Systems of Systems Modeling

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Invited Talk
International Conference on Complex Systems Design & Management

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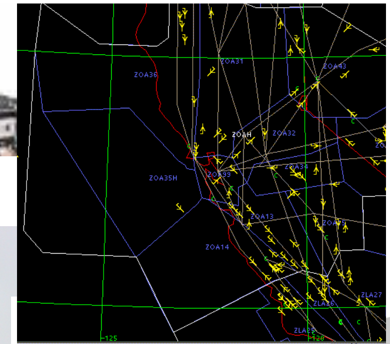
Cyber-Physical Systems (CPS):

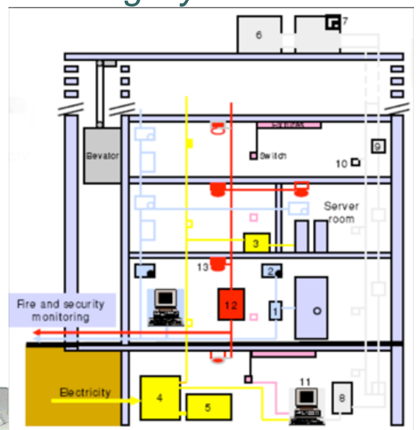
Orchestrating networked computational resources with physical systems

Avionics



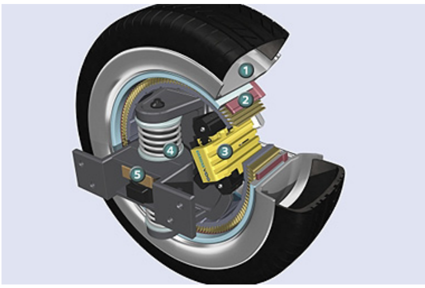
Transportation (Air traffic control at SFO)

Building Systems

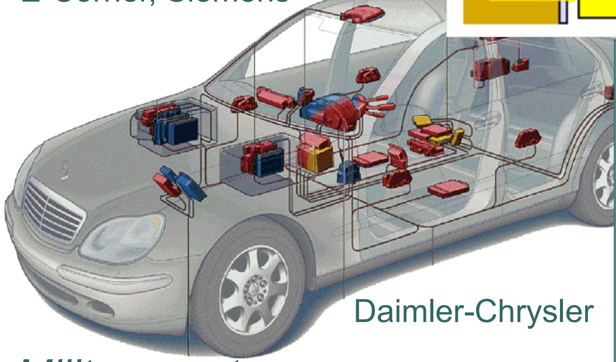


Telecommunications

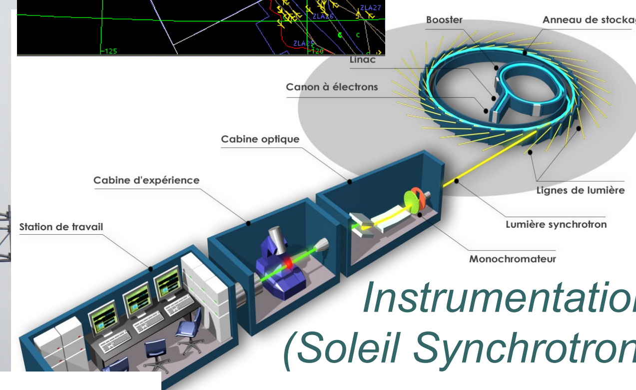
Automotive



E-Corner, Siemens



Daimler-Chrysler



Instrumentation (Soleil Synchrotron)

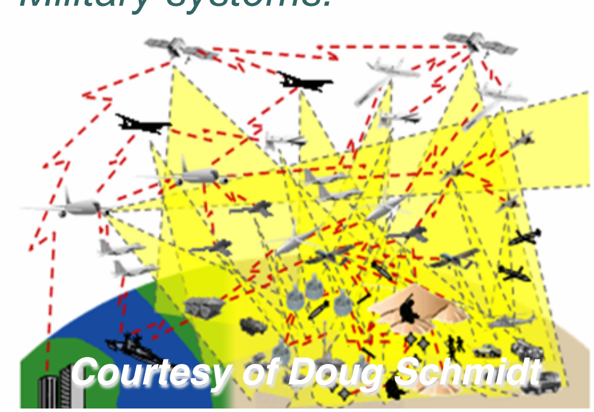
Factory automation

Courtesy of Kuka Robotics Corp.

Power generation and distribution

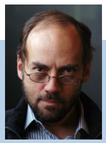
Courtesy of General Electric

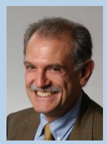
Military systems:

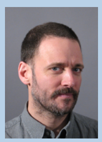


A New Research Center: iCyPhy
Industrial Cyber-Physical Systems

Berkeley:







Ilge Akkaya
Nikunj Bajaj
David Broman
Christopher Brooks
Dai Bui
Patricia Derler
John Eidson, PhD
John B. Finn
Liangpeng Guo
Barb Hoversten
Antonio Iannopollo
Hokeun Kim
Edward A. Lee
Chung-Wei Lin
Marten Lohstroh
Mehdi Maasoumy
Pierluigi Nuzzo
Alberto Puggelli
Alberto Sangiovanni-Vincentelli
Chris Shaver
Christos Stergiou
Stavros Tripakis
Ben Zhang

Caltech:

Scott Livingston
Quentin Malliet
Yilin Mo
Richard Murray
Necmiye Ozay
Mumu Xu

IBM:

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Henry Broodney
Yishai Feldman
Amit Fisher
Lev Greenberg
Itai Jaeger
Michael Masin
Eldad Palachi
Gabi Zodik

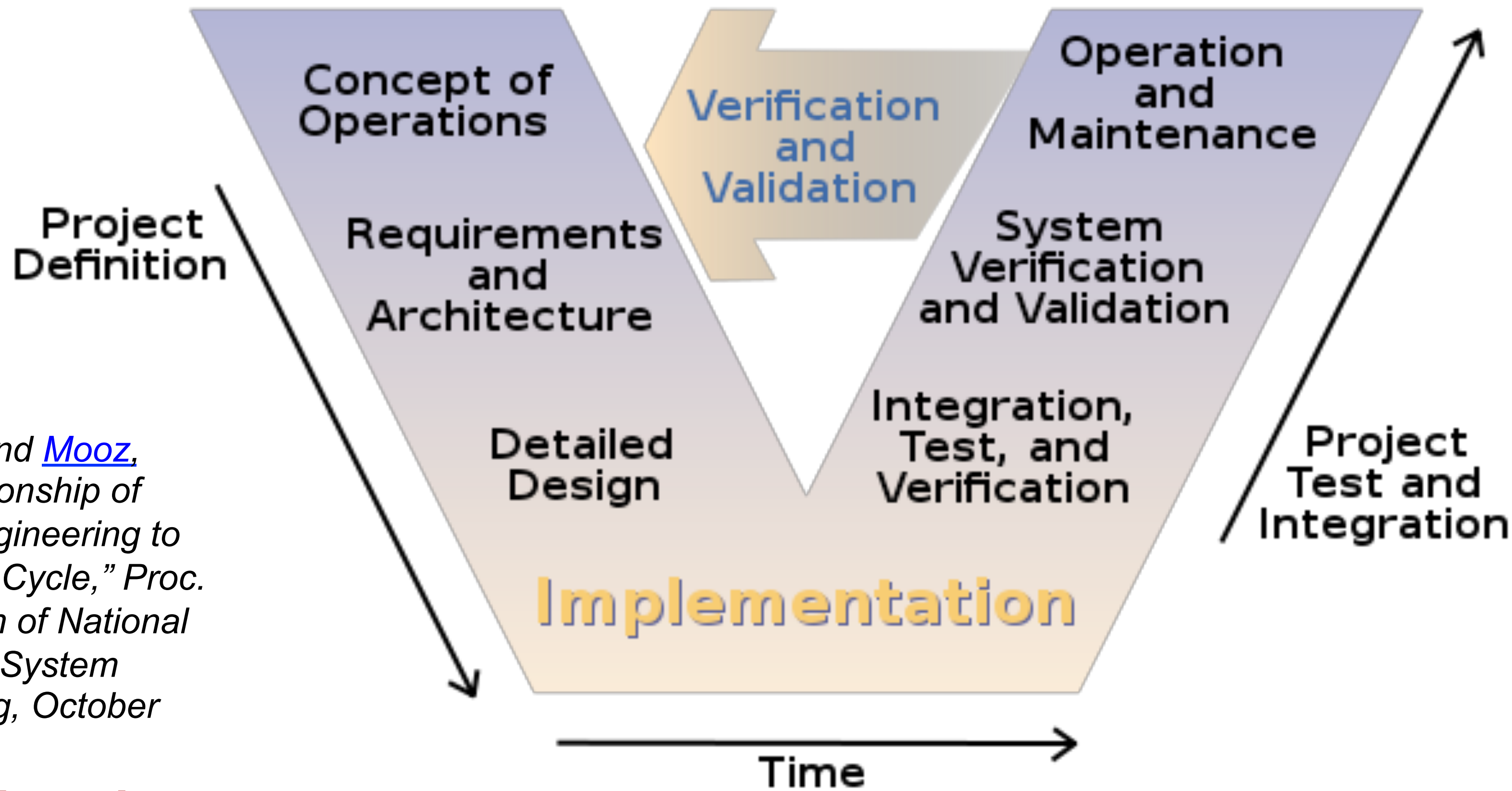
UTC:

Joshua Berg
Gloria F. Byar
Massimiliano Chiodo
Don Chritz
Marco di Natale
Jeff Ernst
Alberto Ferrari
Clas Jacobson
Scott Kaslusky
Al Markunas
Brian T. Murray
Satish Narayanan
Claudio Pinello
Alessandro Pinto
Eelco Scholte

Other Participants:

Johan Akesson (Modelon)
Torsten Blochwitz (Itisim)
Magnus Gafvert (Modelon)
Oscar Mickelin (KTH)
Necmiye Ozay (U. Michigan)
Hubertus Tummescheit (Modelon)
Michael Wetter (LBL)

The Conventional V-Model of System Design

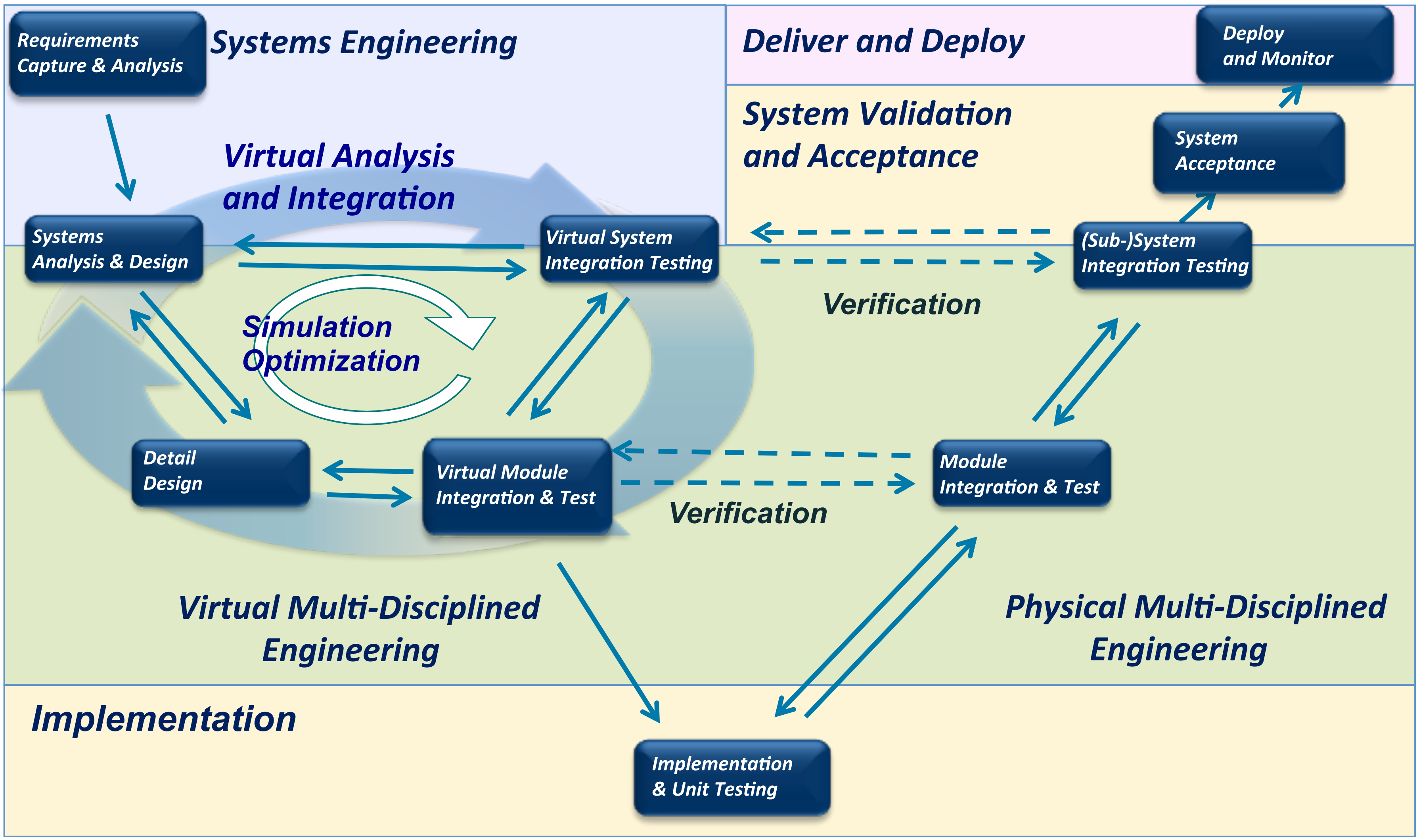


[Forsberg](#) and [Mooz](#), *"The Relationship of System Engineering to the Project Cycle," Proc. Symposium of National Council on System Engineering, October 1991.*

This leads to late validation (at system integration time).

Image source: [Clarus Concept of Operations.](#) Publication No. FHWA-JPO-05-072, Federal Highway Administration (FHWA), 2005.

The iCyPhy Model of System Design



Virtual Integration Requires Working with Models.
Models vs. Reality

Solomon Golomb: Mathematical models – Uses and limitations. Aeronautical Journal 1968

You will never strike oil by drilling through the map!

Solomon Wolf Golomb (1932) mathematician and engineer and a professor of electrical engineering at the University of Southern California. Best known to the general public and fans of mathematical games as the inventor of polyominoes, the inspiration for the computer game Tetris. He has specialized in problems of combinatorial analysis, number theory, coding theory and communications.

But this does not, in any way, diminish the value of a map!

The Kopetz Principle

Prof. Dr. Hermann Kopetz

Many (predictive) properties that we assert about systems (determinism, timeliness, reliability, safety) are in fact not properties of an *implemented* system, but rather properties of a *model* of the system.

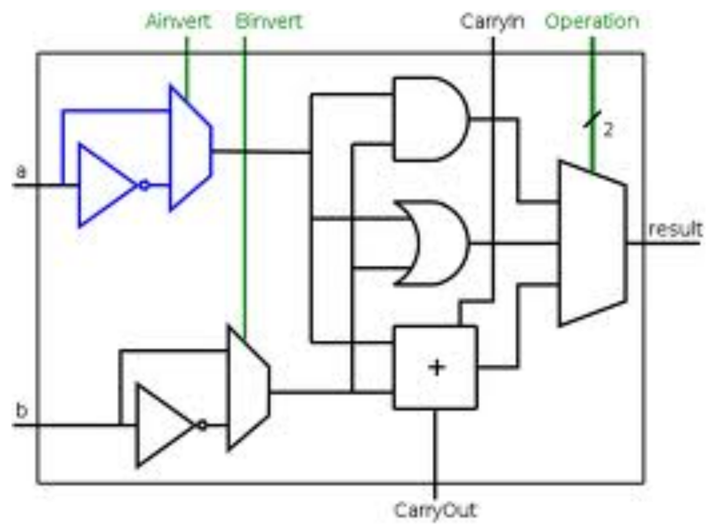
We can make definitive statements about *models*, from which we can *infer* properties of system realizations. The validity of this inference depends on *model fidelity*, which is always approximate.

(paraphrased)

Determinate Models

Physical System

Model



Synchronous digital logic

Determinate Models

Physical System

Model

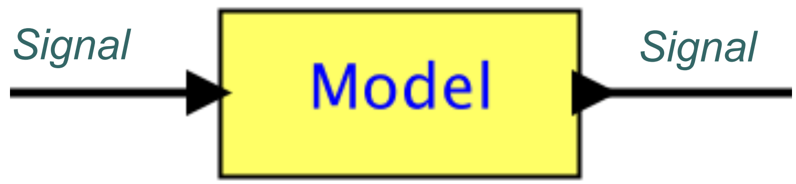

```
/** Reset the output receivers, which are the inside receivers of
 *  the output ports of the container.
 *  @exception IllegalActionException If getting the receivers fails.
 */
private void _resetOutputReceivers() throws IllegalActionException {
    List<IOPort> outputs = ((Actor) getContainer()).outputPortList();
    for (IOPort output : outputs) {
        if (_debugging) {
            _debug("Resetting inside receivers of output port: "
                    + output.getName());
        }
        Receiver[][] receivers = output.getInsideReceivers();
        if (receivers != null) {
            for (int i = 0; i < receivers.length; i++) {
                if (receivers[i] != null) {
                    for (int j = 0; j < receivers[i].length; j++) {
                        if (receivers[i][j] instanceof FSMReceiver) {
                            receivers[i][j].reset();
                        }
                    }
                }
            }
        }
    }
}
```

Single-threaded imperative programs

Determinate Models

Physical System

Model

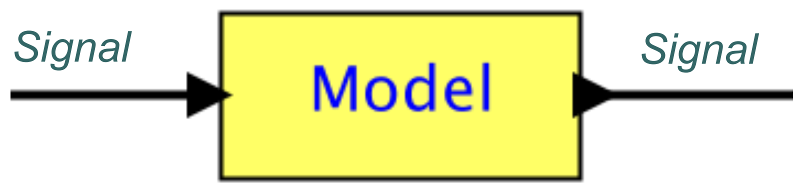


$$\dot{\mathbf{x}}(t) = \dot{\mathbf{x}}(0) + \frac{1}{M}\int_0^t \mathbf{F}(\tau)d\tau$$

Differential Equations

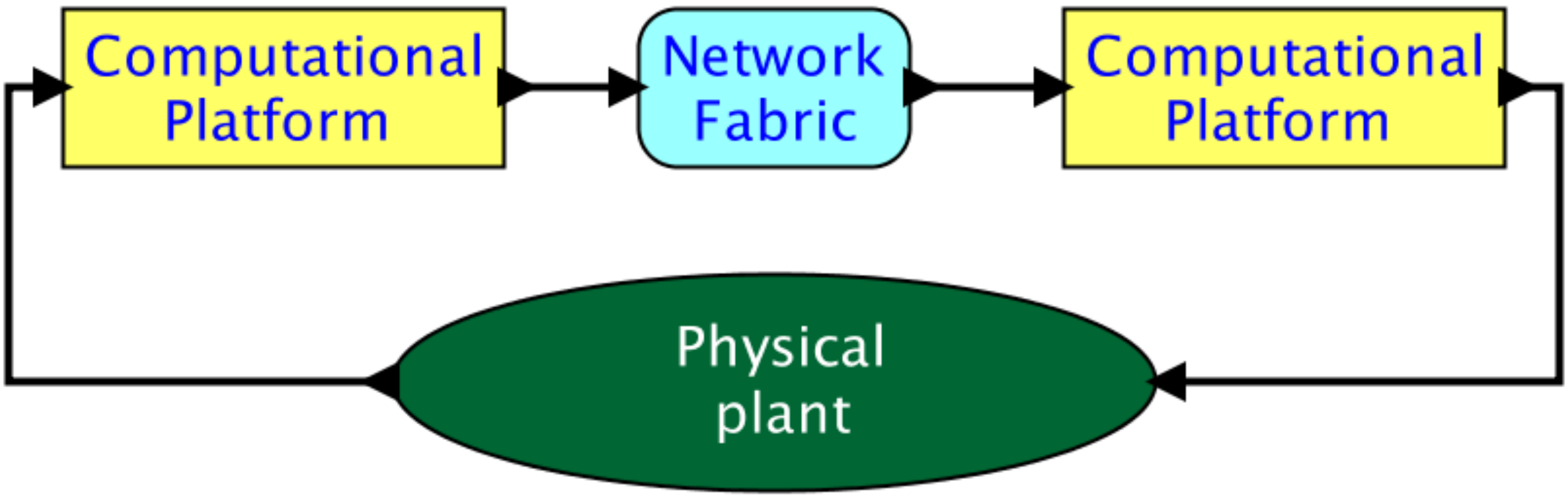
A Major Problem for CPS: Combinations are Nondeterminate


```java
/** Reset the output receivers, which are the inside receivers of
 *  the output ports of the container.
 *  @exception IllegalActionException If getting the receivers fails.
 */
private void _resetOutputReceivers() throws IllegalActionException {
    List<IOPort> outputs = ((Actor) getContainer()).outputPortList();
    for (IOPort output : outputs) {
        if (_debugging) {
            _debug("Resetting inside receivers of output port: "
                    + output.getName());
        }
        Receiver[][] receivers = output.getInsideReceivers();
        if (receivers != null) {
            for (int i = 0; i < receivers.length; i++) {
                if (receivers[i] != null) {
                    for (int j = 0; j < receivers[i].length; j++) {
                        if (receivers[i][j] instanceof FSMReceiver) {
                            receivers[i][j].reset();
                        }
                    }
                }
            }
        }
    }
}
```



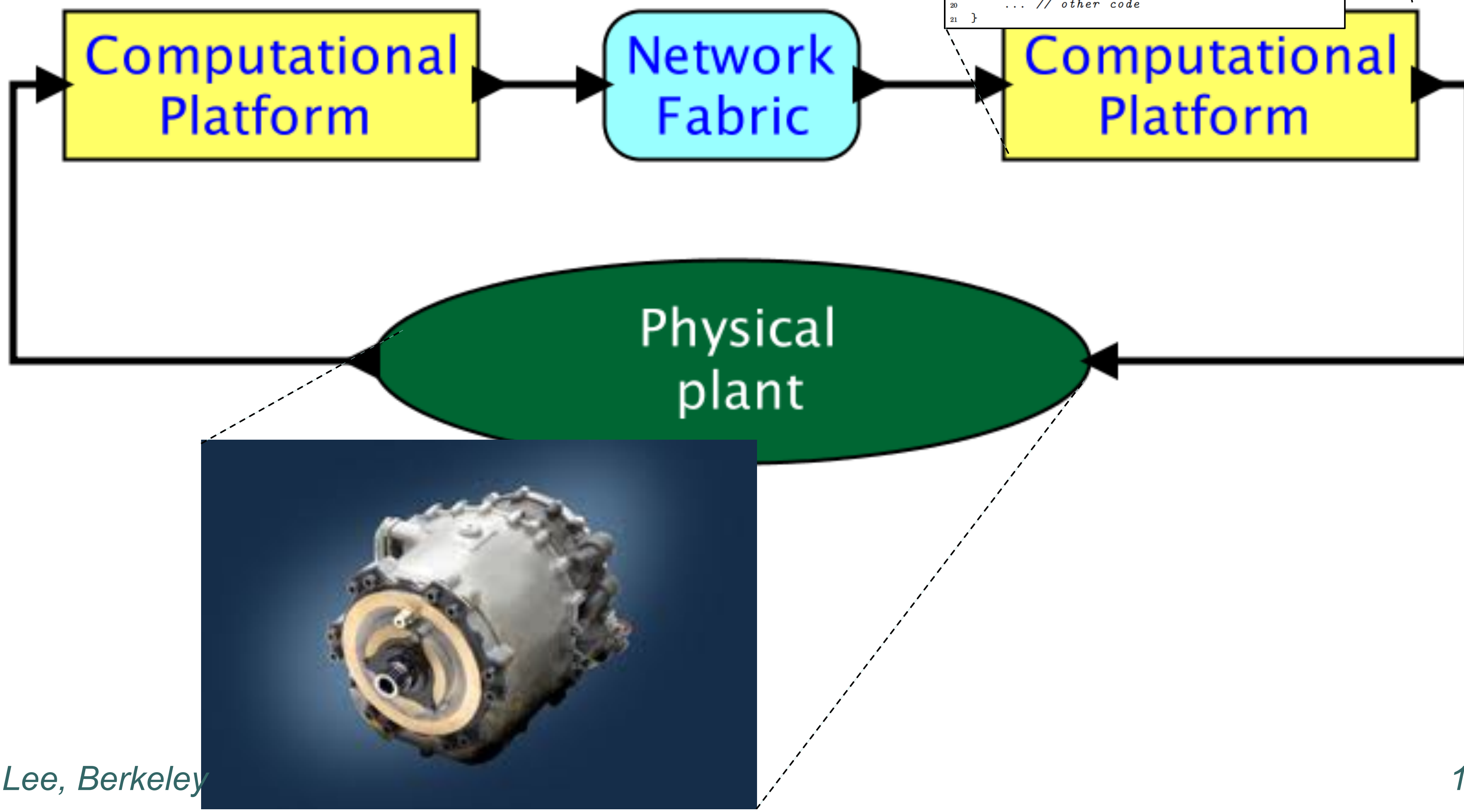
$$\dot{\mathbf{x}}(t) = \dot{\mathbf{x}}(0) + \frac{1}{M}\int_0^t \mathbf{F}(\tau)d\tau$$

Schematic of a simple CPS:

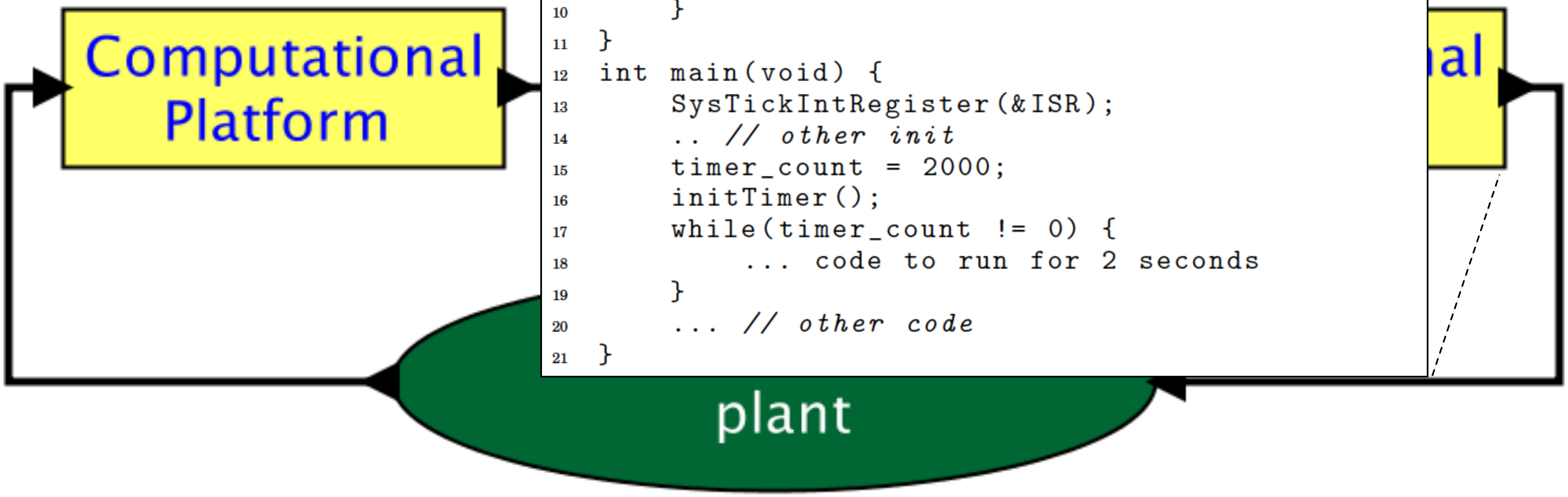


Computation given in an untimed, imperative language. Physical plant modeled with ODEs or DAEs

```
void initTimer(void) {
    SysTickPeriodSet(SysCtlClockGet() / 1000);
    SysTickEnable();
    SysTickIntEnable();
}
volatile uint timer_count = 0;
void ISR(void) {
    if(timer_count != 0) {
        timer_count--;
    }
}
int main(void) {
    SysTickIntRegister(&ISR);
    .. // other init
    timer_count = 2000;
    initTimer();
    while(timer_count != 0) {
        ... code to run for 2 seconds
    }
    ... // other code
}
```

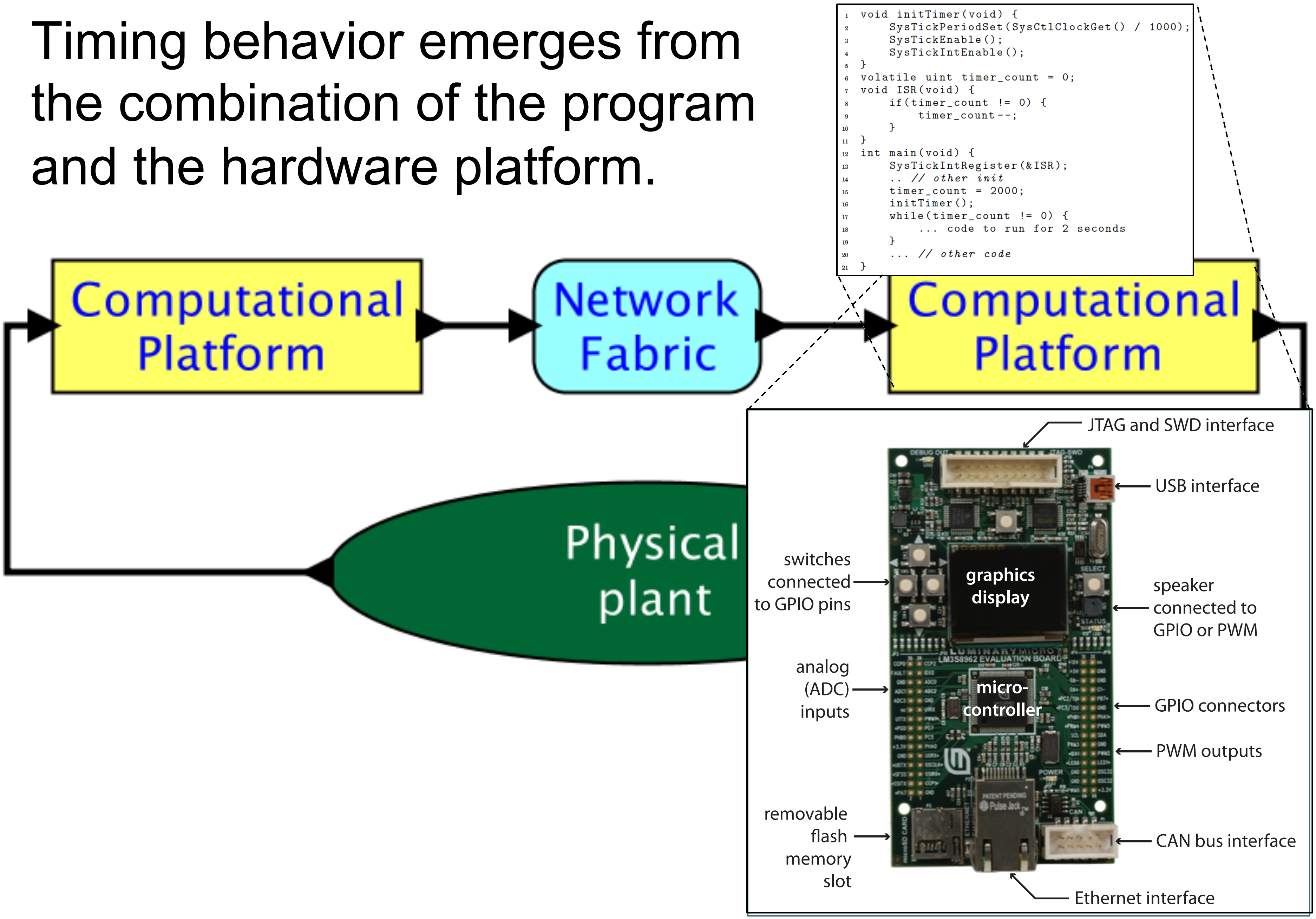


This code is attempting to control timing. But will it really?




```c
void initTimer(void) {
    SysTickPeriodSet(SysCtlClockGet() / 1000);
    SysTickEnable();
    SysTickIntEnable();
}
volatile uint timer_count = 0;
void ISR(void) {
    if(timer_count != 0) {
        timer_count--;
    }
}
int main(void) {
    SysTickIntRegister(&ISR);
    .. // other init
    timer_count = 2000;
    initTimer();
    while(timer_count != 0) {
        ... code to run for 2 seconds
    }
    ... // other code
}
```

Timing behavior emerges from the combination of the program and the hardware platform.



Consequences

When timing affects system behavior, designs are brittle. Small changes in the hardware, software, or environment can cause big, unexpected changes in timing. Testing has to be redone. Results:

- Manufacturers frequently stockpile parts to suffice for the complete production run of a product.
- Manufacturers cannot take advantage of improvements in the hardware (e.g. weight, power). The cost of re-testing and re-certifying is too high.
- Designs are over provisioned, increasing cost, weight, and energy usage.

A Key Challenge:
Timing is not Part of Software Semantics

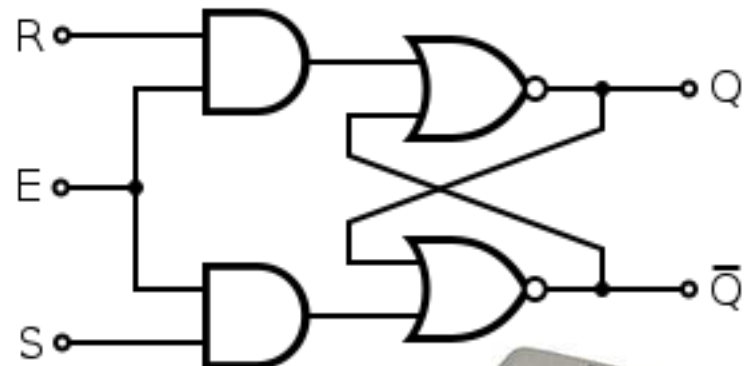
Correct *execution of a program in C, C#, Java, Haskell, OCaml, etc. has nothing to do with how long it takes to do anything. Nearly all our computation and networking abstractions are built on this premise.*

Programmers have to step *outside* the programming abstractions to specify timing behavior.

Programmers have no map!

The hardware out of which we build computers is capable of delivering "correct" computations and precise timing…

The synchronous digital logic abstraction removes the messiness of transistors.



… but the overlaying software abstractions discard the timing precision.

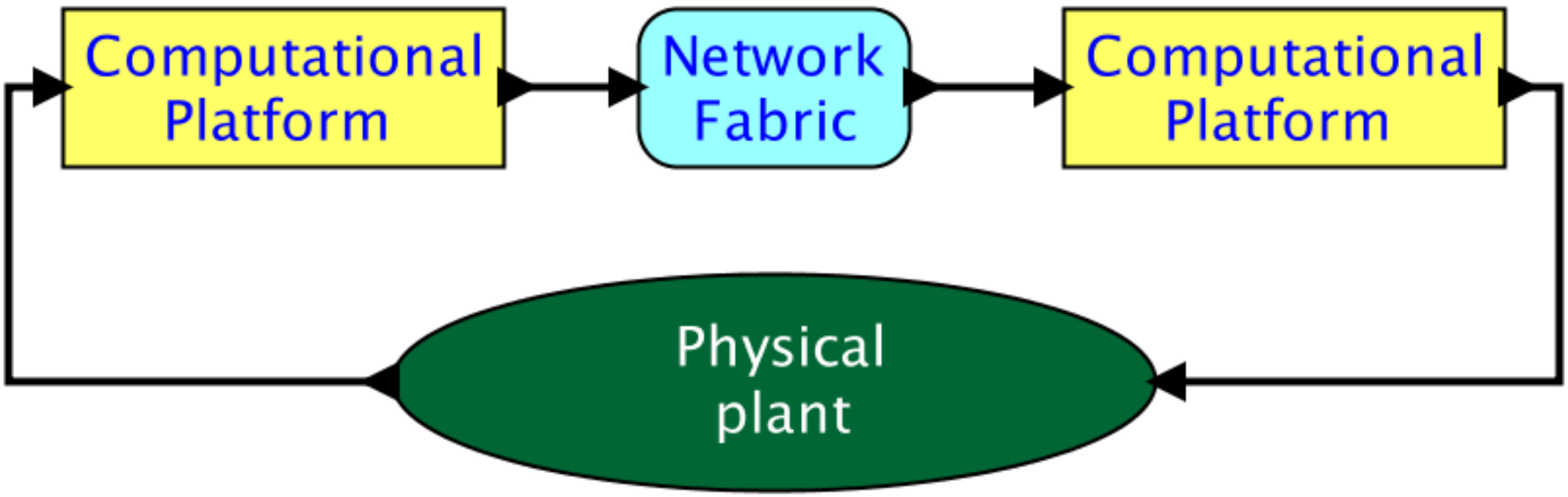
```
// Perform the convolution.
for (int i=0; i<10; i++) {
  x[i] = a[i]*b[j-i];
  // Notify listeners.
  notify(x[i]);
}
```

Challenge

Can we change programming models so that a *correct* execution of a program always delivers the same temporal behavior (up to some precision) at the subsystem I/O?

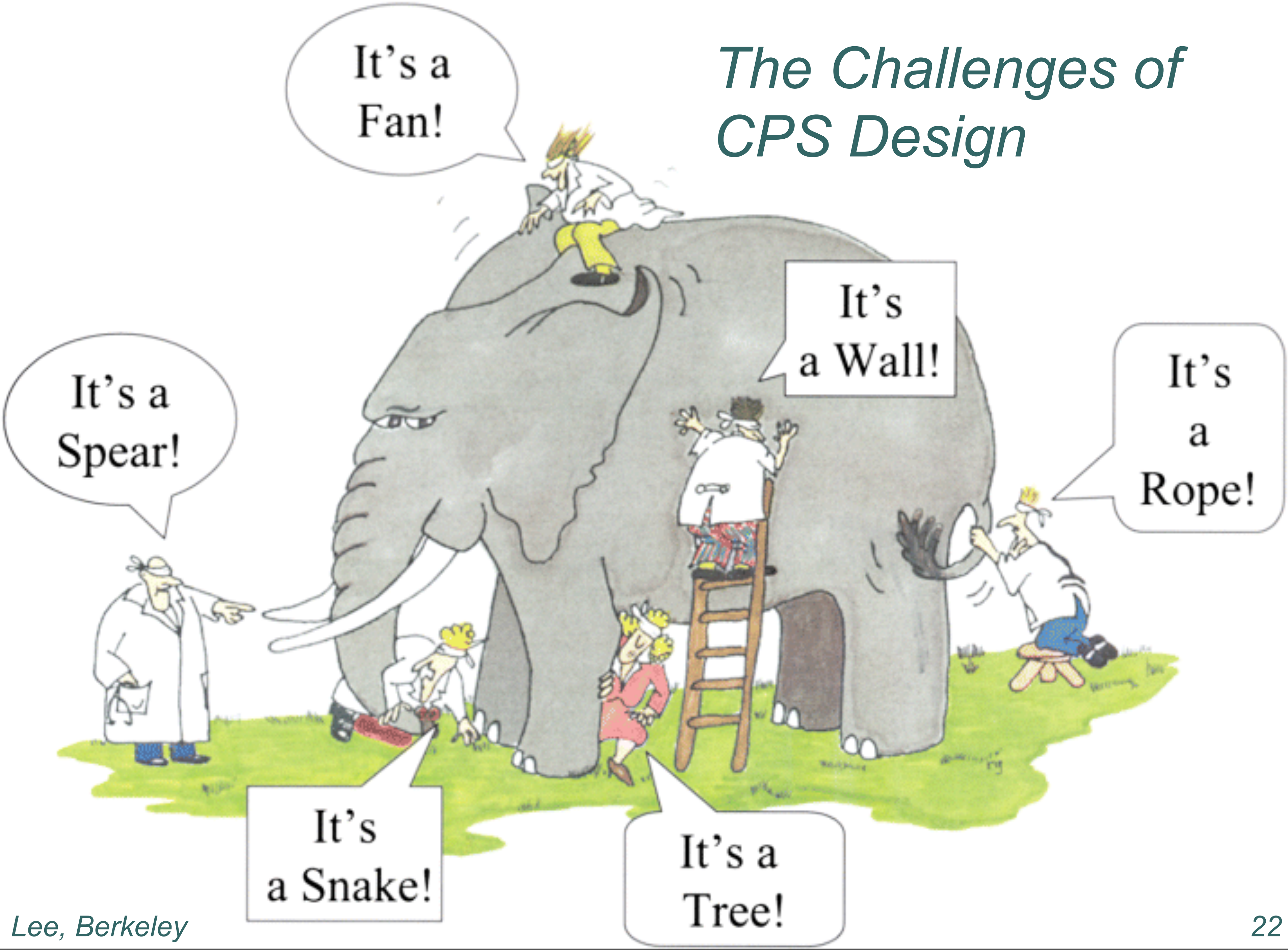
i.e. we need determinate CPS models

Engineering Abstractions *and* Engineering Methodology



Components in such a system come from multiple vendors in diverse engineering disciplines with distinct domain expertise.

The Challenges of CPS Design



E.g. Electric Power Systems (EPS) for Aircraft

Physically:

- Generators
- Contactors
- Busses
- Loads

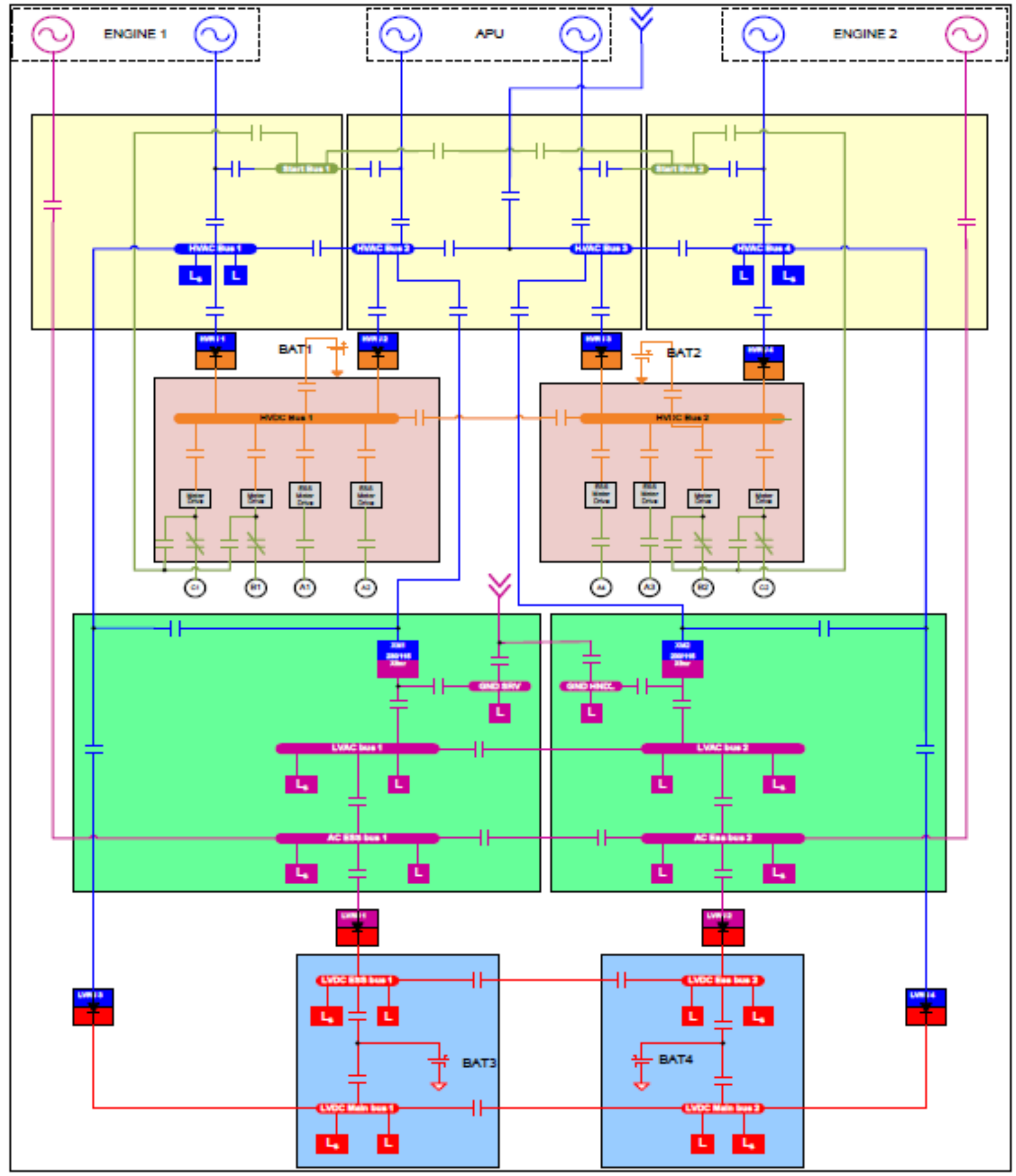
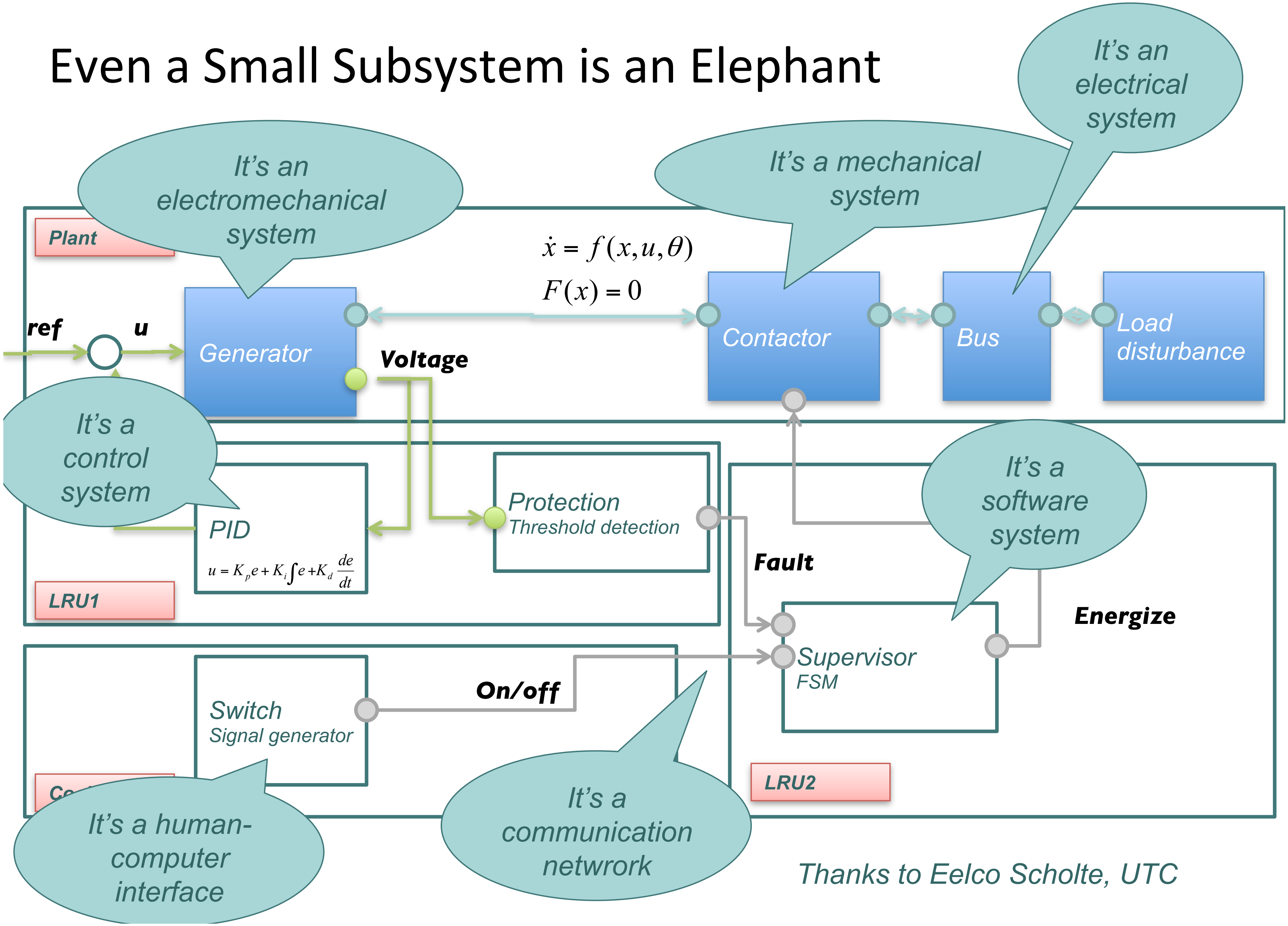


Figure 1: Single line diagram of an electric power system adapted from Honeywell Patent US 7,439,634 B2. Figure courtesy of Rich Poisson, Hamilton-Sundstrand.

Even a Small Subsystem is an Elephant



Thanks to Eelco Scholte, UTC

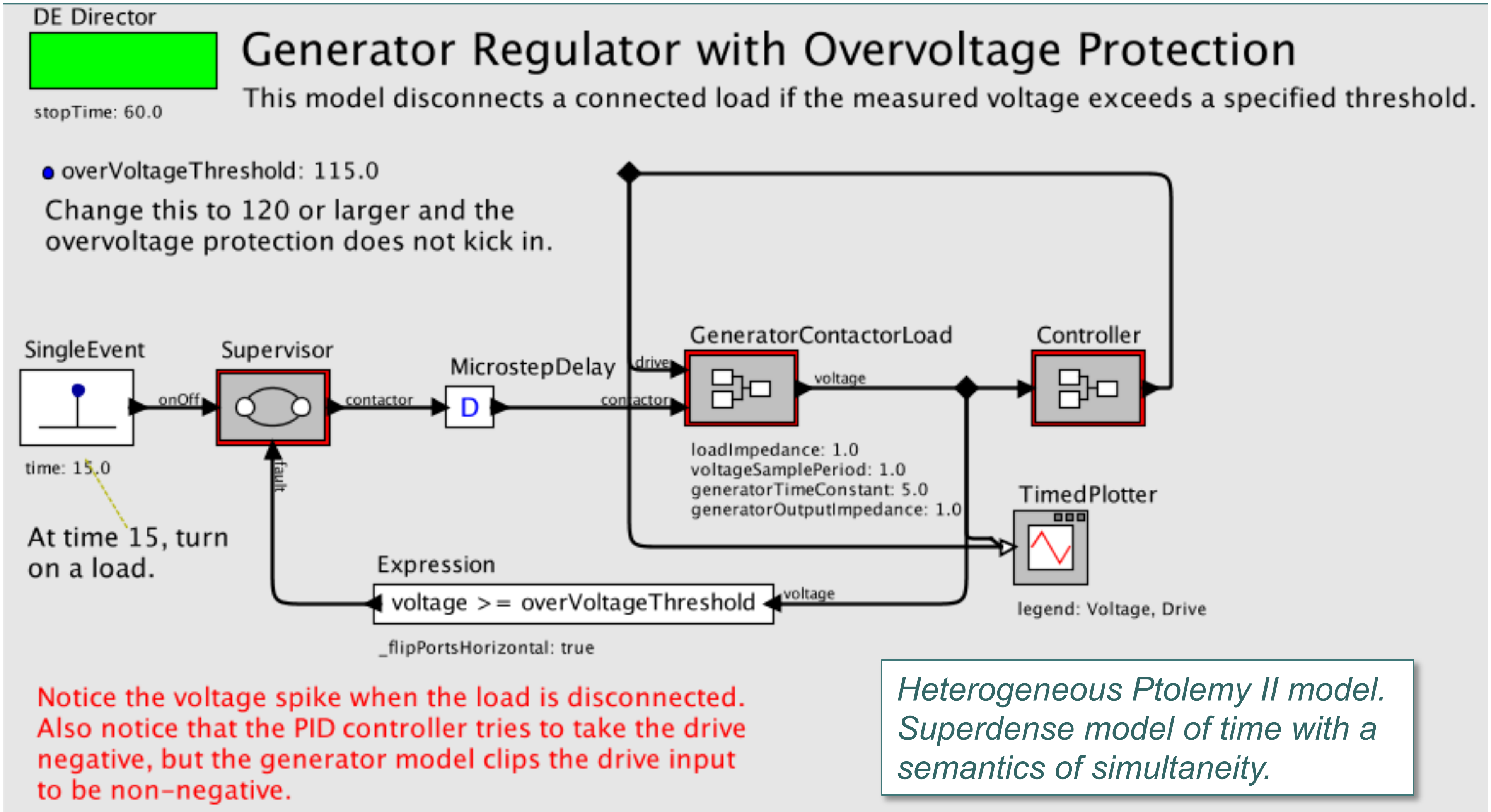
Challenge

How can we define interfaces between components that bridge engineering disciplines and clarify requirements and expectations?

i.e. we need a discipline of "model engineering"

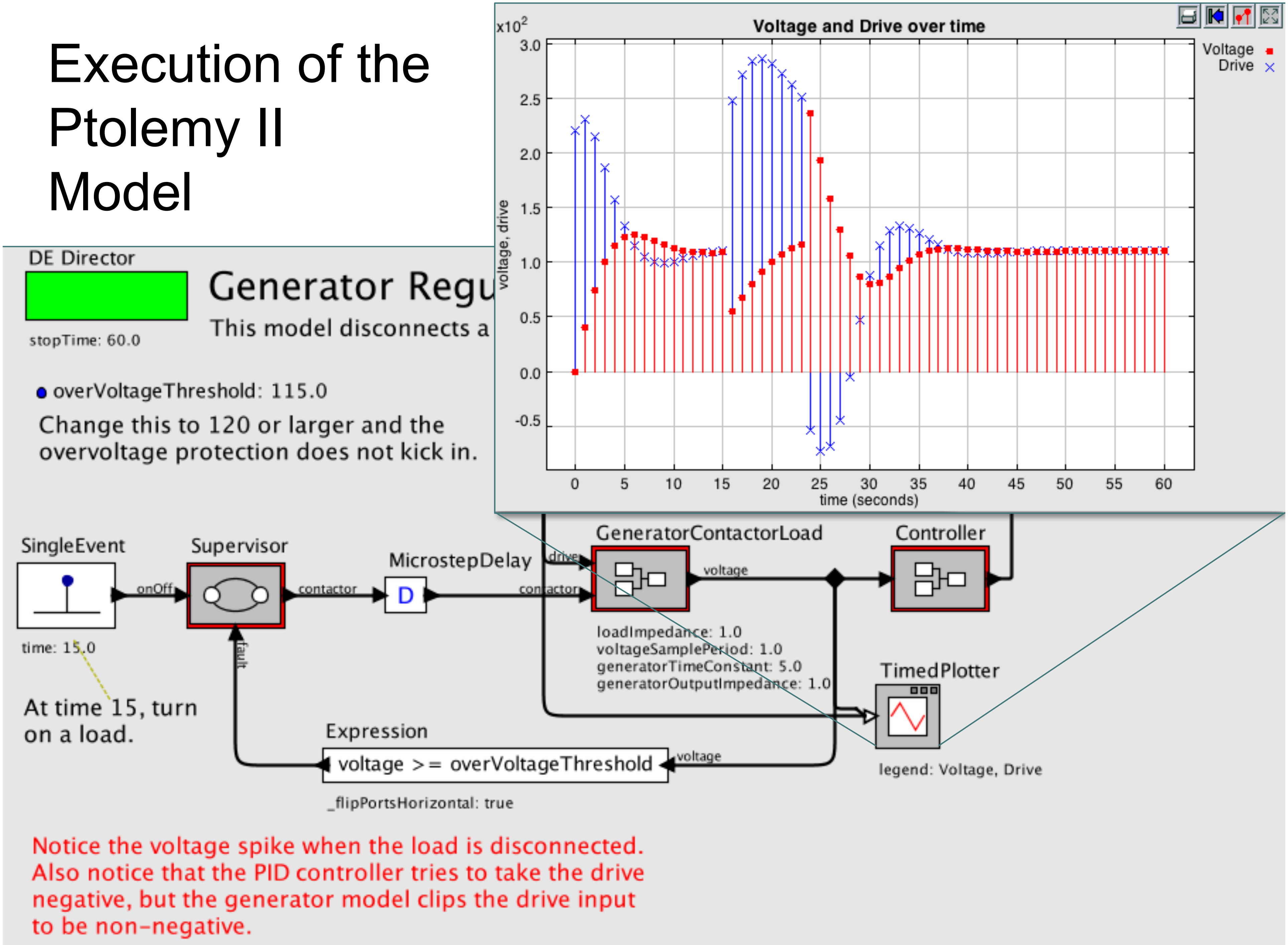
Heterogeneous Models:

Discrete-Event (DE) Model of a Generator-Regulator-Protector in Ptolemy II

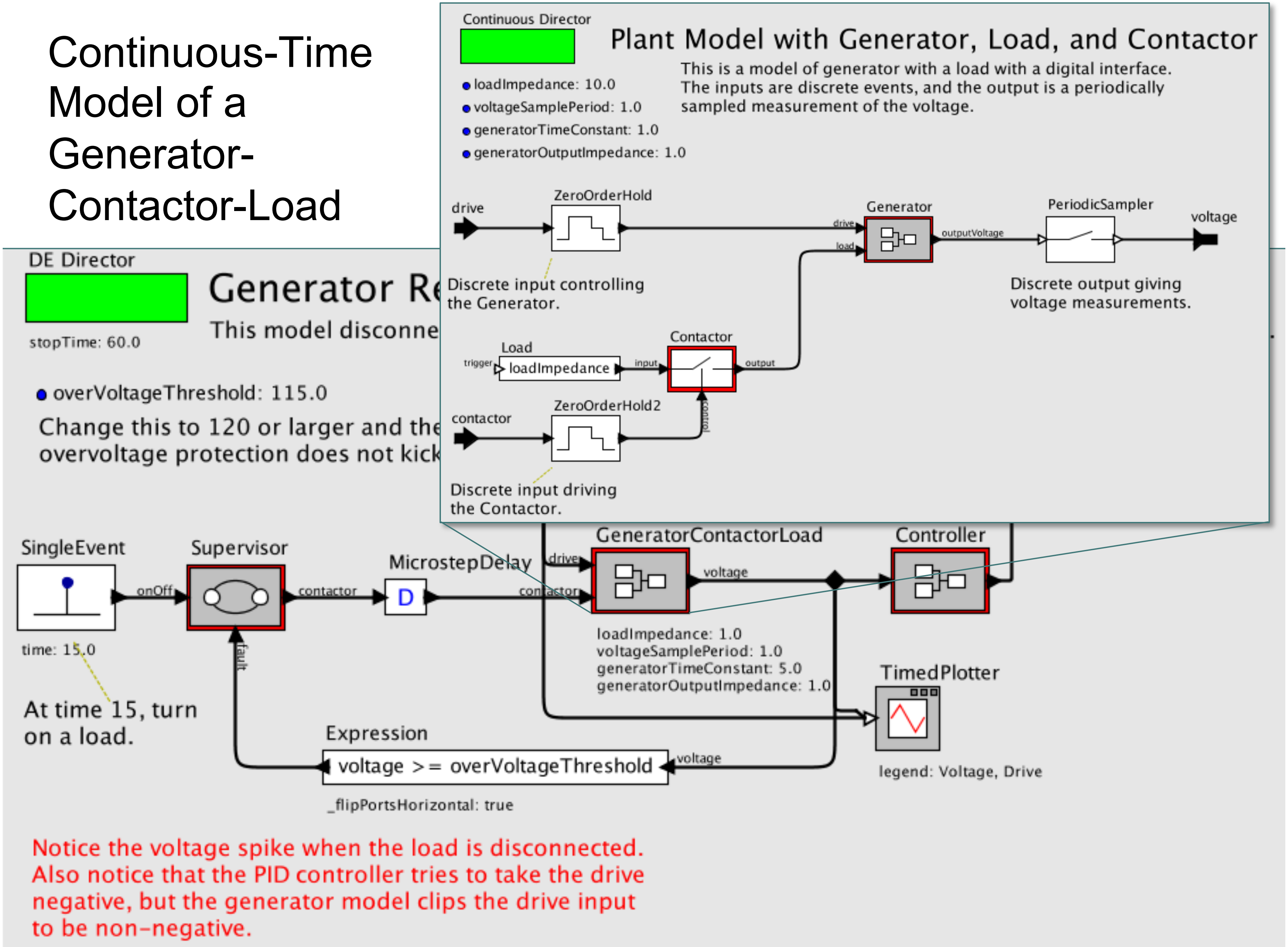


Heterogeneous Ptolemy II model. Superdense model of time with a semantics of simultaneity.

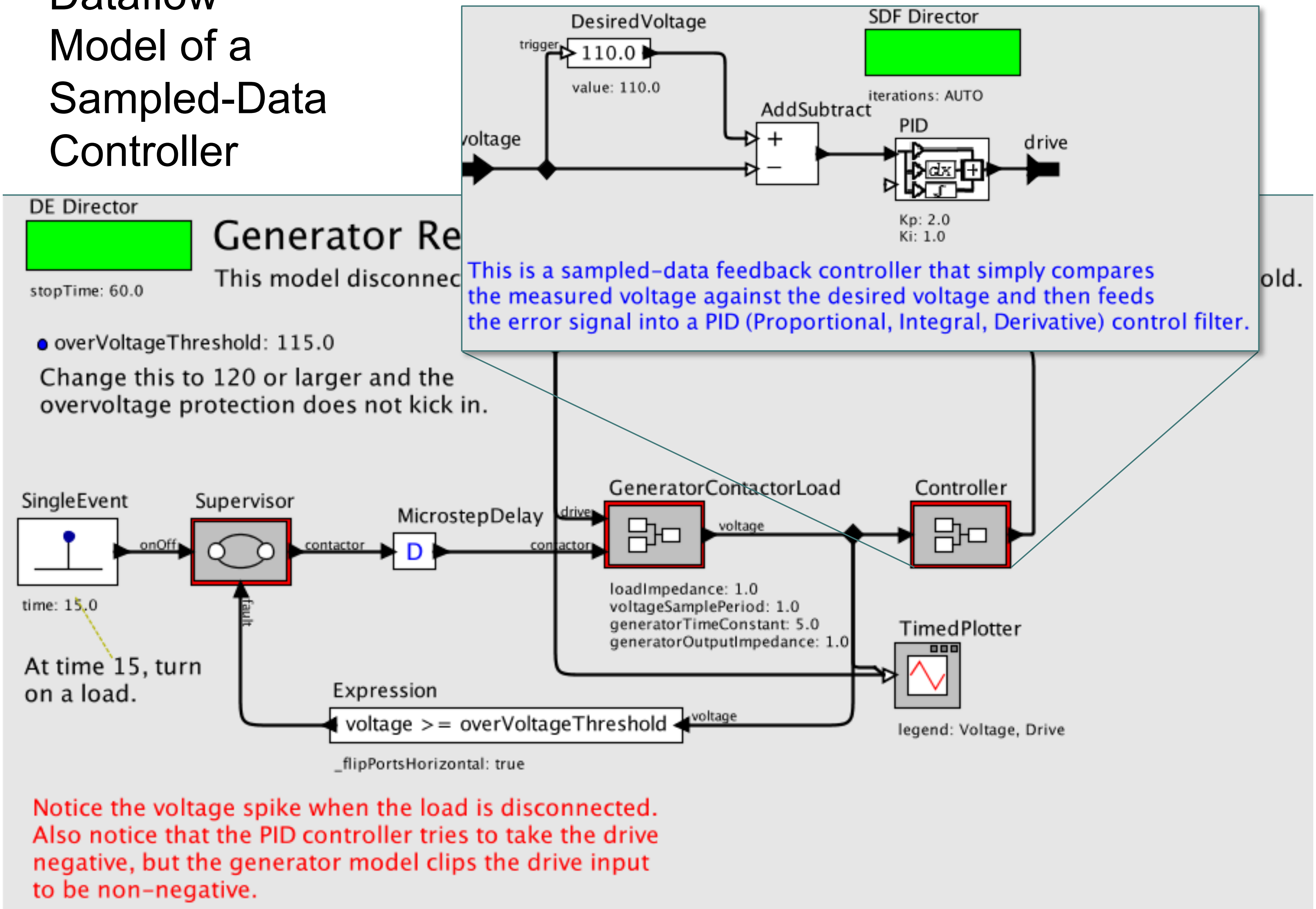
Execution of the Ptolemy II Model



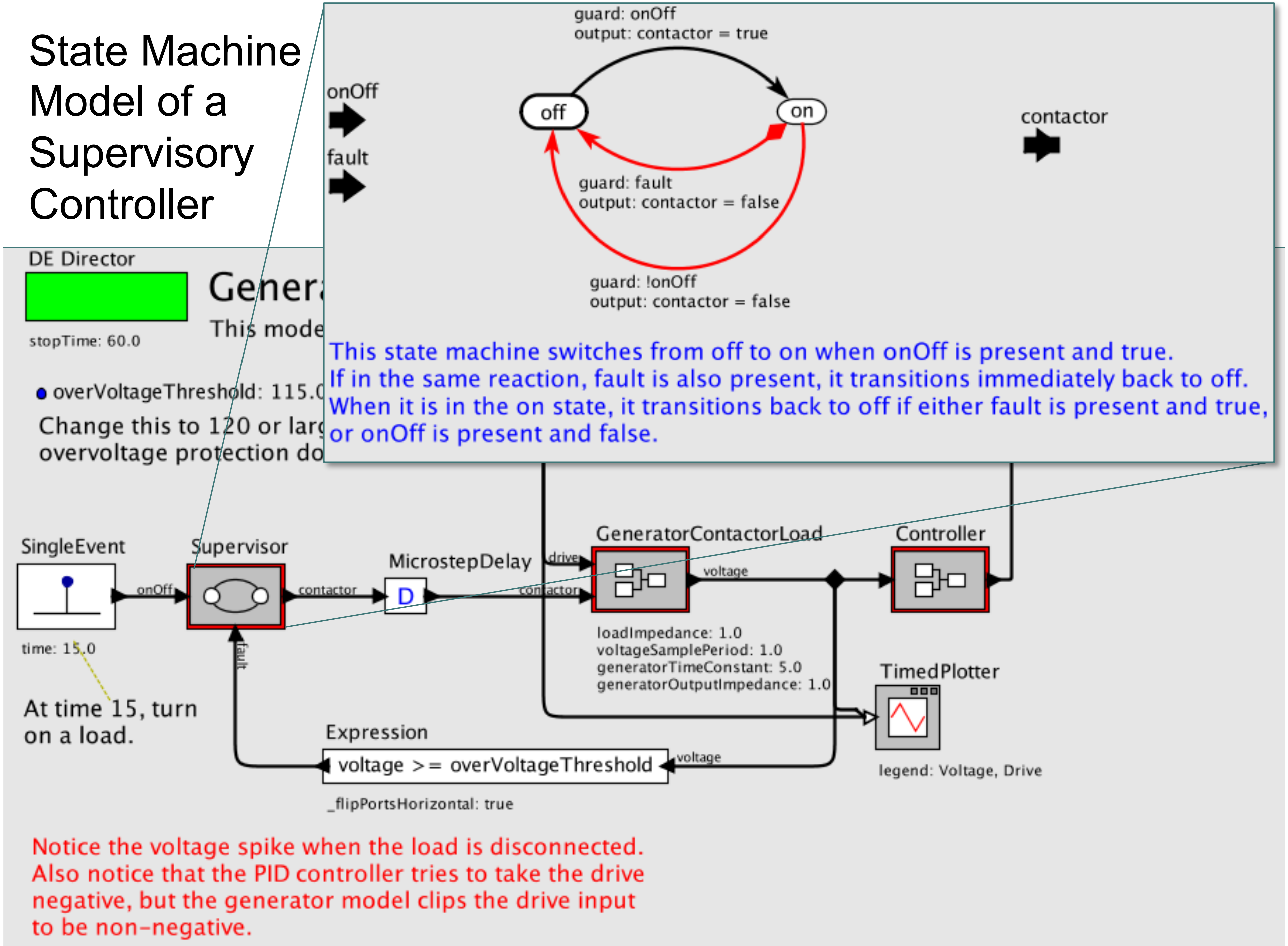
Continuous-Time Model of a Generator-Contactor-Load



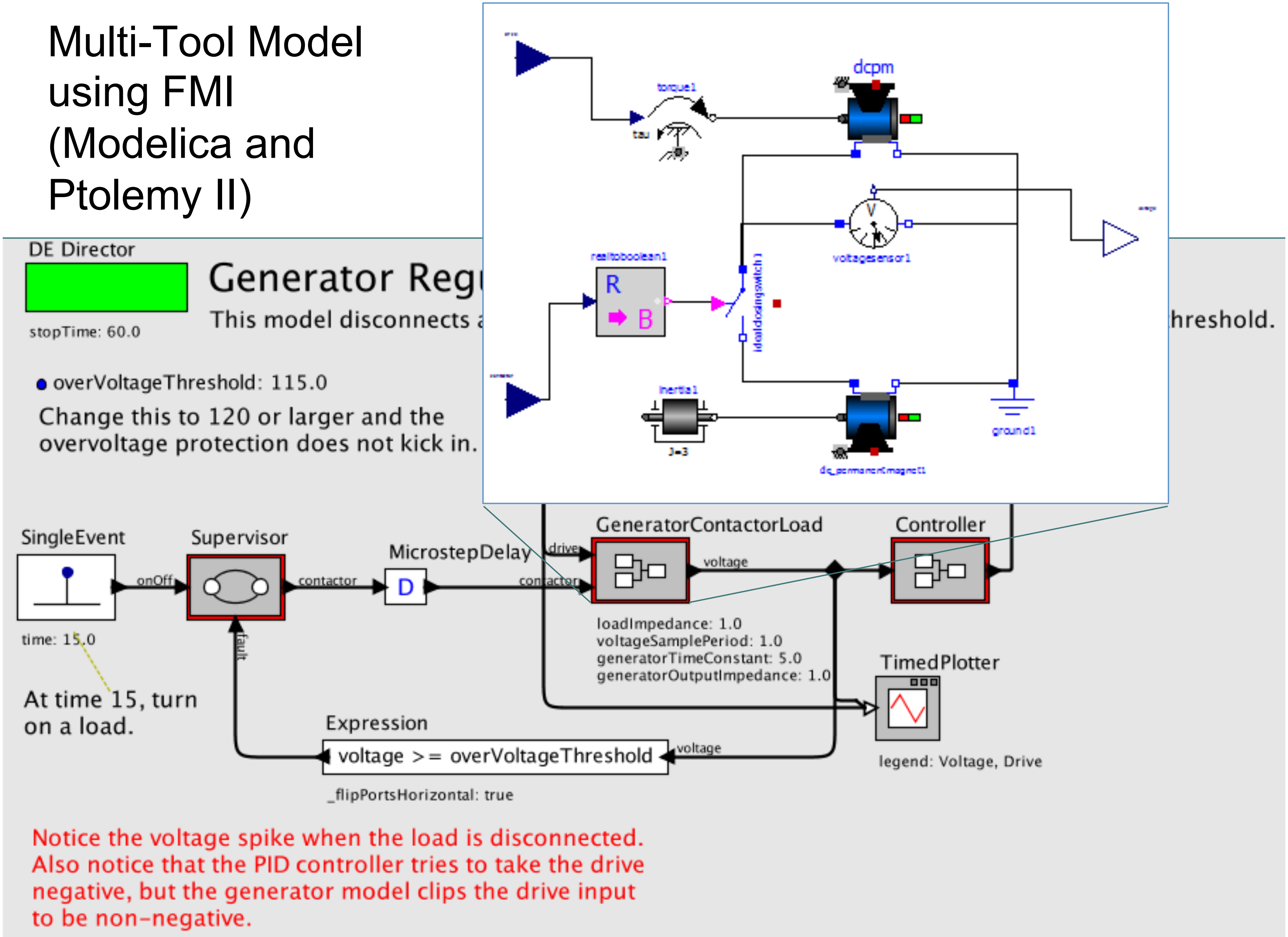
Dataflow Model of a Sampled-Data Controller



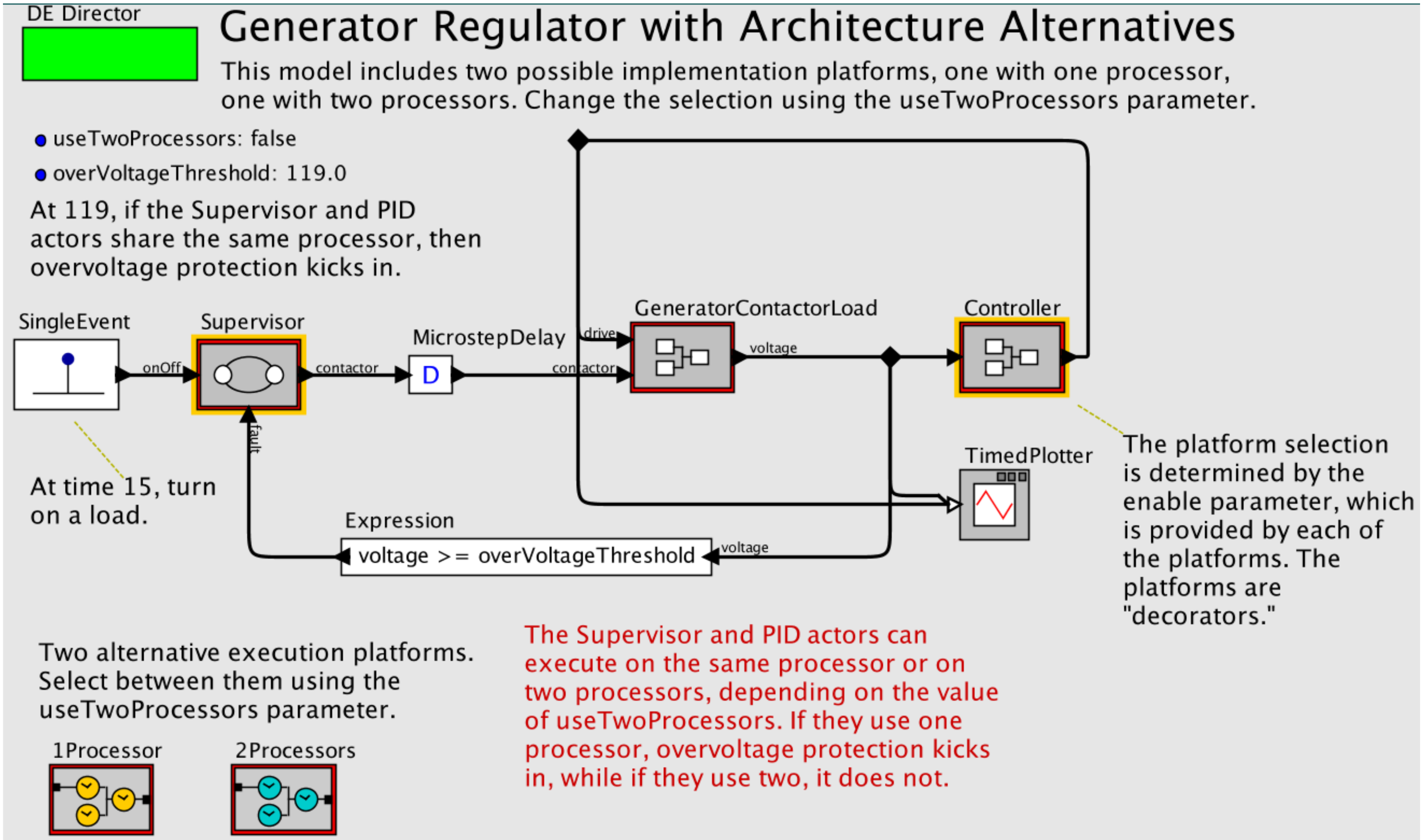
State Machine Model of a Supervisory Controller



Multi-Tool Model using FMI (Modelica and Ptolemy II)

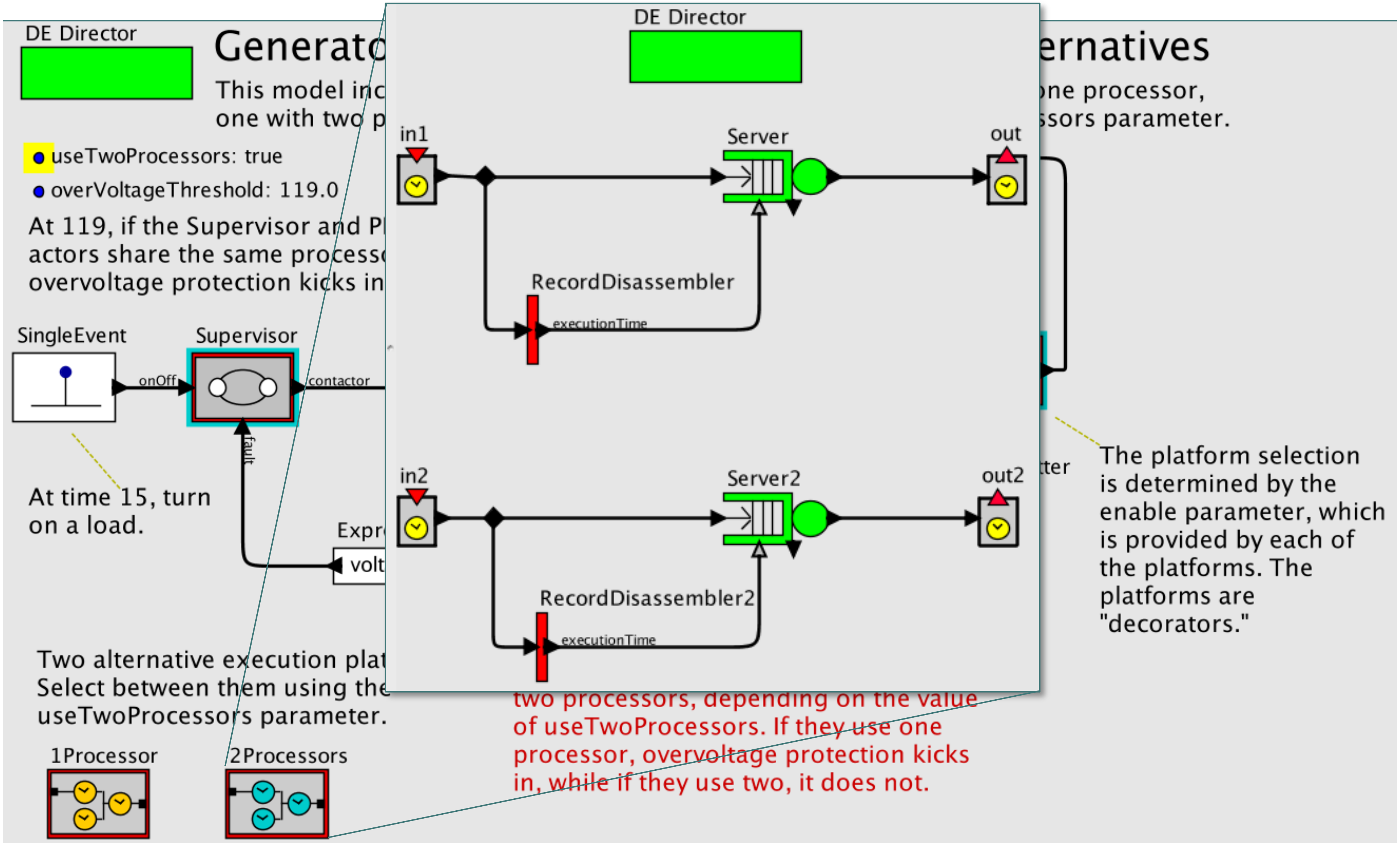


Aspect-Oriented Modeling in Ptolemy II



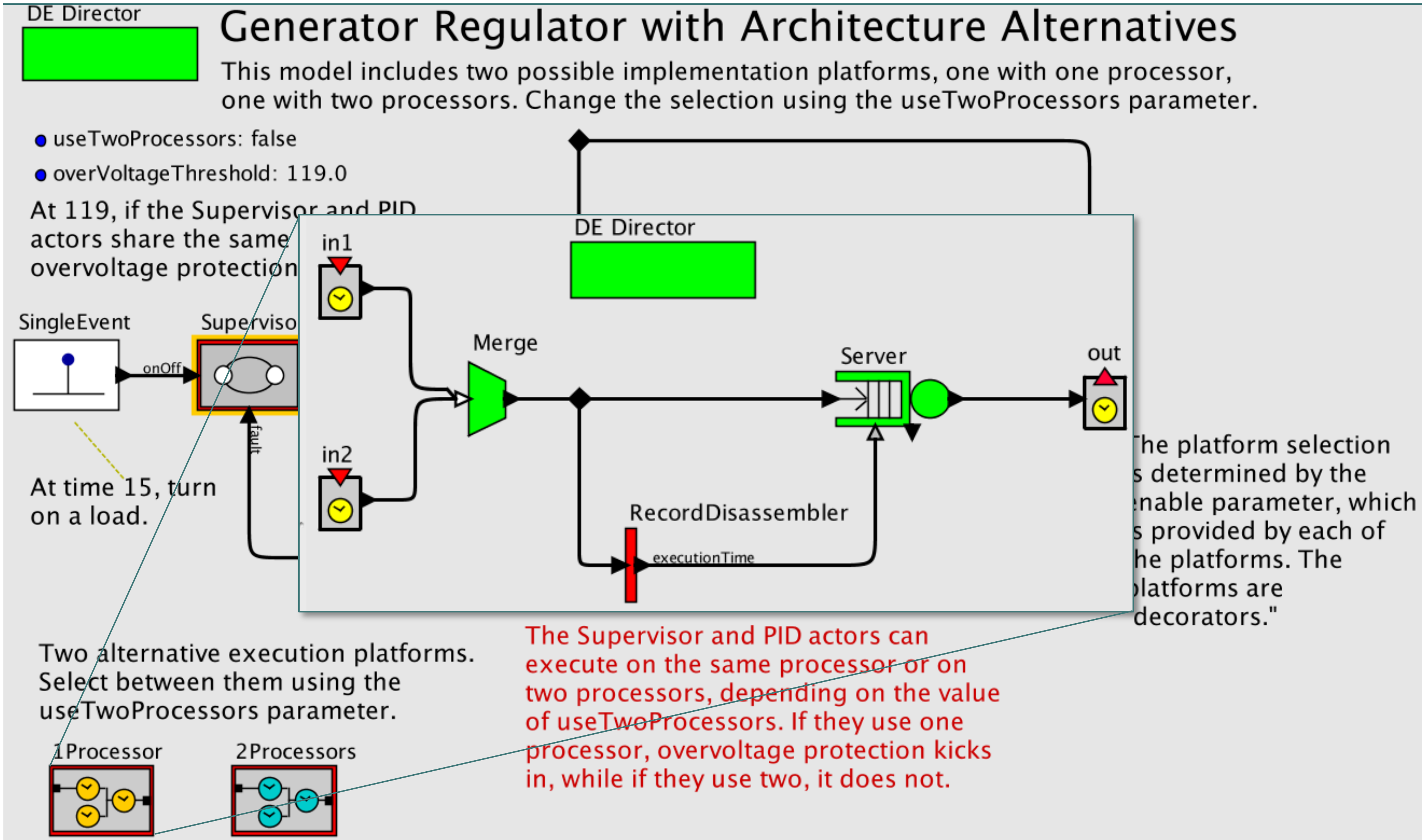
Aspect-Oriented Modeling in Ptolemy II

Two Processor Architecture Model



Aspect-Oriented Modeling in Ptolemy II

One Processor Architecture Model



Other Uses of Aspect-Oriented Modeling

- Modeling communication system architecture
- Modeling the effects of communication impairments
- Modeling faults
- Creating observers:
  - Anomaly detection
  - Contract monitoring
- Security attack models
- …

In Ptolemy II, all of these models are cleanly separated from the functional system model.

Their effect on the model is "woven in" at run time.

Ptolemy II

http://ptolemy.org

- *Open source*
- *Open architecture*
- *Well documented*

Free Book:

Claudius Ptolemaeus, Editor

http://ptolemy.org/systems

This is an open-source book about open source software solutions to pressing industrial problems.

Systems of Systems Modeling

A discipline of “model engineering”

- Embrace models for virtual system integration
- Avoid accidental nondeterminism
- Embrace heterogeneity
- Use aspect-oriented modeling

Raffaello Sanzio da Urbino – The Athens School