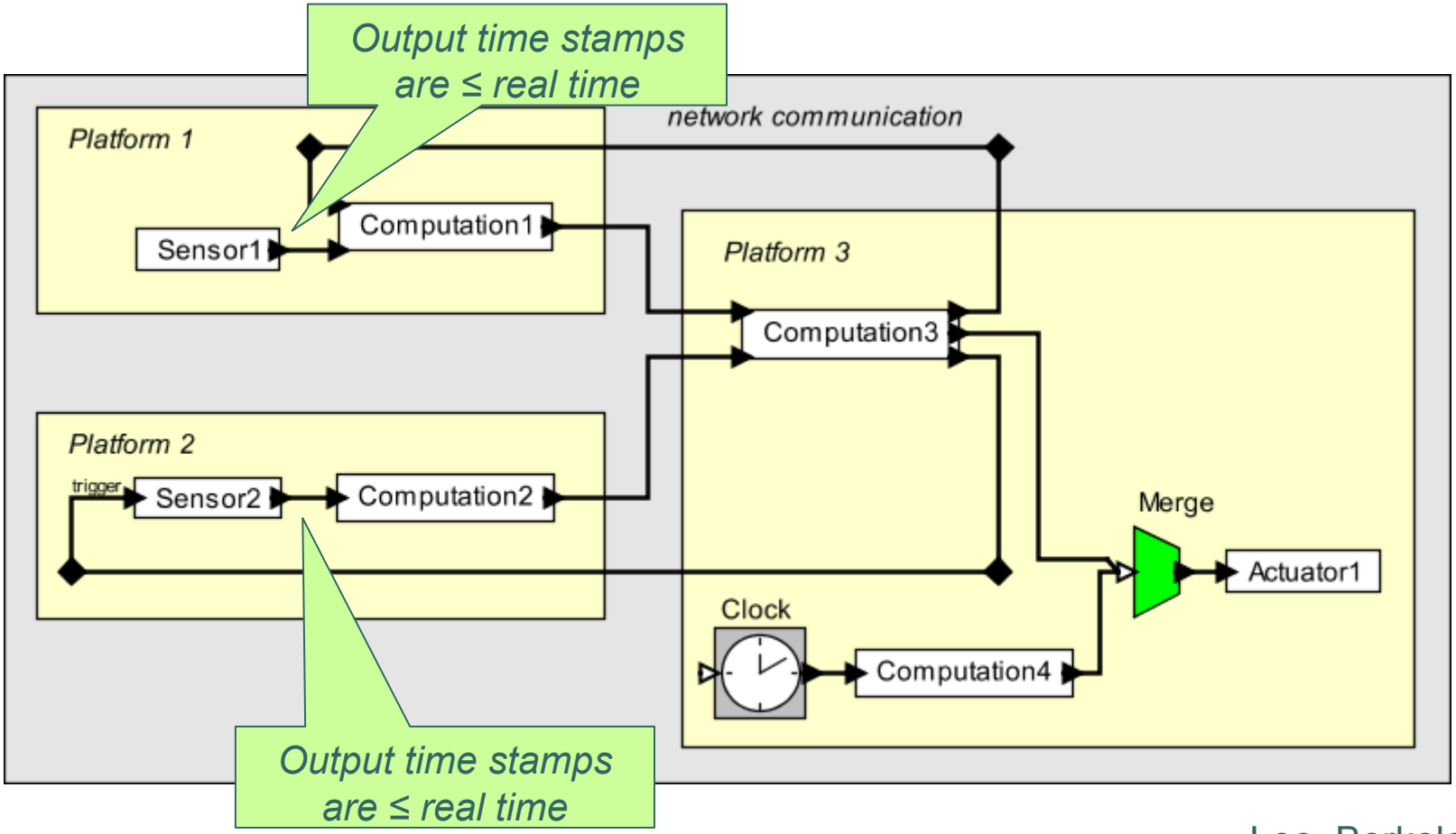
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

Assumption: Wall clocks on the distributed platforms are synchronized to some known precision (e.g. NTP, IEEE 1588)



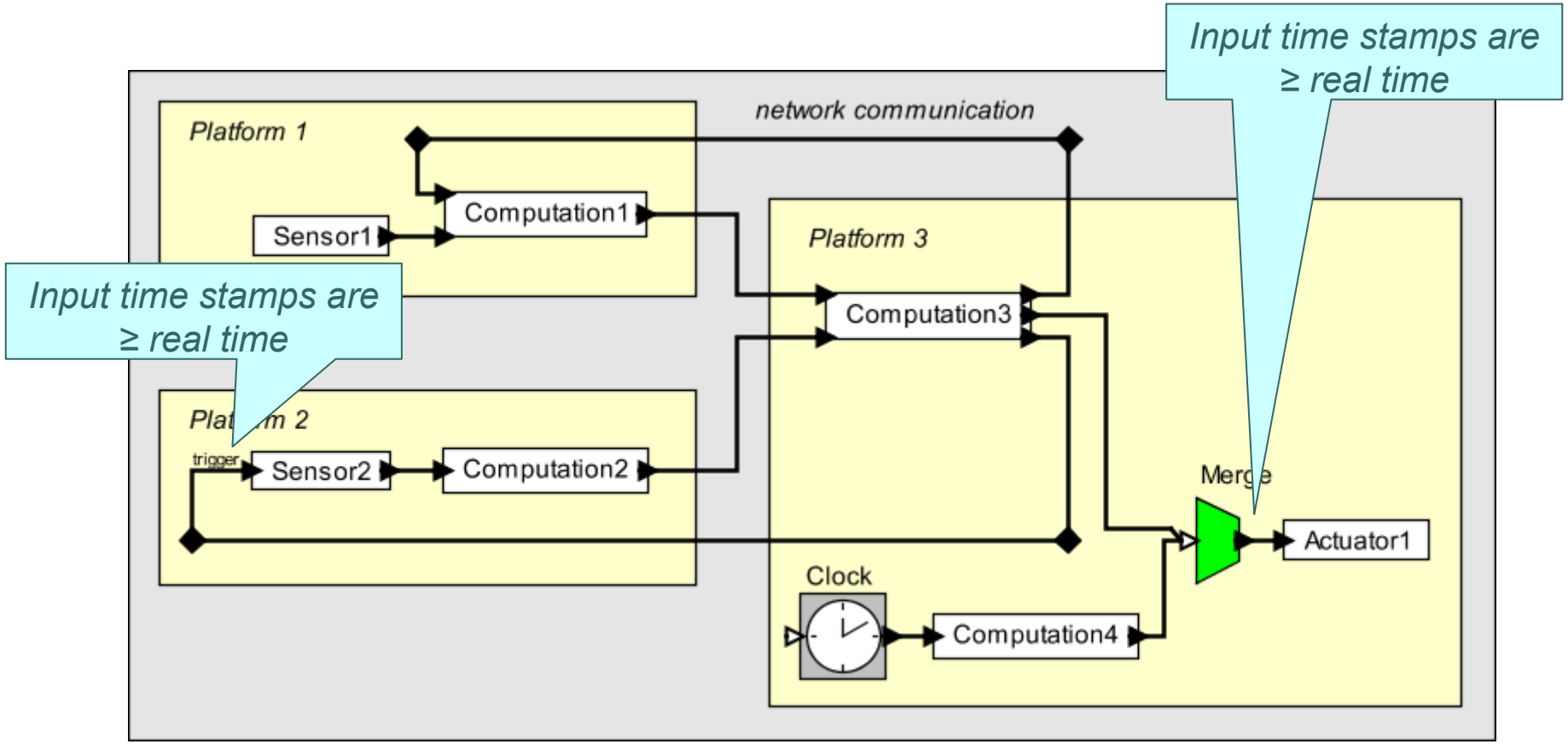
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

Bind model time to real time at the *sensors*:



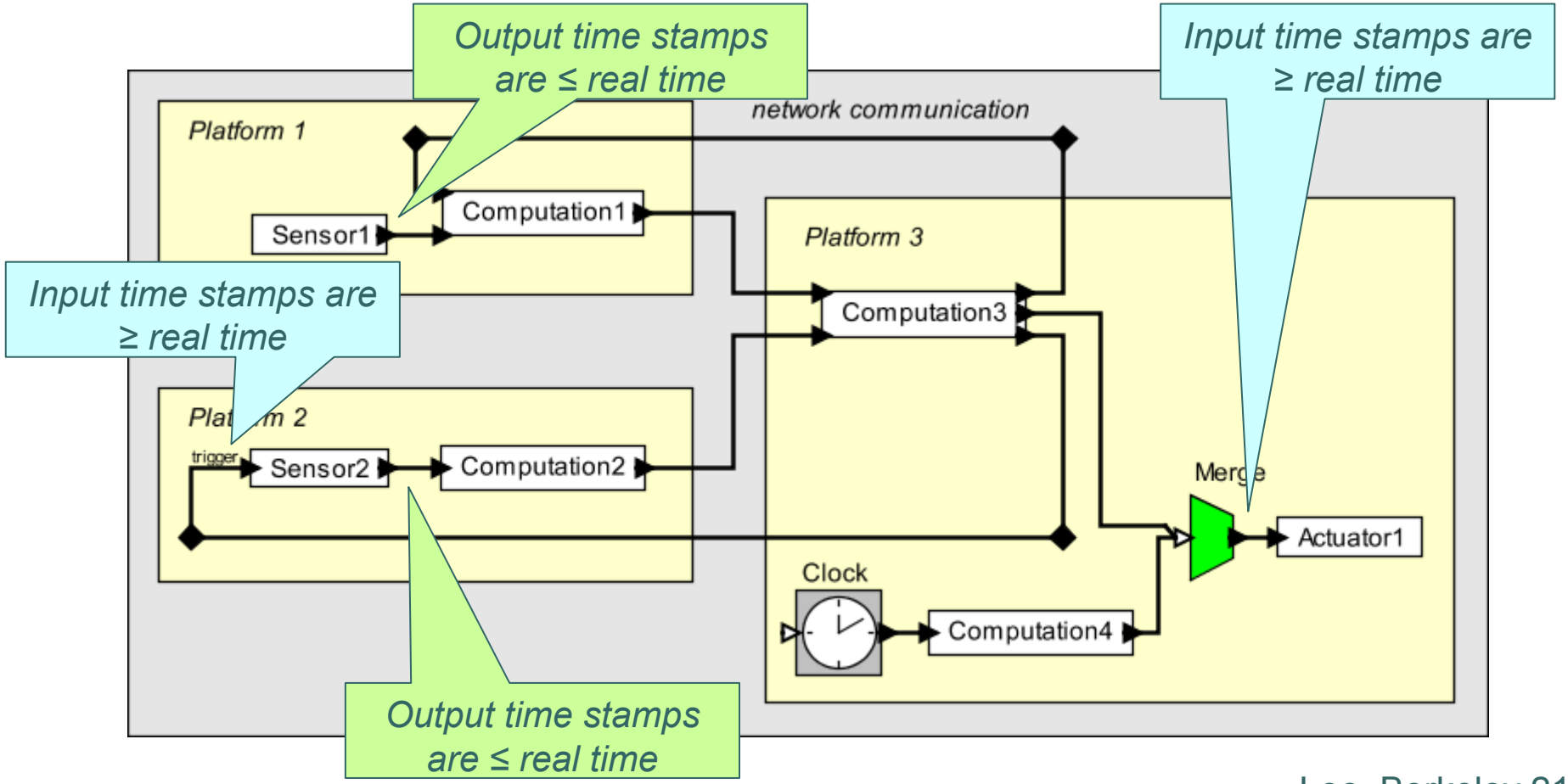
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

Bind model time to real time at the *actuators*:



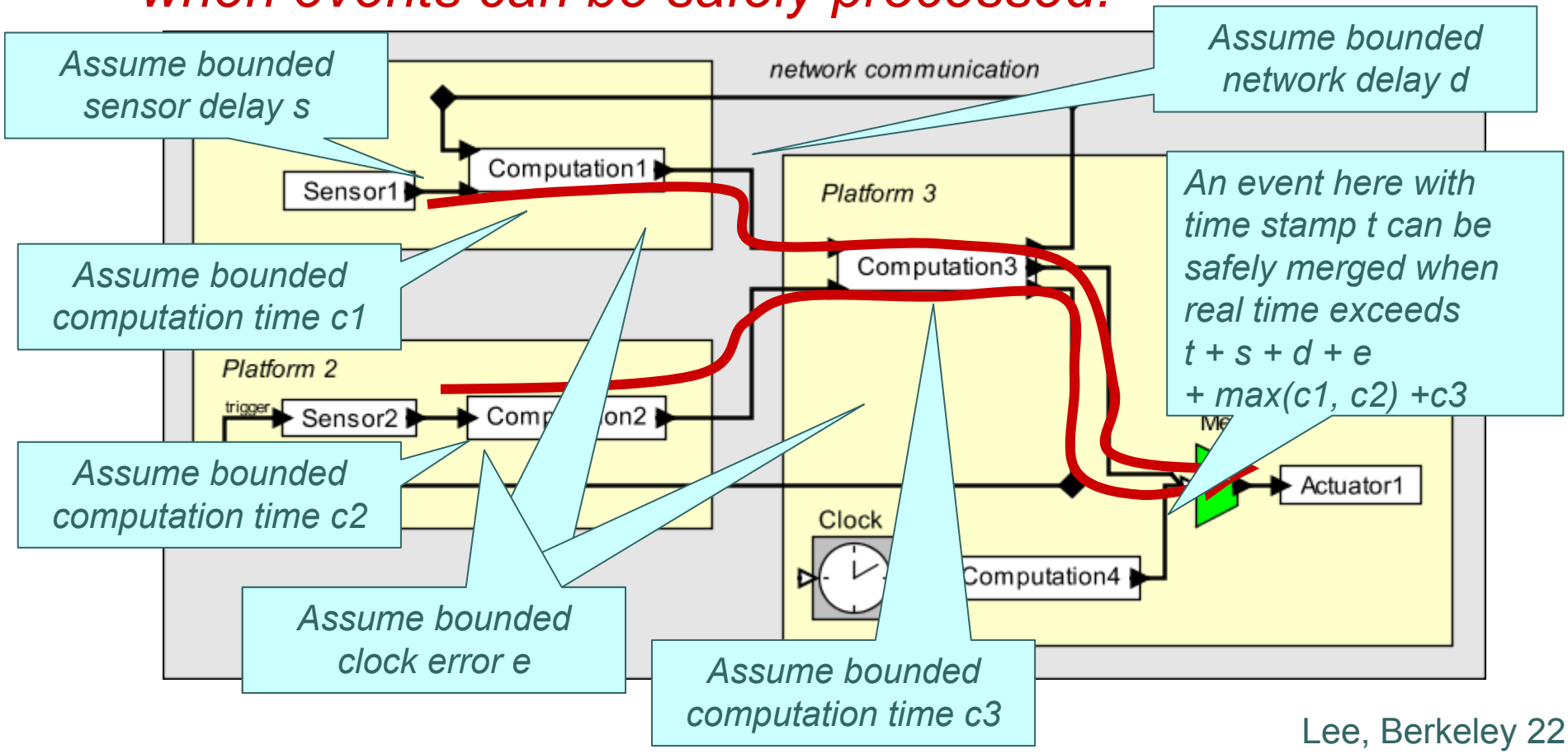
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

Feasibility is not violating these timing inequalities.



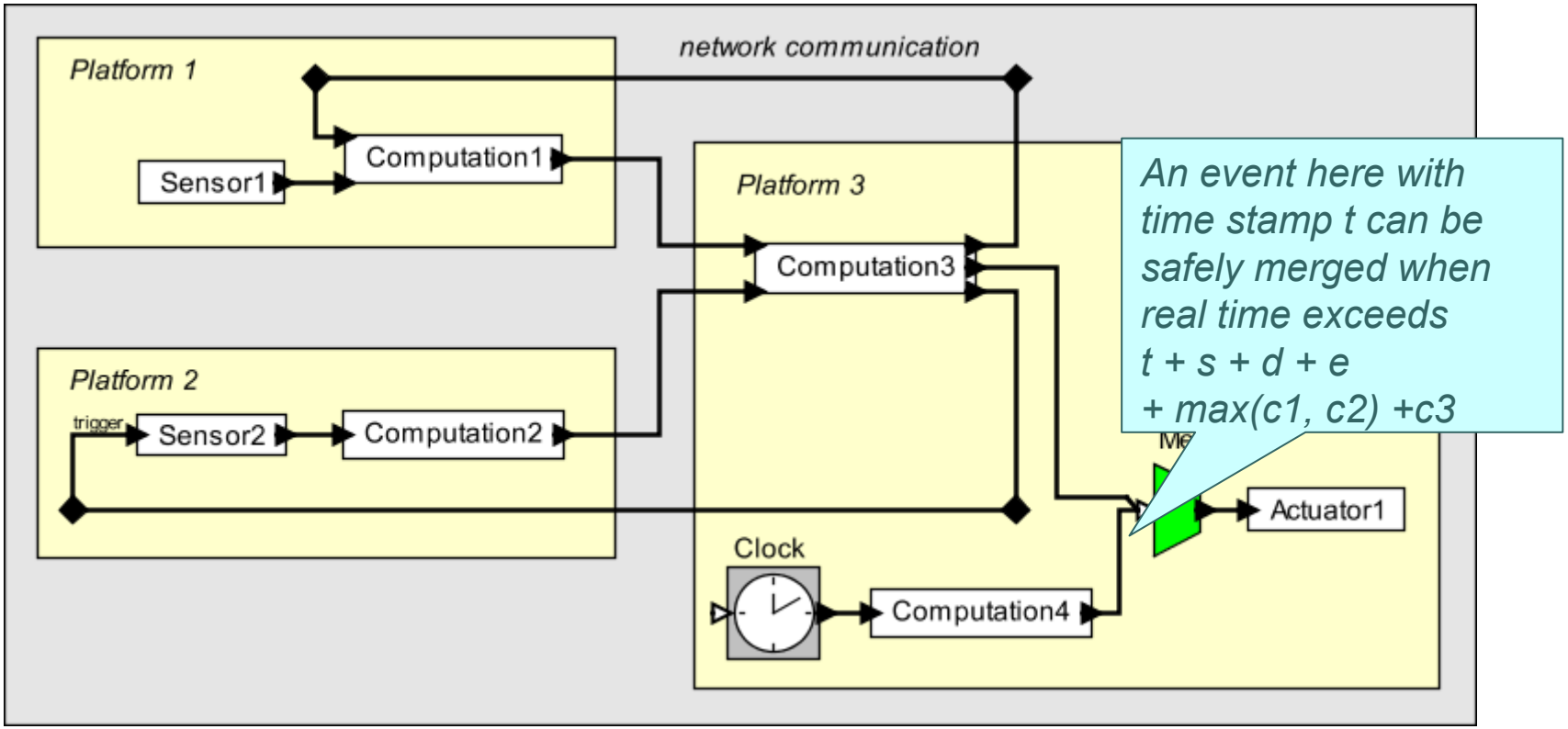
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

PTIDES uses static causality analysis to determine when events can be safely processed.



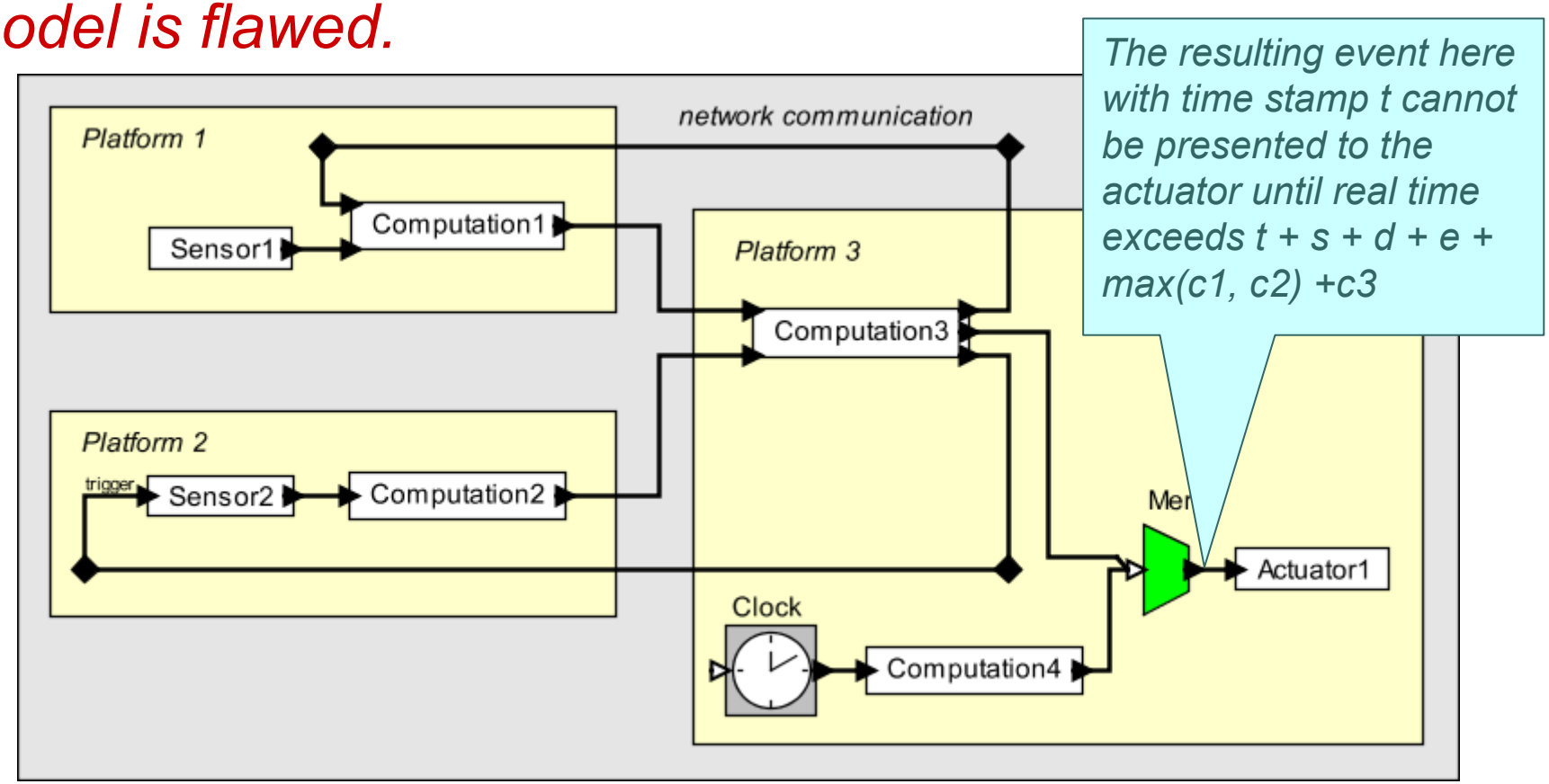
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

The execution model prevents remote processes from blocking local ones, and does not require backtracking.



PTIDES: Programming Temporally Integrated Distributed Embedded Systems

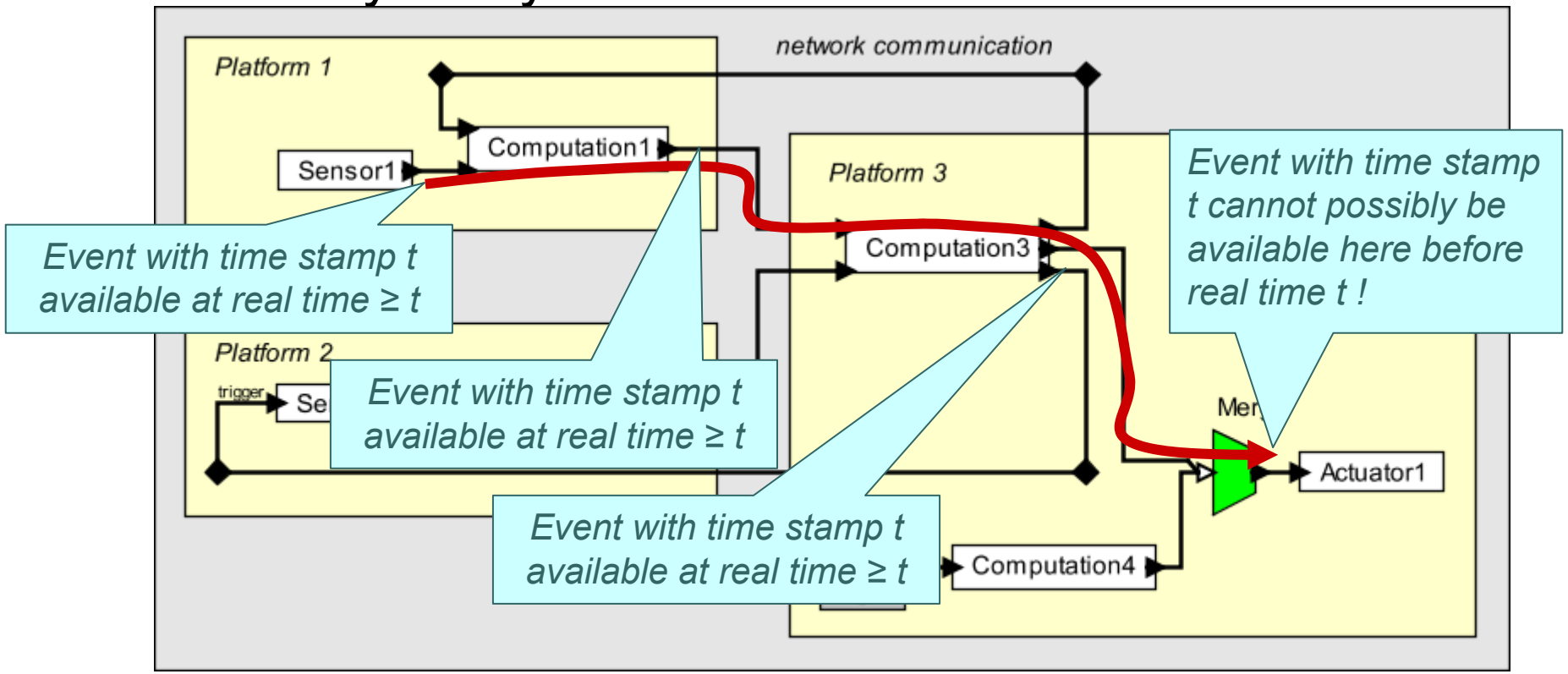
However, feasibility analysis tells us this particular model is flawed.



PTIDES: Programming Temporally Integrated Distributed Embedded Systems

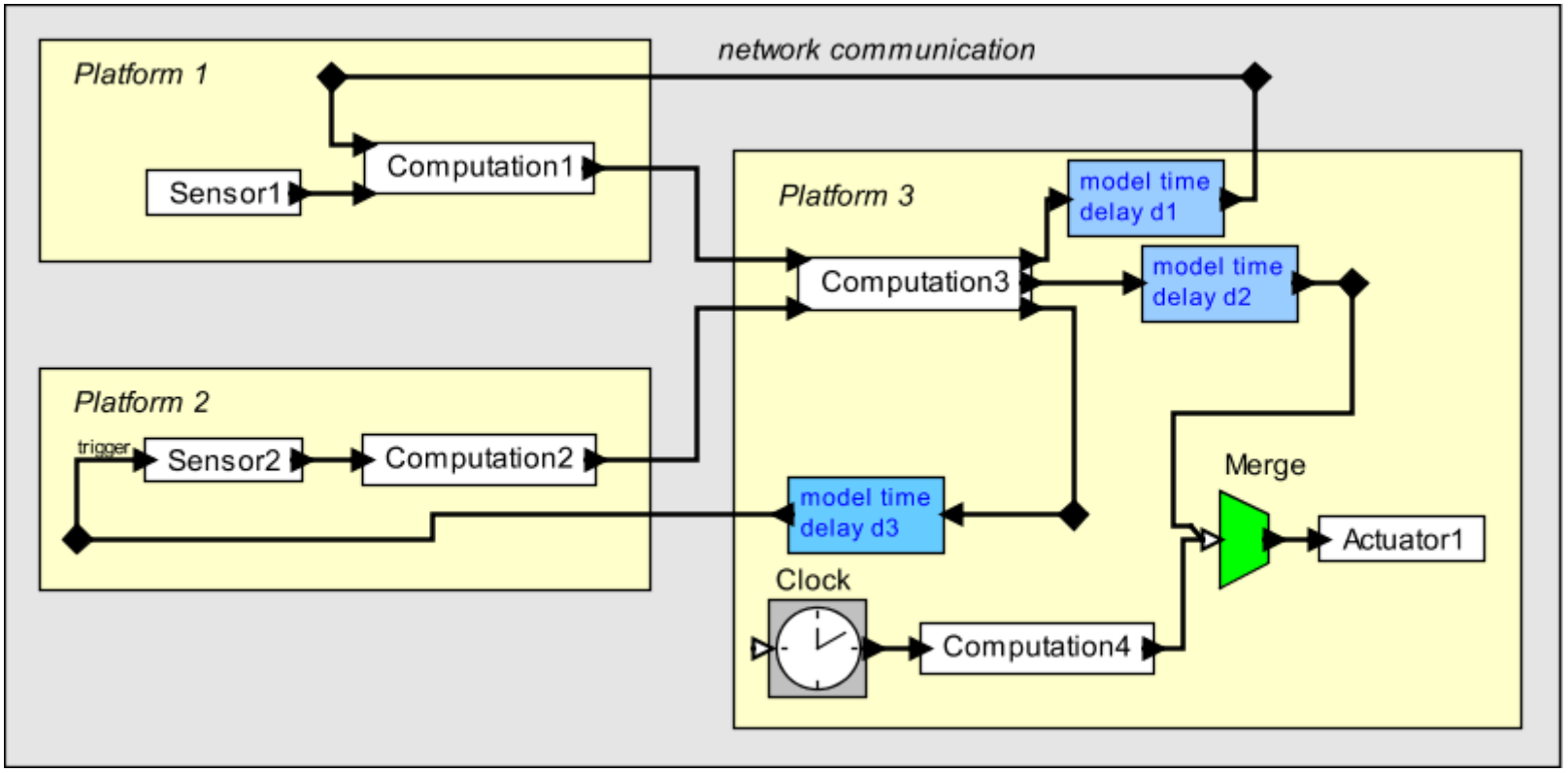
Remote events can also trigger real-time violations.

Feasibility analysis tells us the model is flawed.



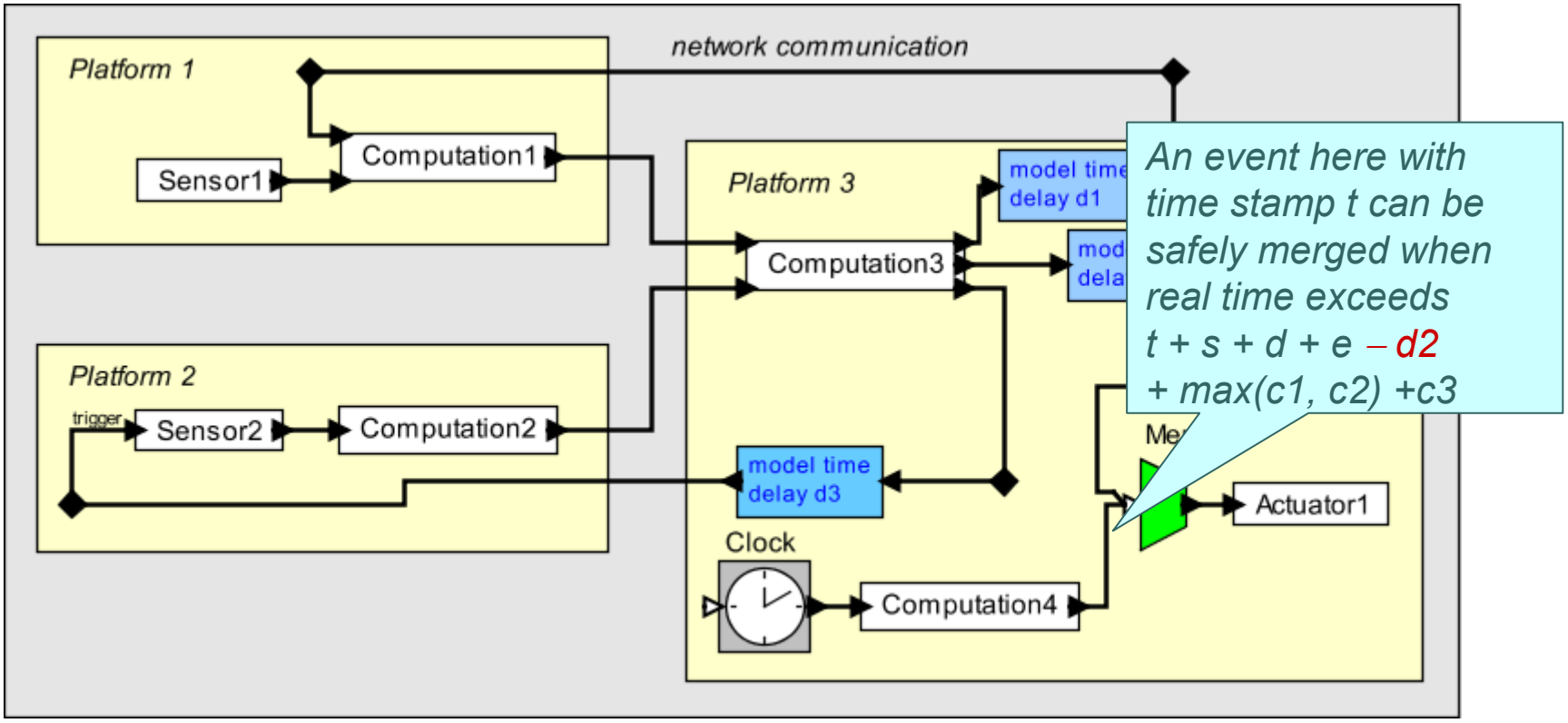
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

The model can be made feasible with actors that increment the time stamps (model-time delays).



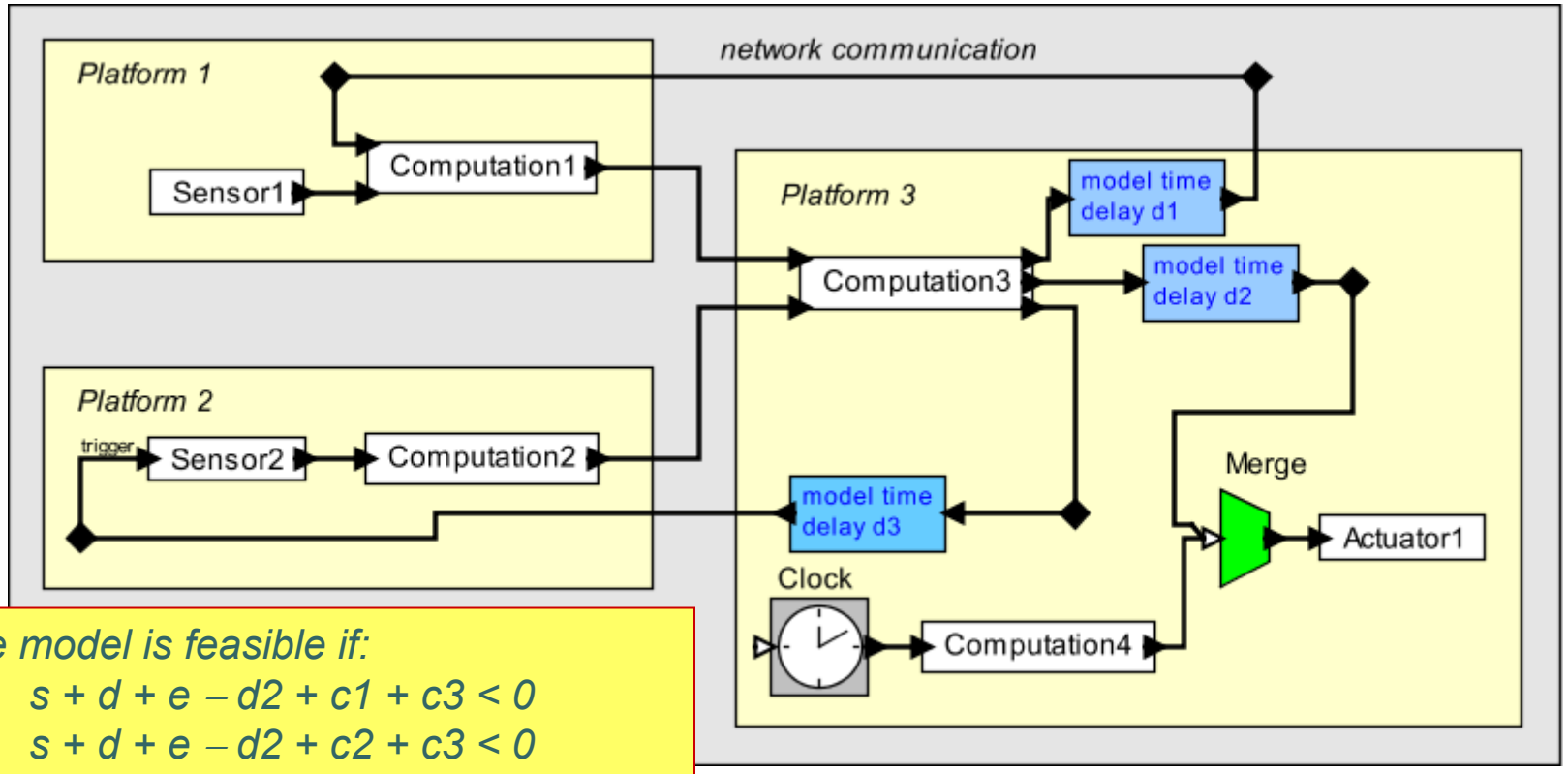
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

This relaxes scheduling constraints...



PTIDES: Programming Temporally Integrated Distributed Embedded Systems

Through static analysis we can derive sufficient conditions for feasibility…

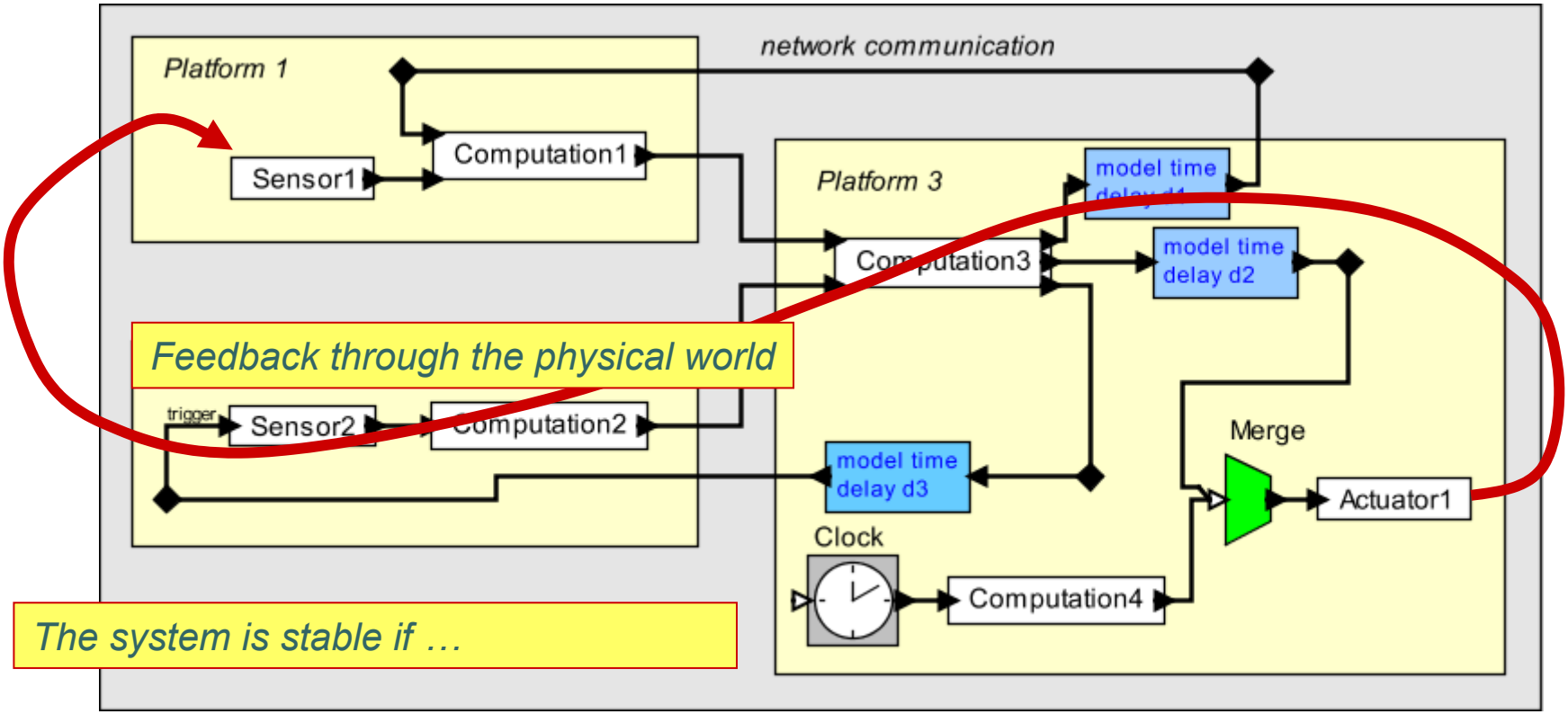


The model is feasible if:

1) $s + d + e - d2 + c1 + c3 < 0$
2) $s + d + e - d2 + c2 + c3 < 0$
3) …

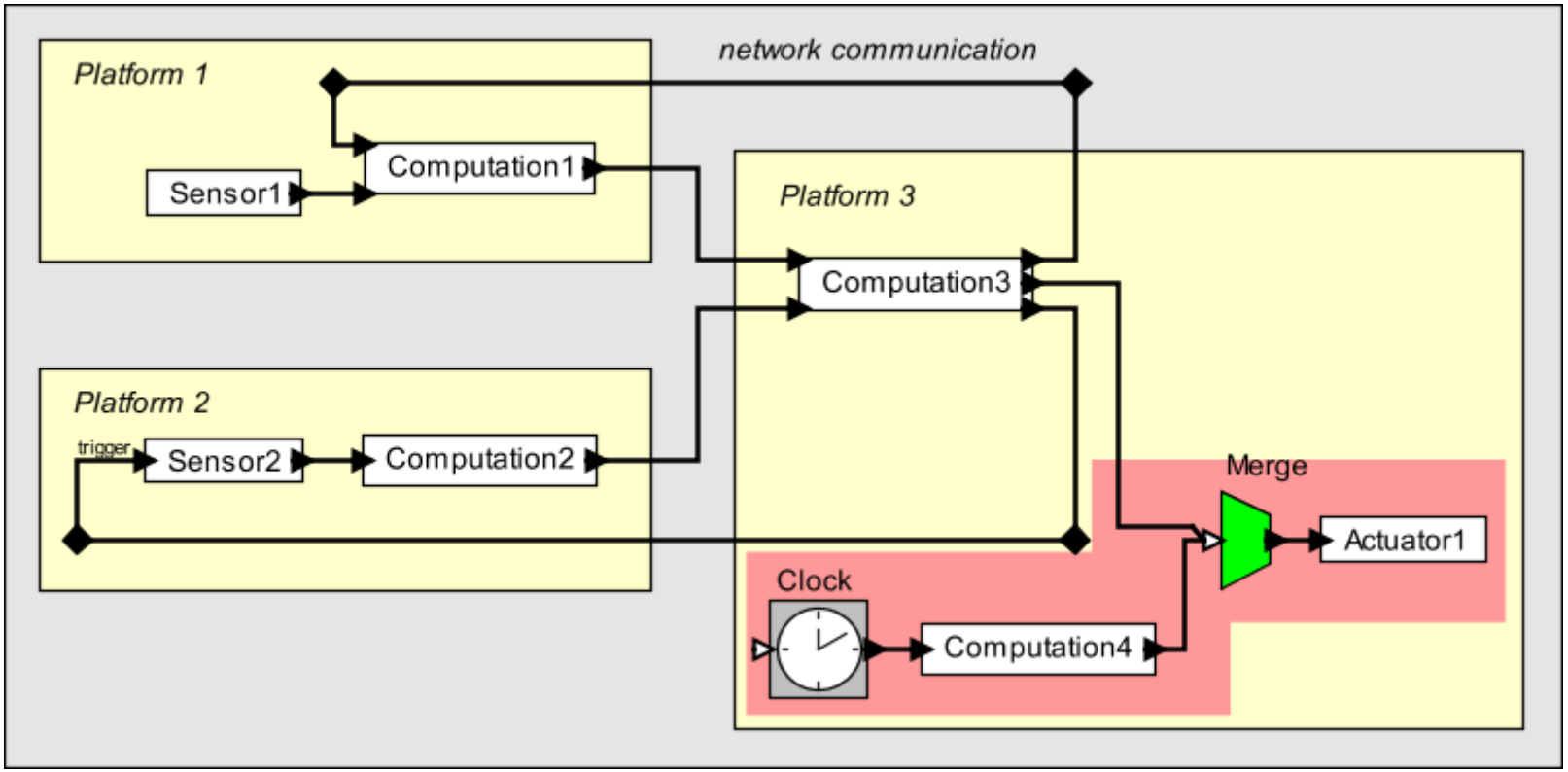
PTIDES: Programming Temporally Integrated Distributed Embedded Systems

… and being explicit about time delays means that we can analyze control system dynamics…



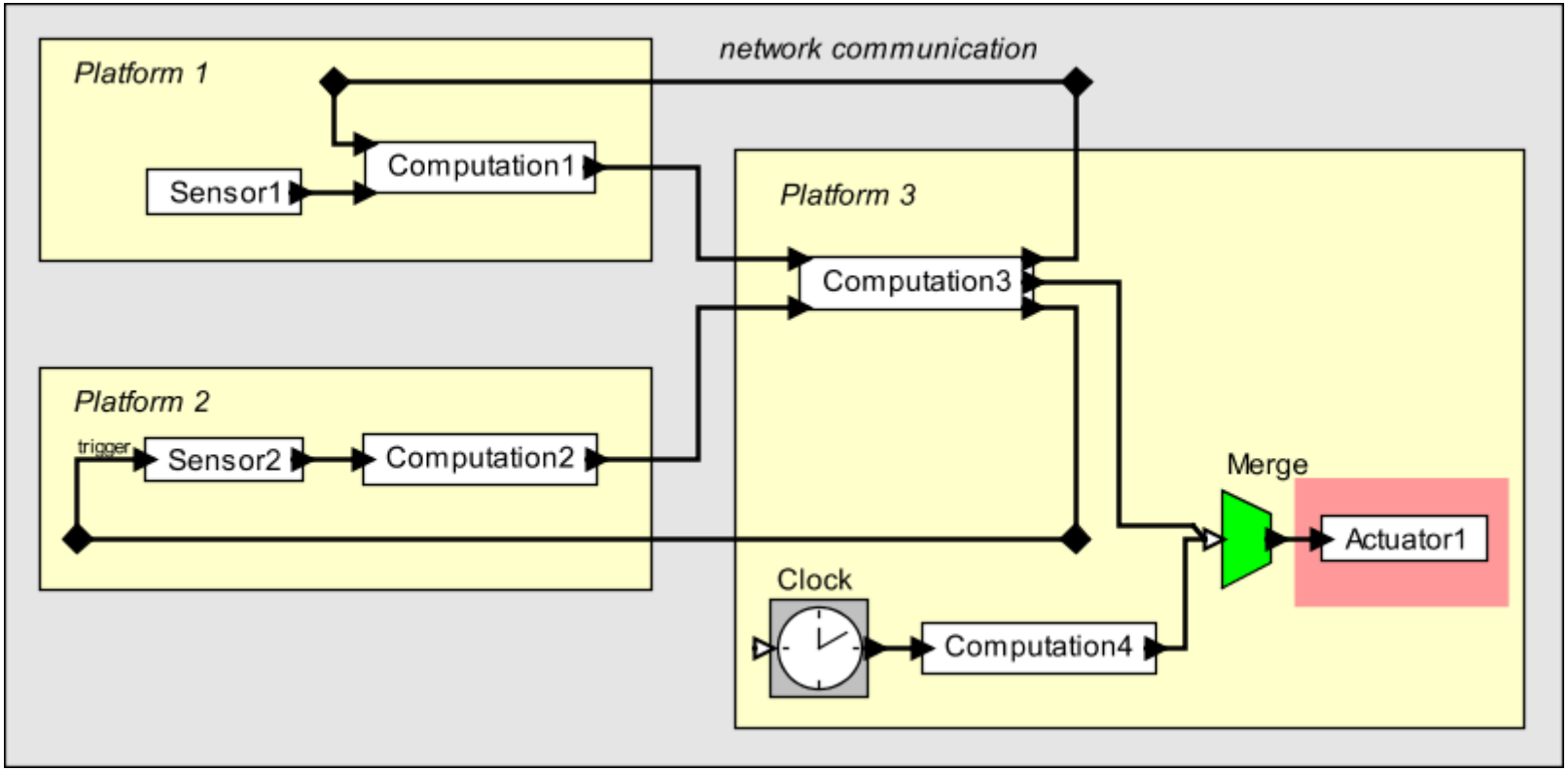
Compare with Classical Distributed DE Simulation Technologies

Conservative distributed DE (Chandy & Misra) would block actuation unnecessarily.



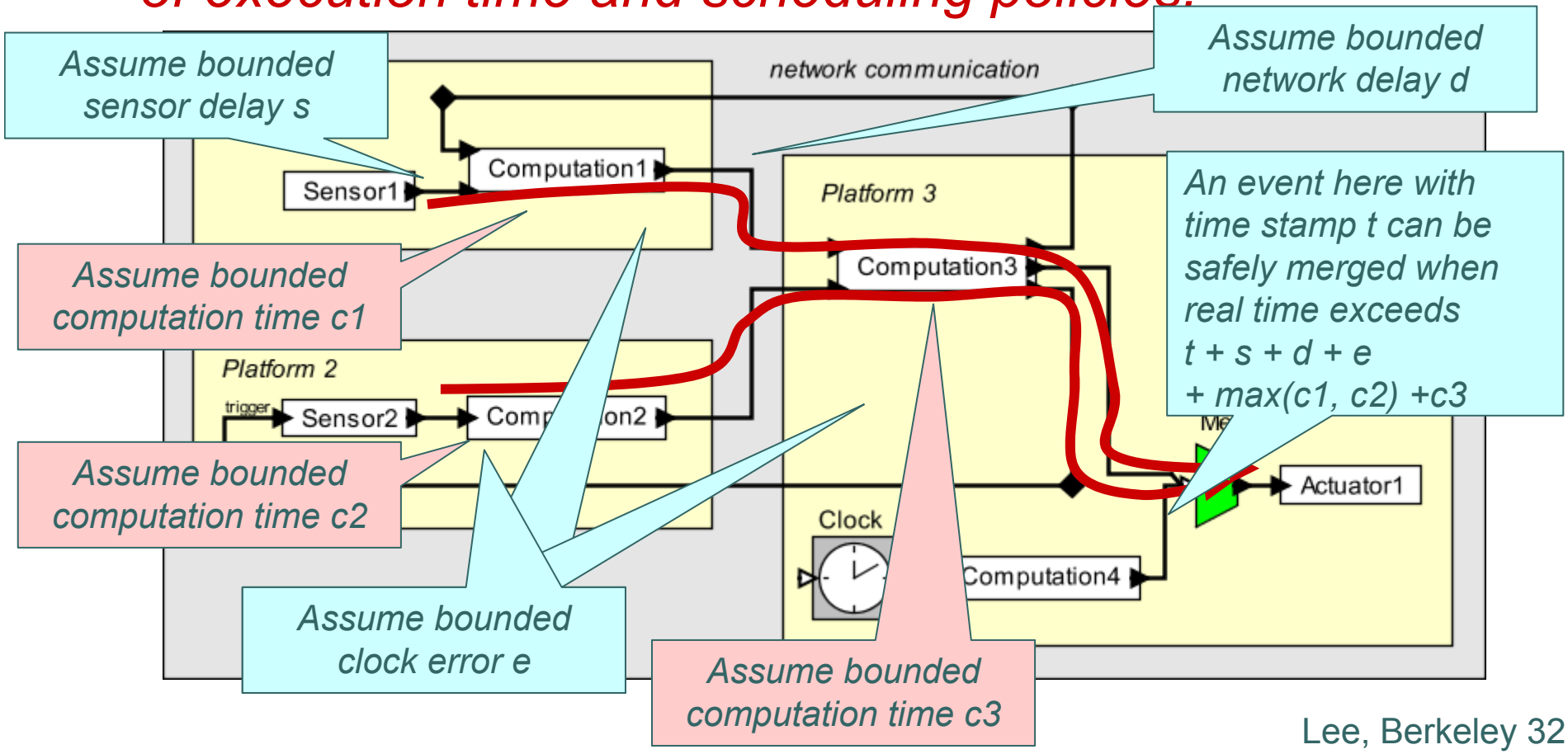
Compare with Classical Distributed DE Simulation Technologies

Optimistic distributed DE (Jefferson) would require being able to roll back the physical world.



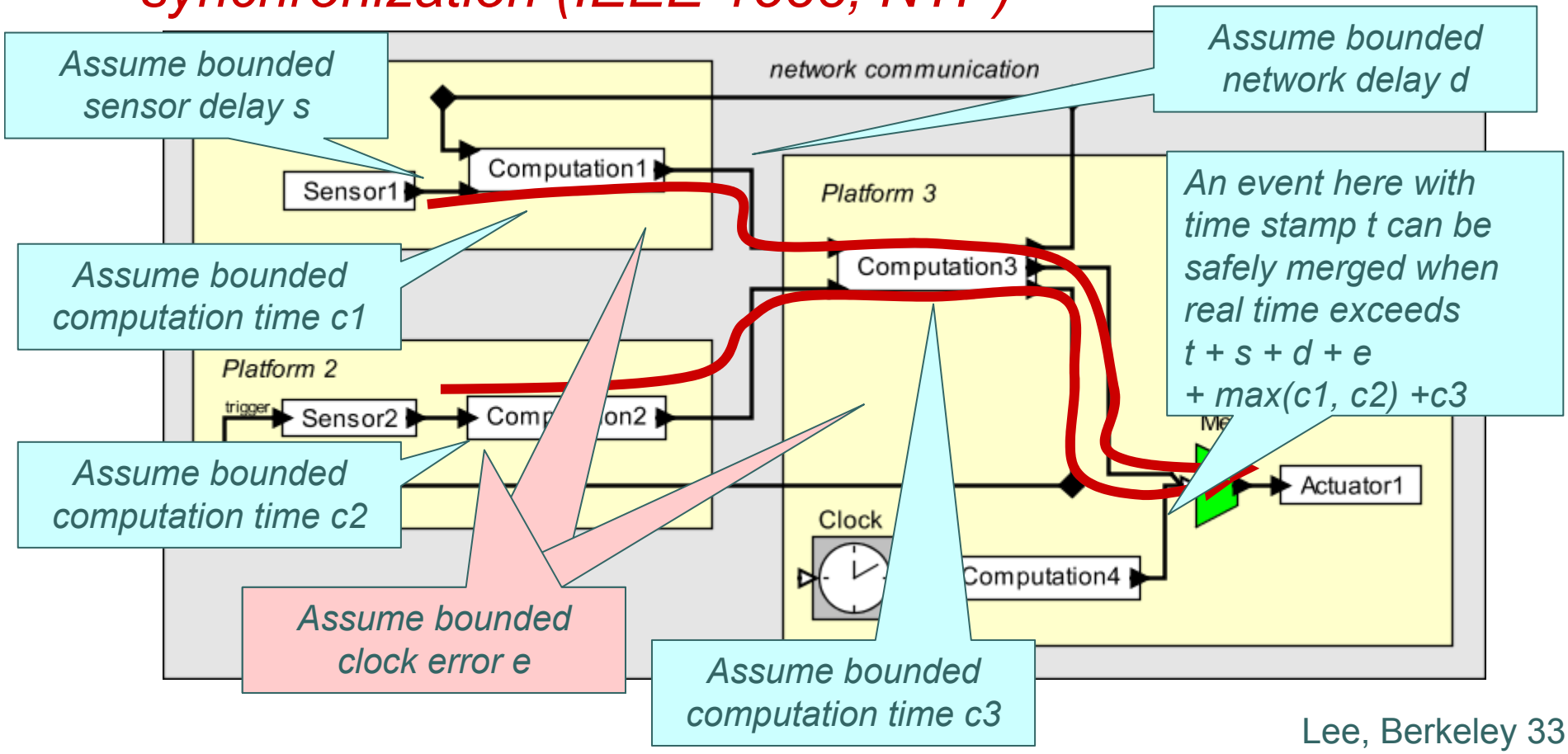
But this feasibility analysis is not quite as easy as it might look

Bounding computation time requires careful analysis of execution time and scheduling policies.



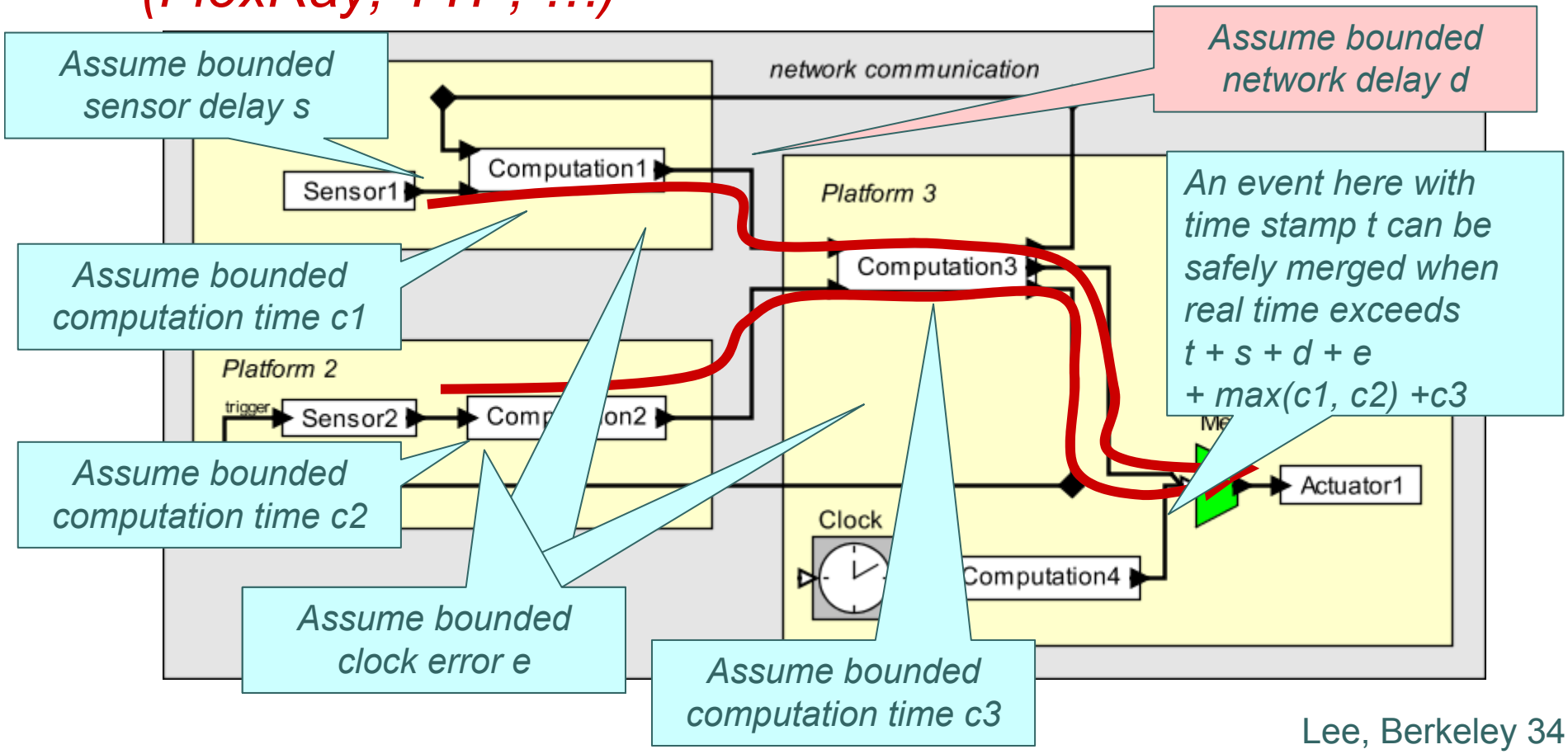
But this feasibility analysis is not quite as easy as it might look

Bounding clock error requires network time synchronization (IEEE 1588, NTP)



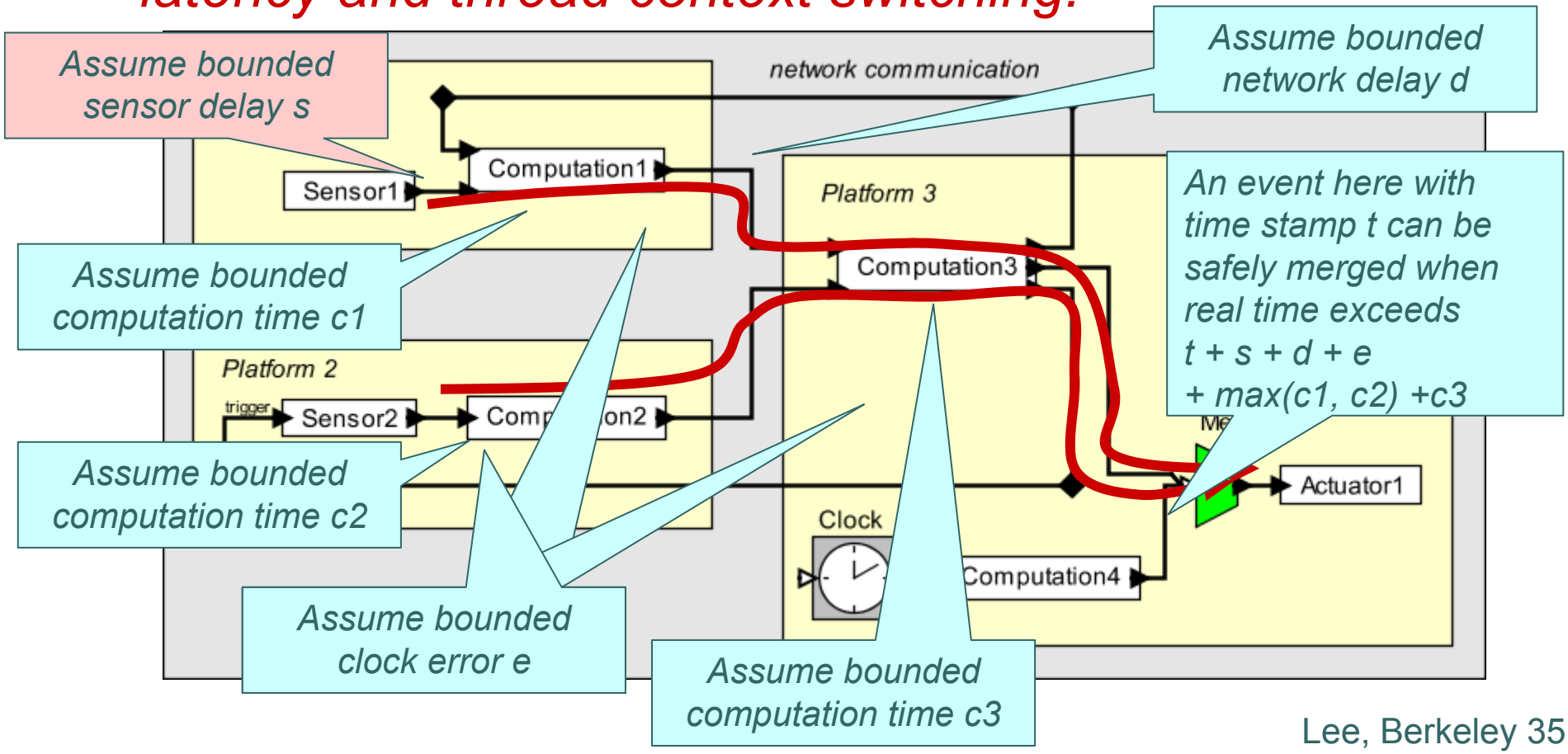
But this feasibility analysis is not quite as easy as it might look

Bounding network delay requires a real-time network (FlexRay, TTP, …)



But this feasibility analysis is not quite as easy as it might look

Bounding sensor delay requires bounding interrupt latency and thread context switching.



Making Schedulability Analysis Systematic

Levels of analysis:

1. Assume zero execution time for actors (exposes modeling errors)
2. Assume known worst-case execution time (WCET) for actors, unbounded compute resources (exposes complexity problems).
3. Assume WCET and a scheduling policy over finite resources (exposes resources limitations).

Our analysis builds on *causality interfaces*.

[1] Y. Zhou and E. A. Lee, "Causality Interfaces for Actor Networks," ACM Transactions on Embedded Computing Systems (TECS), April 2008.

Observations

- DE models are natural specifications of distributed real-time behavior.
- PTIDES extends DE with connections to real time at sensors and actuators.
- The resulting model has deterministic end-to-end latencies.
- Feasibility analysis exposes modeling errors and resource limitations.
- We are building execution environments on RTOS's and bare iron.

Exposing Modeling Errors

Levels of analysis:

1. Assume zero execution time for actors (exposes modeling errors)
2. Assume known worst-case execution time (WCET) for actors, unbounded compute resources (exposes inadequate compute speed).
3. Assume WCET and a scheduling policy over finite resources (exposes resources limitations).

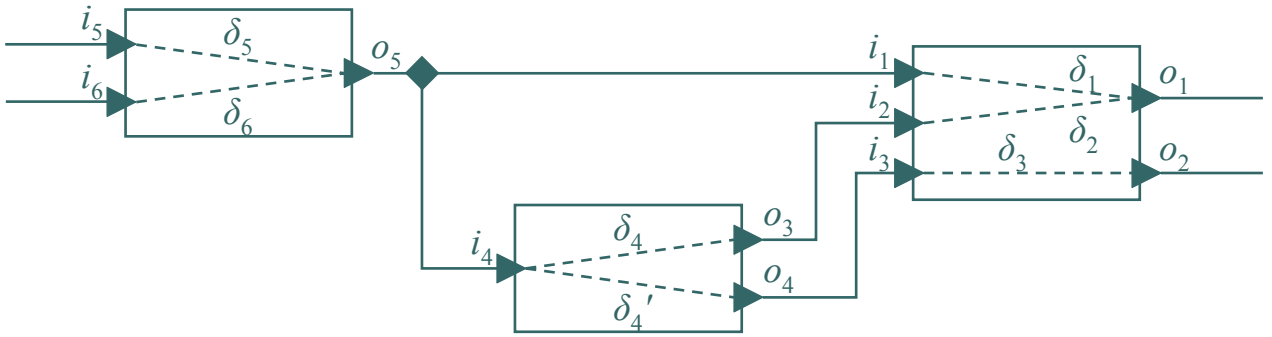
Do this using *causality interfaces*.

[1] Y. Zhou and E. A. Lee, "Causality Interfaces for Actor Networks," ACM Transactions on Embedded Computing Systems (TECS), April 2008.

Causality Interfaces

$\delta : P \times P \rightarrow R^+ \cup \{\infty\}$ yields the minimum model-time delay between any two ports (a *causality interface*).

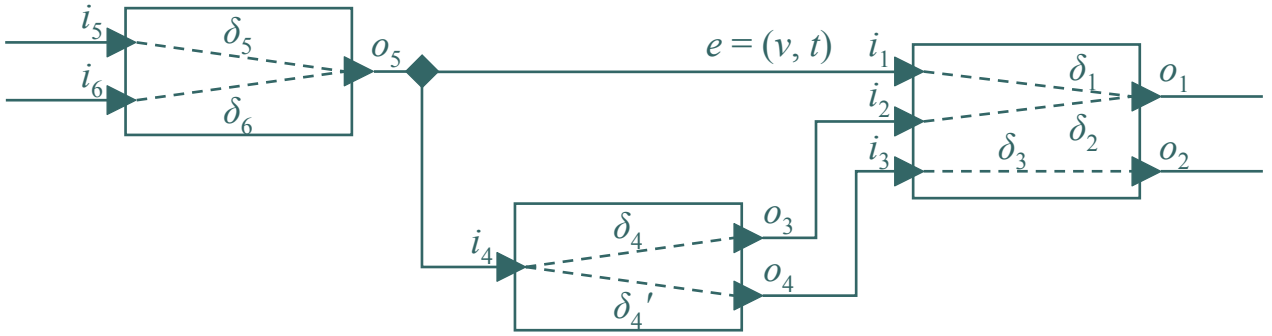
(P – set of ports; R^+ – set of non-negative real numbers)



Infer causality from causality interfaces using a min-plus algebra.

Example: $\delta(i_5, o_1) = \min\{\delta_5+\delta_1, \delta_5+\delta_4+\delta_2\}$, where $\delta_1, \ldots, \delta_6 \in R^+$ are pre-defined.

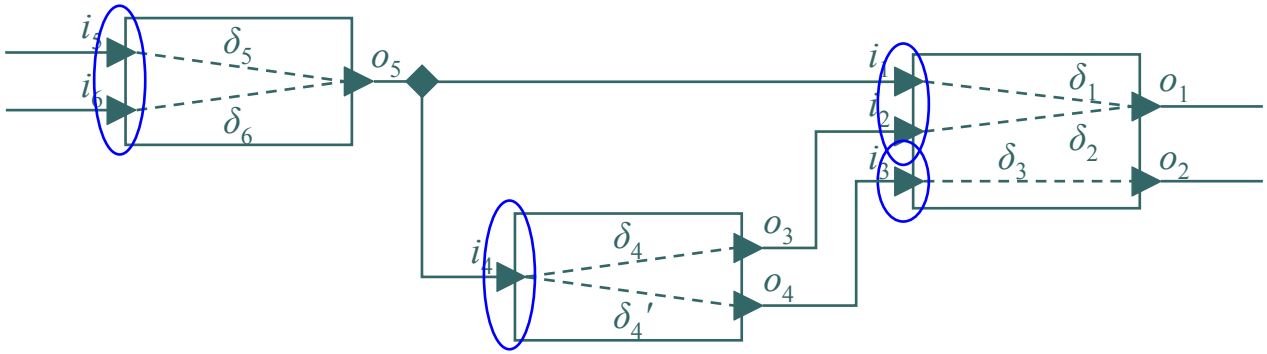
From Causality Interfaces to an Execution Strategy



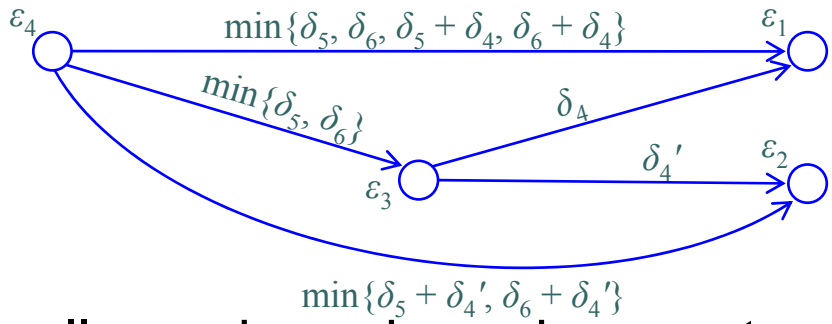
When is it safe to process $e = (v, t)$ at i_1?

1. future events at i_1, i_2 and i_3 have time stamps ≥ t (conventional), or
2. future events at i_1 and i_2 have time stamps ≥ t, or
3. future events at i_1 have time stamps ≥ t, and future events at i_2 depend on events at i_4 with time stamps ≥ $t - \delta_4$, or
4. future events at i_1 and i_2 depend on events at i_5 and i_6 with time stamps ≥ $t - \min\{\delta_5, \delta_6, \delta_5 + \delta_4, \delta_6 + \delta_4\}$.

Relevant Dependency [Ye Zhou]



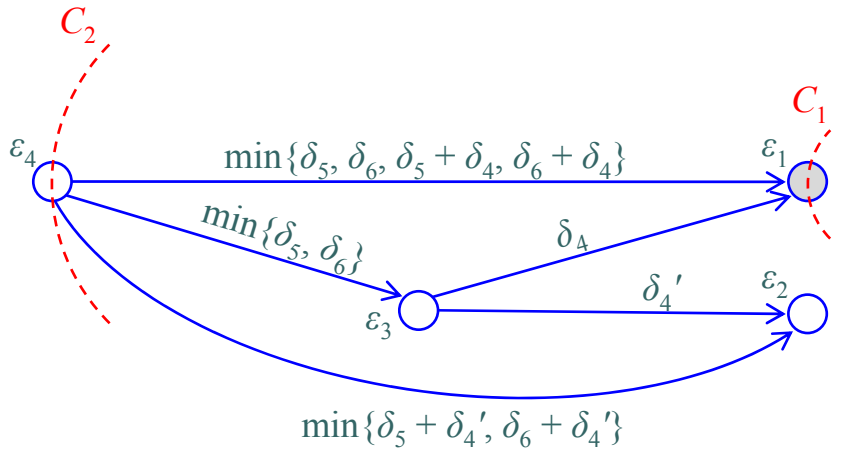
$i \sim i'$ iff they are input of the same actor and affect a common output. An *equivalence class* is a transitive closure of ~.



Construct a collapsed graph, and compute *relevant dependency* between equivalence classes.

$$d(\varepsilon', \varepsilon) = \min_{i' \in \varepsilon',\, i \in \varepsilon} \{\delta(i', i)\}$$

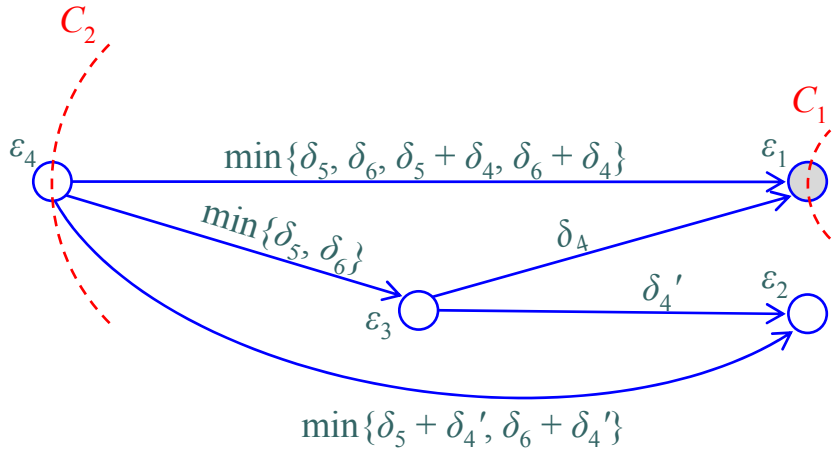
Dependency Cut [T. Feng, Y. Zhou, J. Zou]



A *dependency cut for ε* is a minimal but complete set of equivalence classes that needs to be considered to process an event at *ε*.

Example: C_1 and C_2 are both dependency cuts for ε_1.

Choosing a Dependency Cut

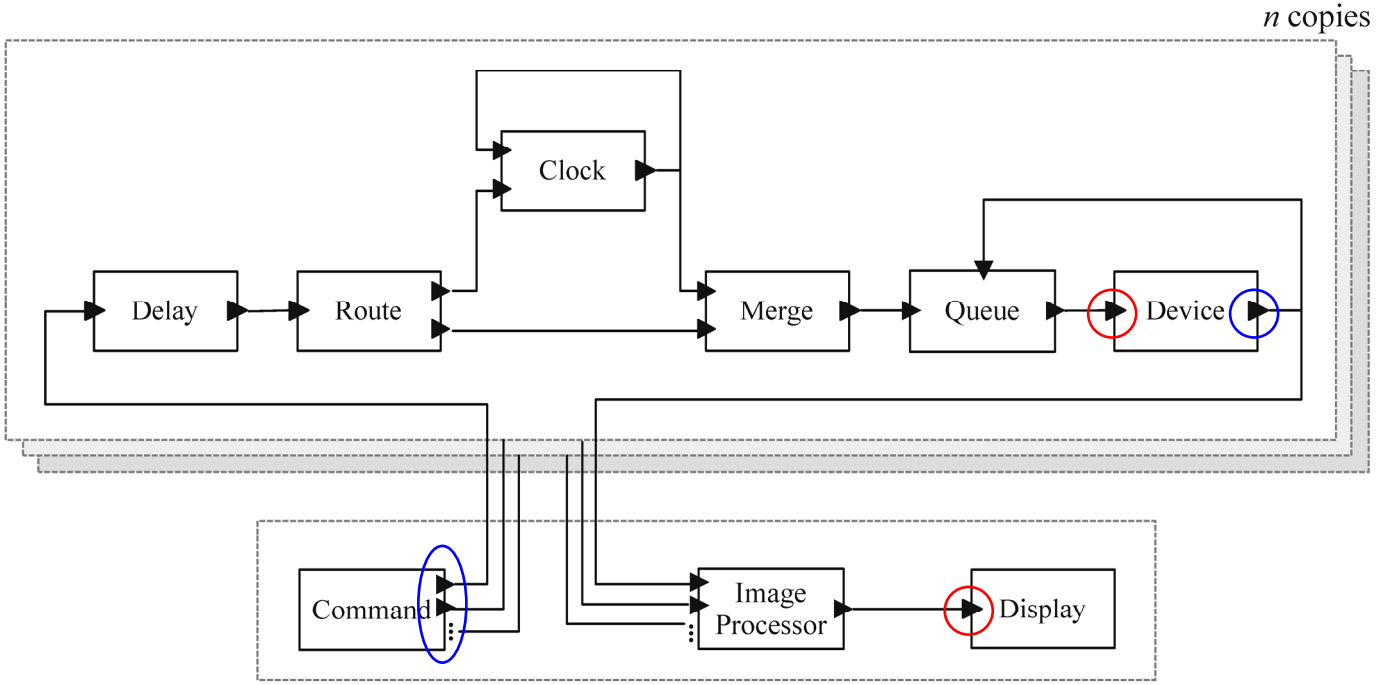


Determine earliest event $e = (v, t)$ at ε_1 safe to process

- If we choose C_1: all unprocessed events at ε_1 will have time stamps $\geq t$.
- If we choose C_2: for any $\varepsilon \in C_2$, all unprocessed events at in ε_1 depend on events at ε with time stamps $\geq t - d(\varepsilon, \varepsilon_1)$.
- We can freely choose a dependency cut.

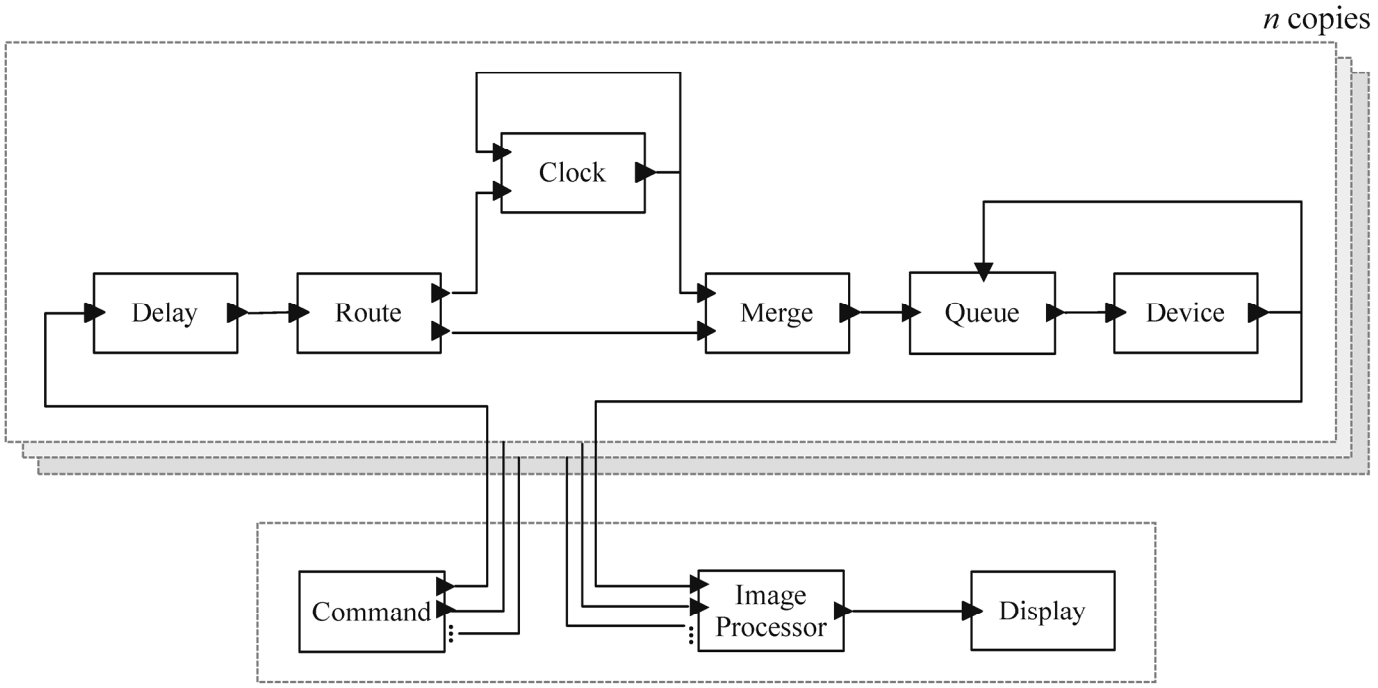
Reference Application: Distributed Cameras

- *n* cameras located around a football field, all connected to a central computer.
- Events at blue ports satisfy $t \leq \tau$
  (t – time stamp of any event; τ – real time)
- Events at red ports satisfy $t \geq \tau$

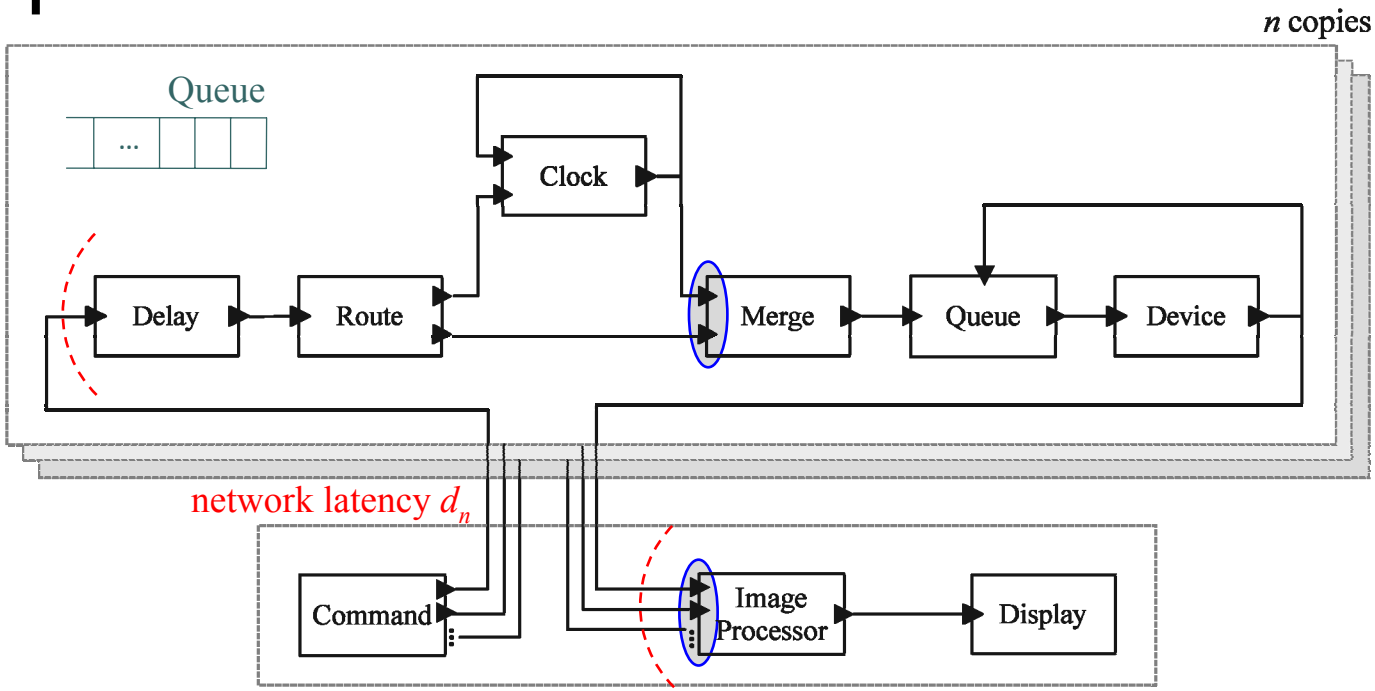


Problems to solve

- Make event-processing decisions locally
- Guarantee timely command delivery to the Devices
- Guarantee real-time update at the Display
- Tolerate images loss or corruption at Image Processor



Choose Dependency Cuts at Platform Boundaries



- n + 1 platforms with synchronized clocks (IEEE 1588).
- Choose dependency cuts at platform boundary.
- A queue stores events local to the platform.
- At real time τ, future events have time stamps $\geq \tau - d_n$.