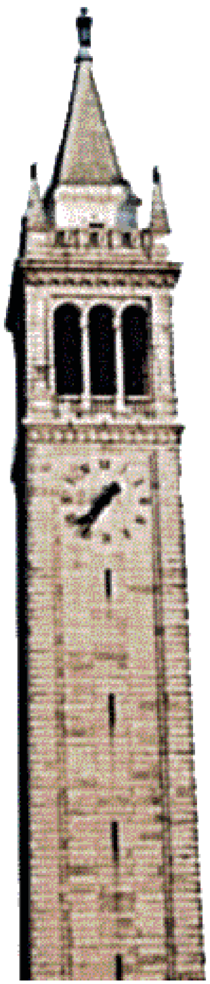


Special Thanks to:

- *David Broman*
- *Isaac Liu*
- *Hiren Patel*
- *Jan Reineke*
- *Michael Zimmer*

Architectural Support for Cyber-Physical Systems

Edward A. Lee

Robert S. Pepper Distinguished Professor
UC Berkeley

Keynote
Architectural Support for Programming Languages and Operating Systems
ASPLOS 2015

March 14-18, 2015.
Istanbul, Turkey

The Context for this Talk: Cyber-Physical Systems

The Internet of Important Things

Orchestrating networked computational resources and physical systems.

Bosch Rexroth Printing Press

Roots of the term CPS:

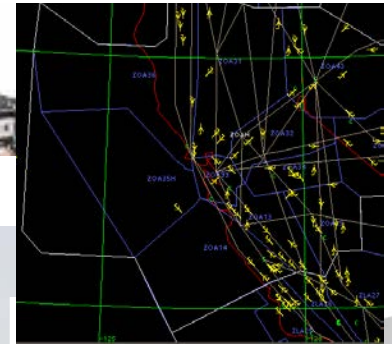
- Coined around 2006 by Helen Gill at the National Science Foundation in the US
- ***Cyberspace**: attributed William Gibson, who used the term in the novel Neuromancer.*
- ***Cybernetics**: coined by Norbert Wiener in 1948, to mean the* conjunction of control and communication.

Cyber-Physical Systems (CPS):

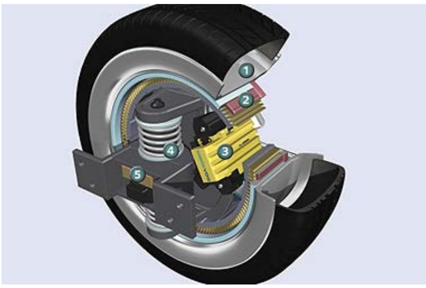
Orchestrating networked computational resources with physical systems

Avionics

Transportation (Air traffic control at SFO)

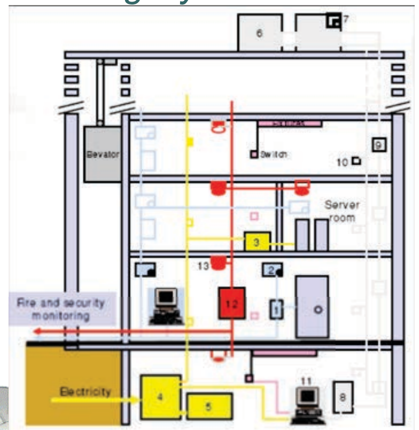


Automotive

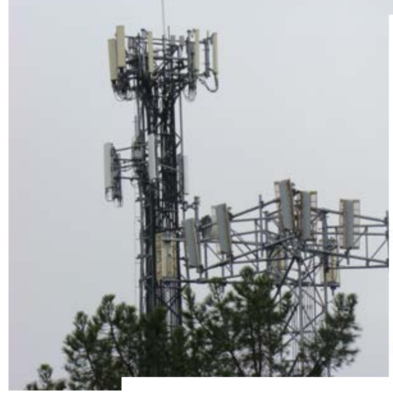


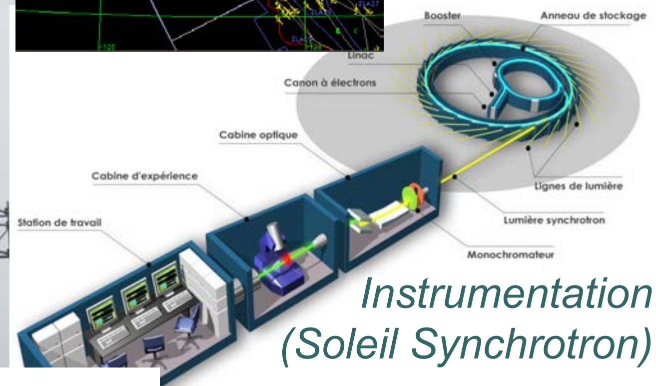
E-Corner, Siemens

Building Systems

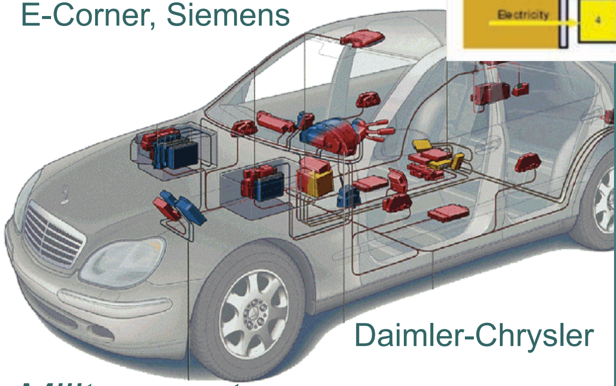


Telecommunications



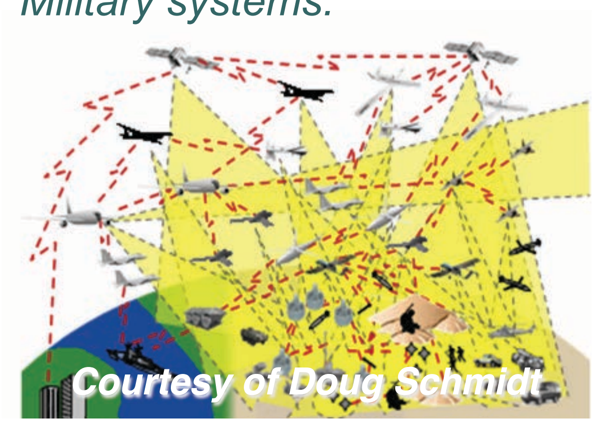


Instrumentation (Soleil Synchrotron)



Daimler-Chrysler

Military systems:



Courtesy of Doug Schmidt

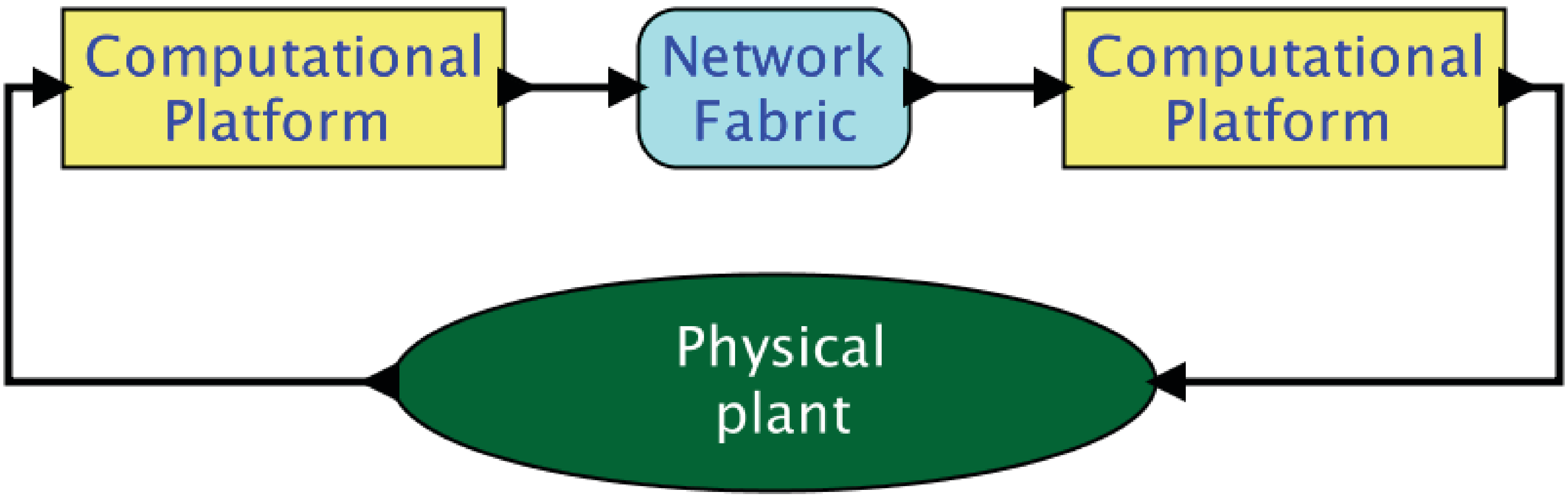
Power generation and distribution

Courtesy of General Electric

Factory automation

Courtesy of Kuka Robotics Corp.

Schematic of a simple CPS



In CPS, "cyber" == "software" and "physical" == "not software". Digital hardware sits in a gray area…

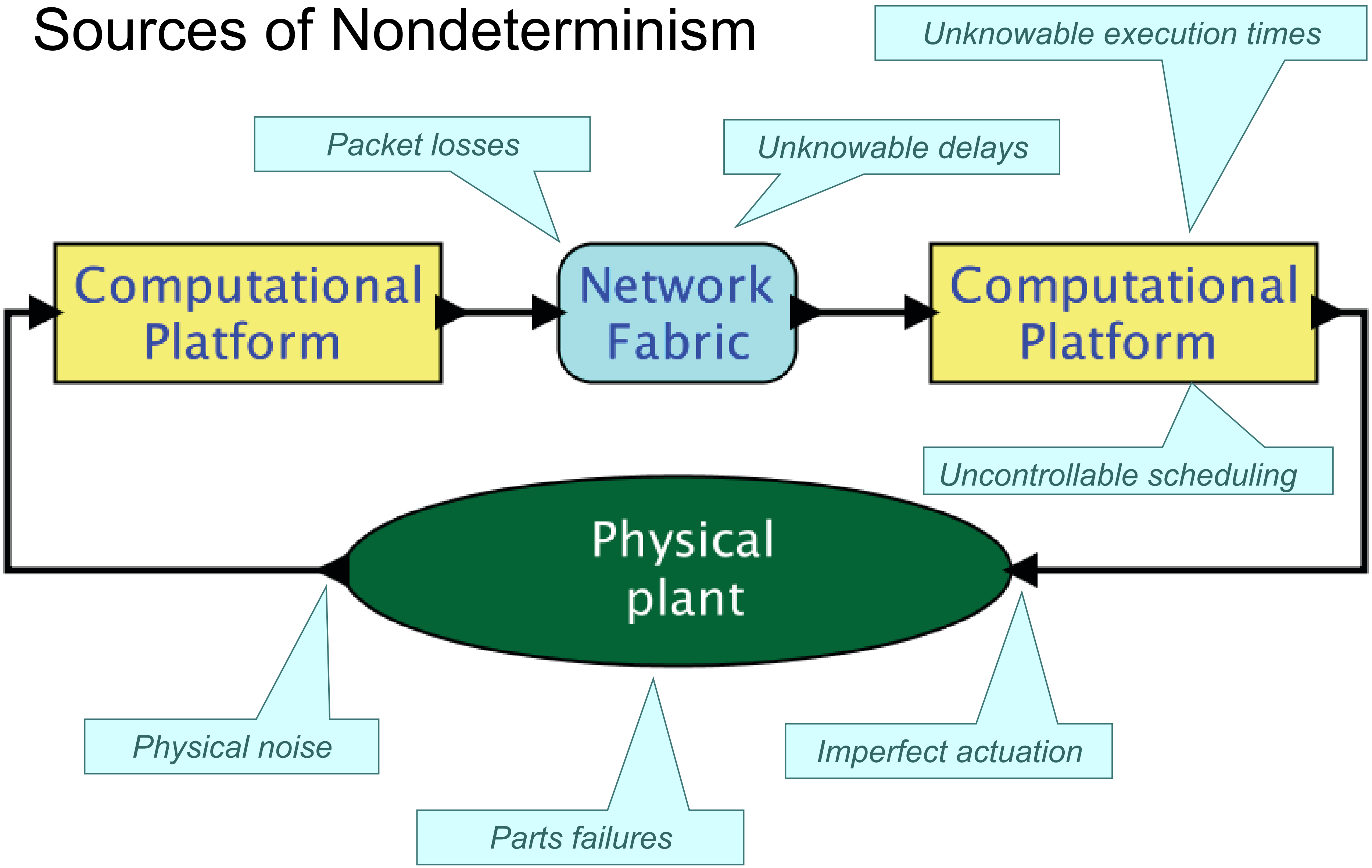
The Theme of This Talk

Determinacy

or

Better Engineering through Better Models

Sources of Nondeterminism

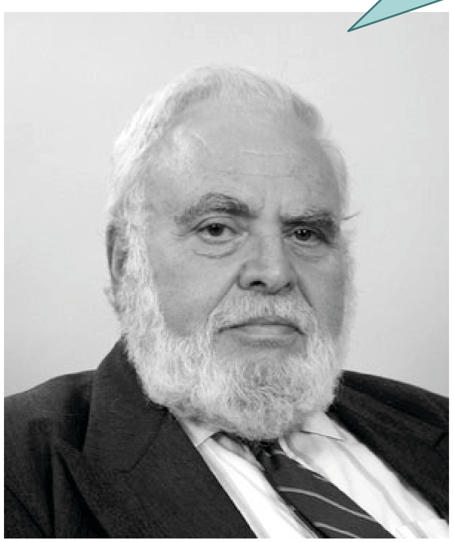


In the face of such nondeterminism, does it make sense to talk about deterministic models for cyber-physical systems?

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.

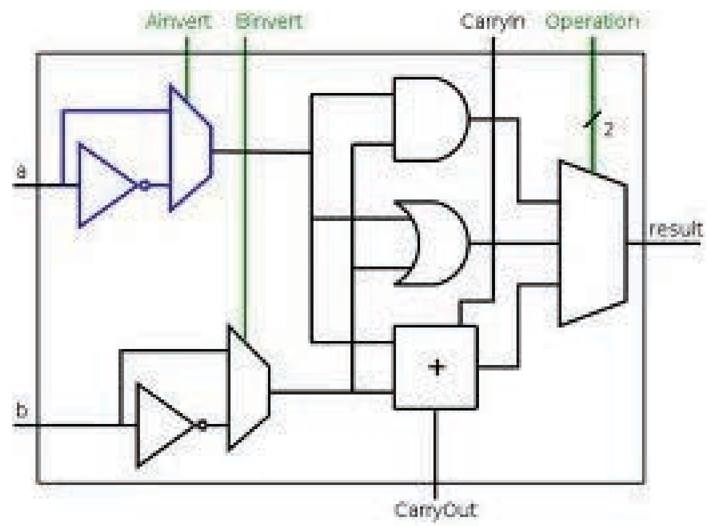
(paraphrased)

Deterministic Models of Nondeterministic Systems

Physical System

Model

Image: Wikimedia Commons



Synchronous digital logic

Deterministic Models of Nondeterministic Systems

Physical System

Model

Image: Wikimedia Commons

Integer Register-Register Operations

RISC-V defines several arithmetic R-type operations. All operations read the *rs1* and *rs2* registers as source operands and write the result into register *rd*. The *funct* field selects the type of operation.

31 — 27	26 — 22	21 — 17	16 — 7	6 — 0
rd	rs1	rs2	funct10	opcode
5	5	5	10	7
dest	src1	src2	ADD/SUB/SLT/SLTU	OP
dest	src1	src2	AND/OR/XOR	OP
dest	src1	src2	SLL/SRL/SRA	OP
dest	src1	src2	ADDW/SUBW	OP-32
dest	src1	src2	SLLW/SRLW/SRAW	OP-32

Waterman, et al., The RISC-V Instruction Set Manual, UCB/EECS-2011-62, 2011

Instruction Set Architectures (ISAs)

Deterministic Models of Nondeterministic Systems

Physical System

Image: Wikimedia Commons

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

Deterministic Models of Nondeterministic Systems

Physical System

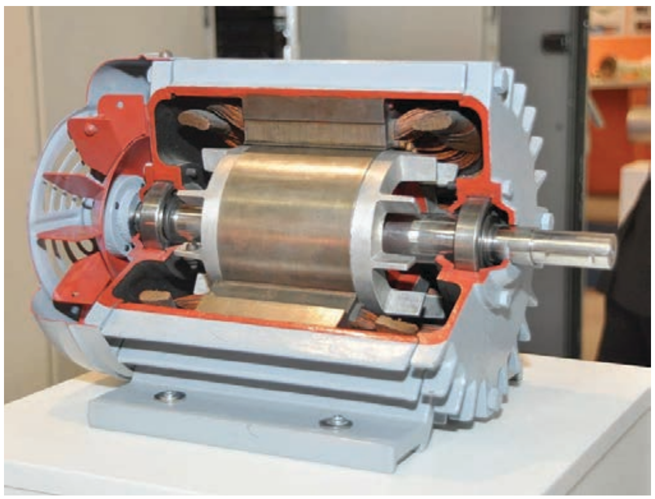
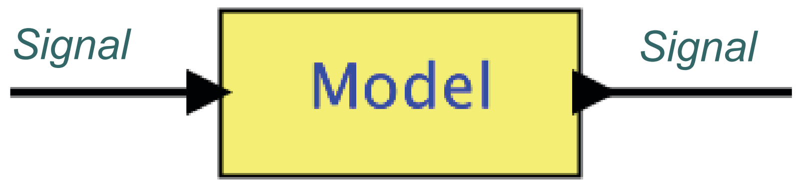


Image: Wikimedia Commons

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 of these Models are Nondeterministic

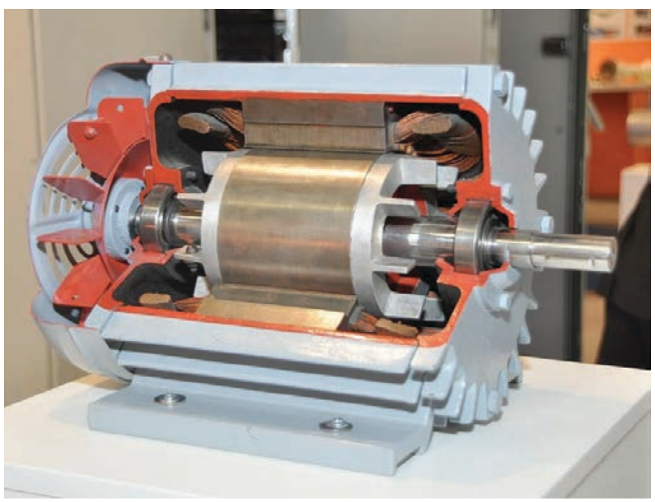
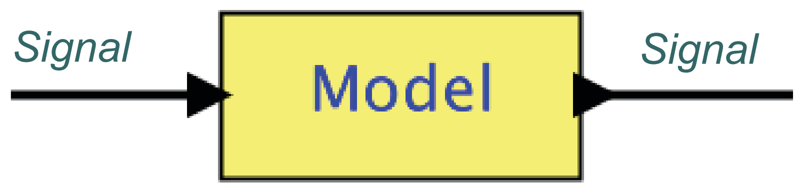


Image: Wikimedia Commons

```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();
                        }
                    }
                }
            }
        }
    }
}
```



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

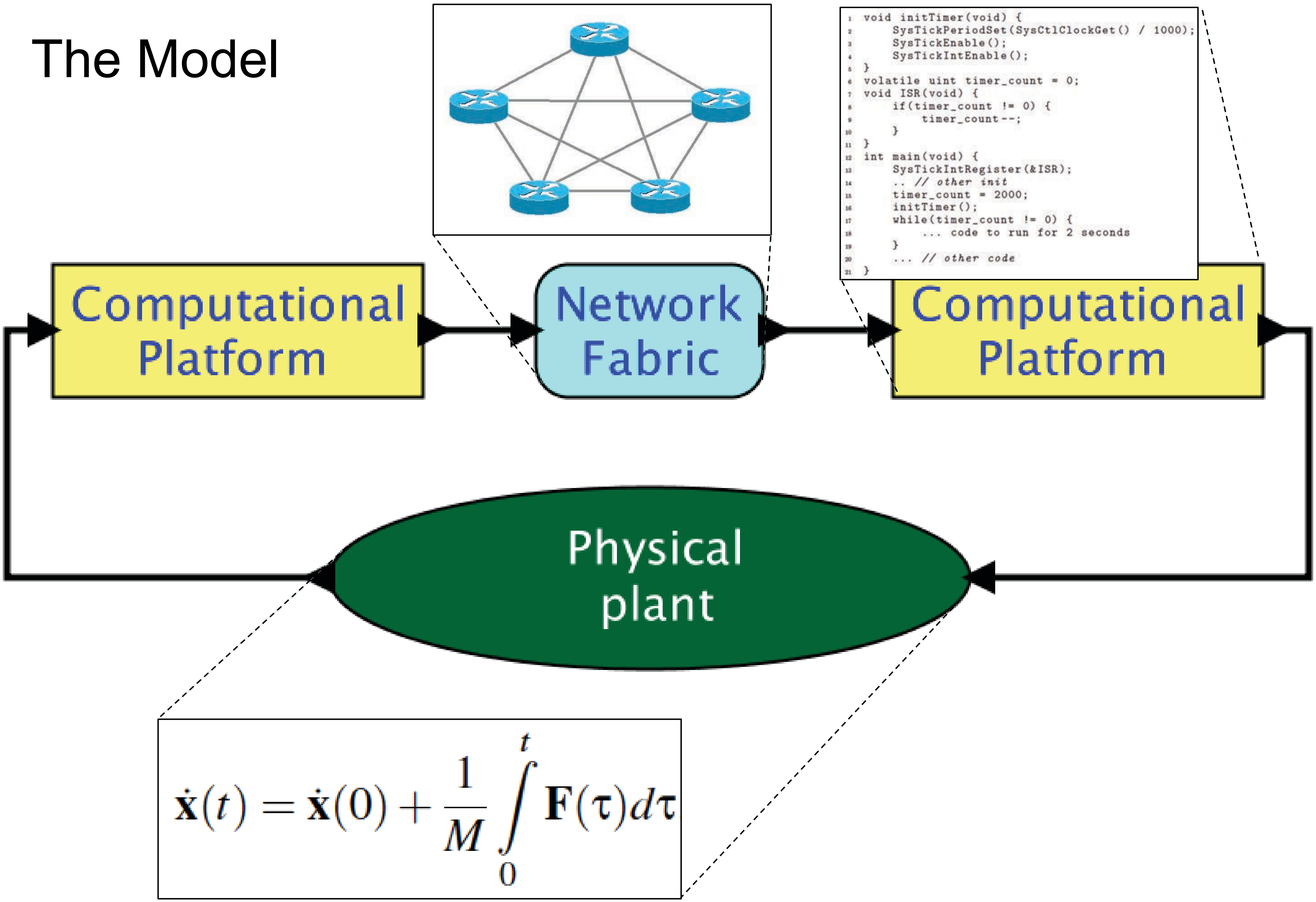
A Key Challenge:
Timing is not Part of Software Semantics

***Correct** execution of a program in C, C#, Java, Haskell, OCaml, Esterel, 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 Model



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
}
Computational Platform
Network Fabric
Computational Platform
Physical plant
$\dot{\mathbf{x}}(t) = \dot{\mathbf{x}}(0) + \frac{1}{M}\int_0^t \mathbf{F}(\tau)d\tau$

The Reality

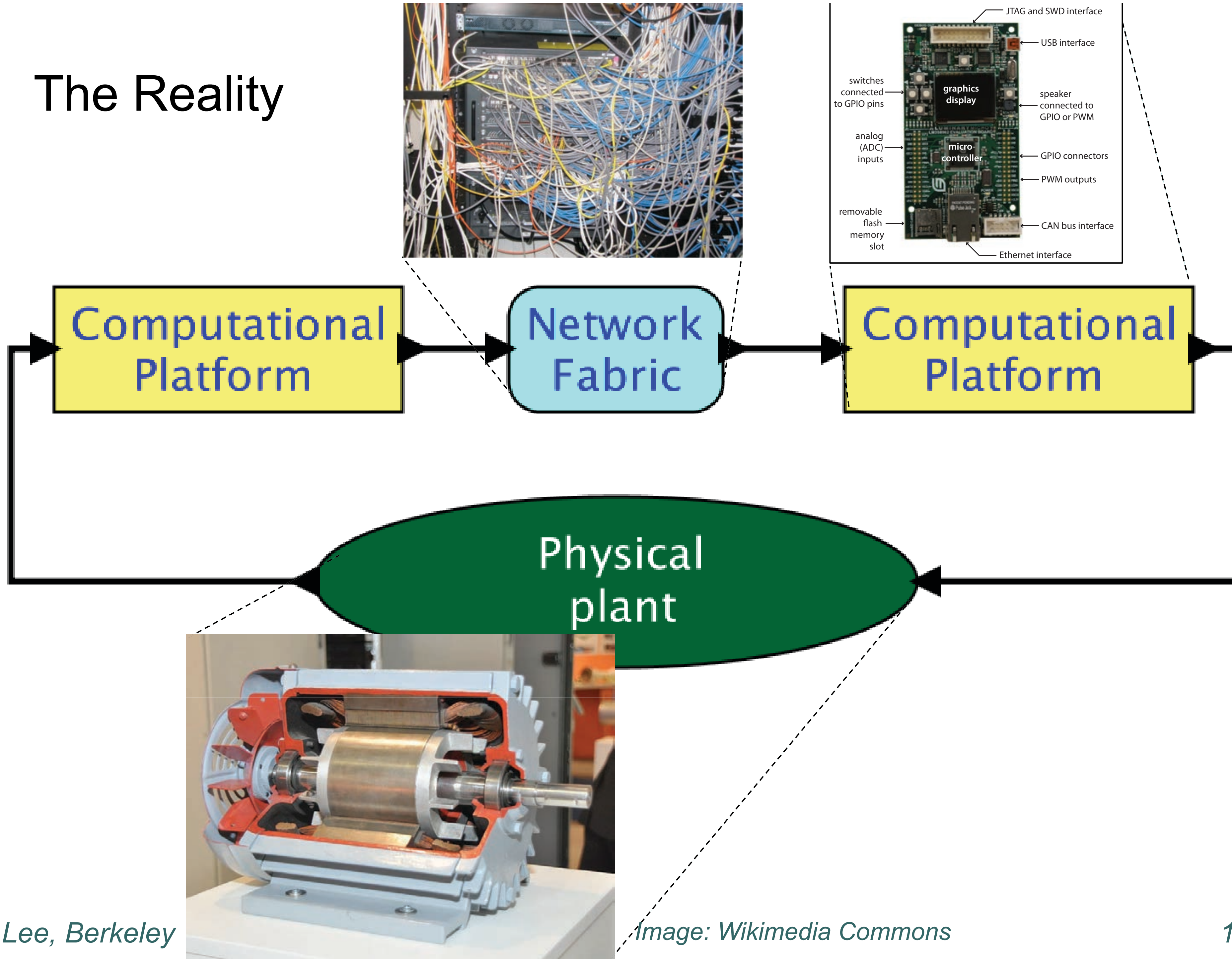
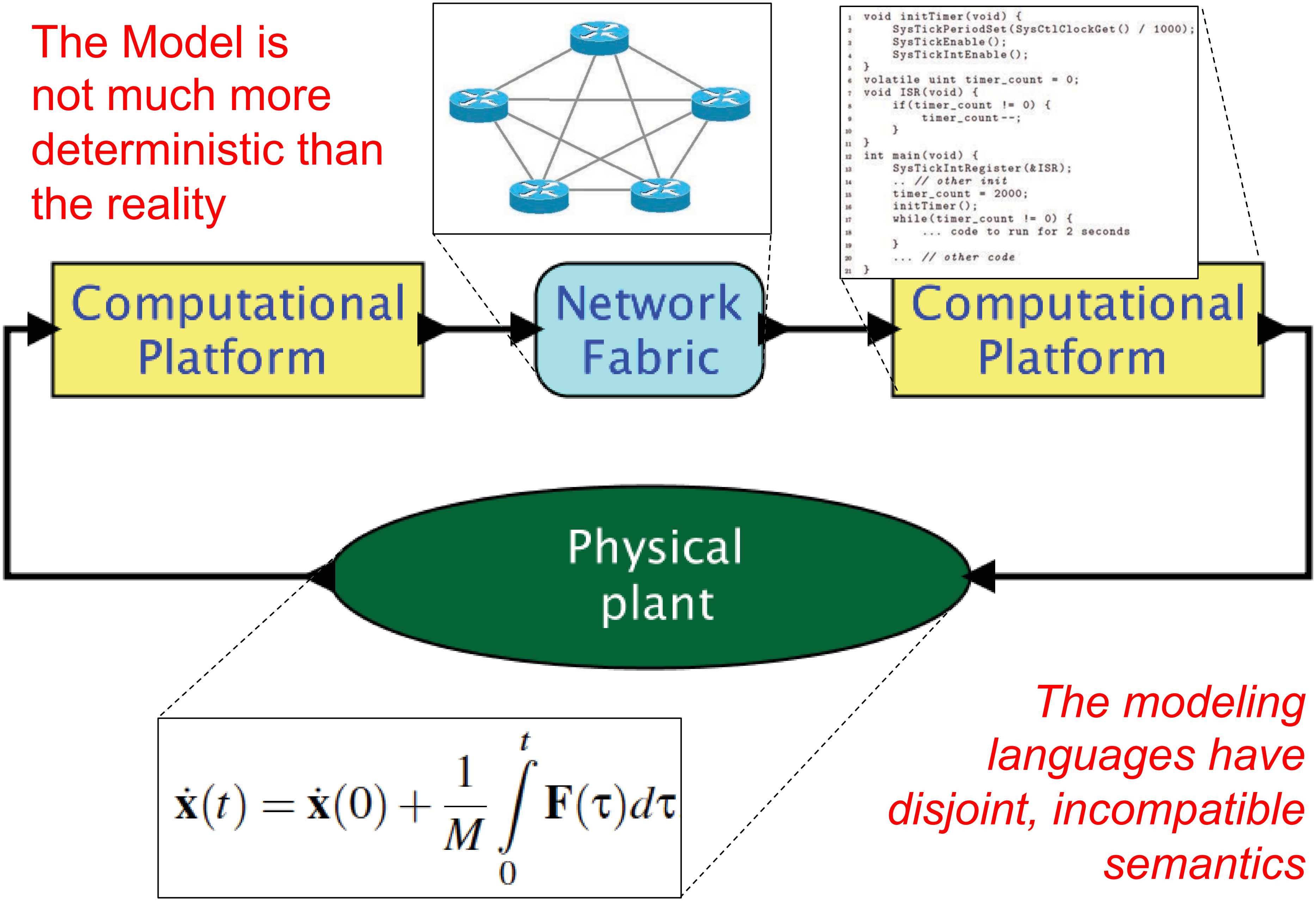


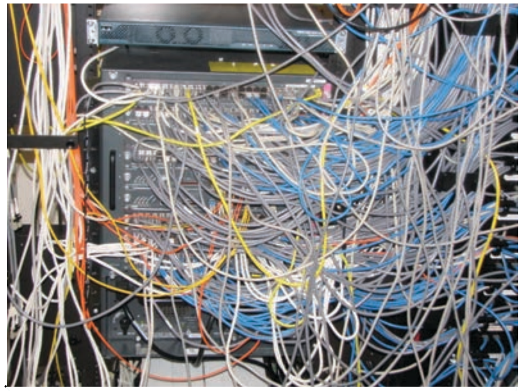
Image: Wikimedia Commons

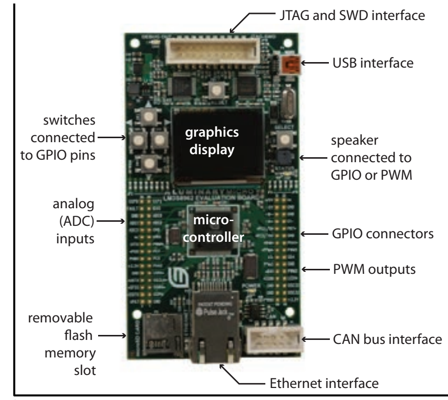
The Model is not much more deterministic than the reality

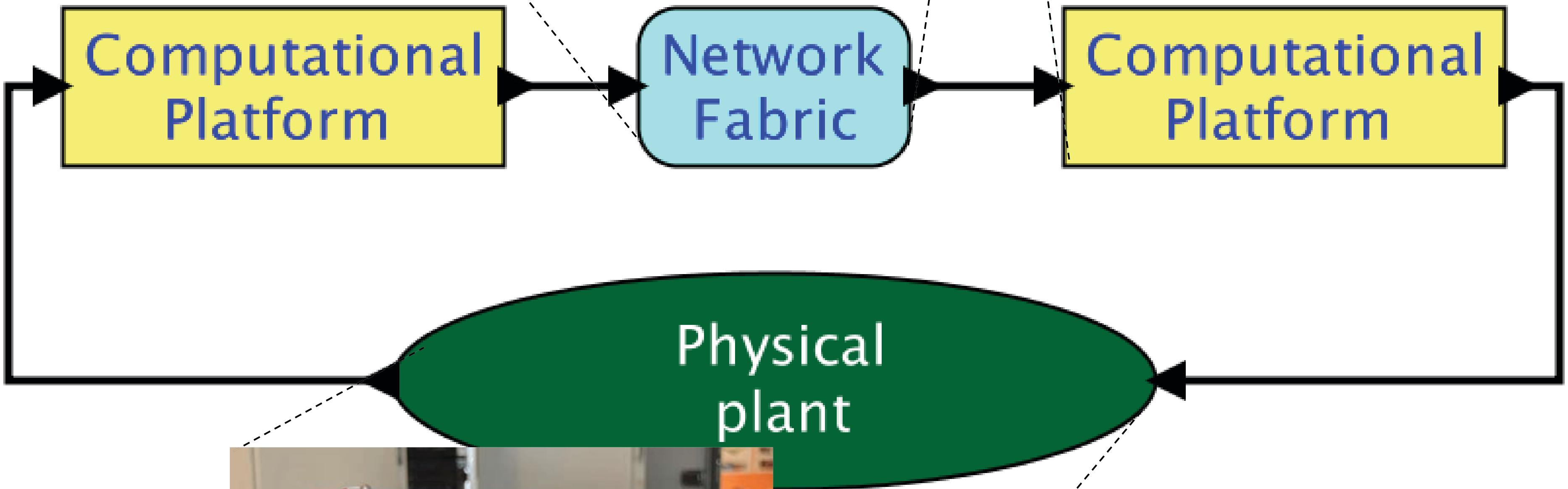


The modeling languages have disjoint, incompatible semantics

System dynamics emerges from the physical realization



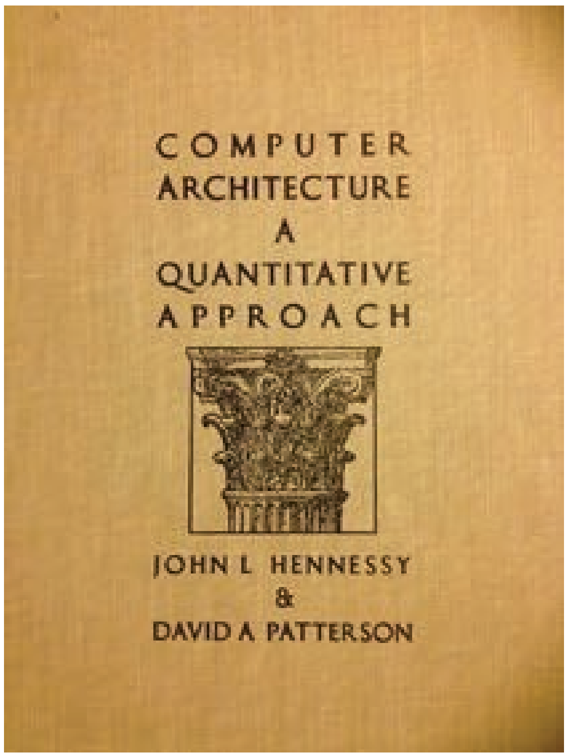




… leading to a "prototype and test" style of design

Image: Wikimedia Commons

Computer Science has not *completely* ignored timing…



The first edition of Hennessy and Patterson (1990) revolutionized the field of computer architecture by making performance metrics the dominant criterion for design.

Today, for computers, timing is merely a performance metric.

It needs to be a correctness criterion.

Correctness criteria

We can safely assert that line 8 does not execute

(In C, we need to separately ensure that no other thread or ISR can overwrite the stack, but in more modern languages, such assurance is provided by construction.)

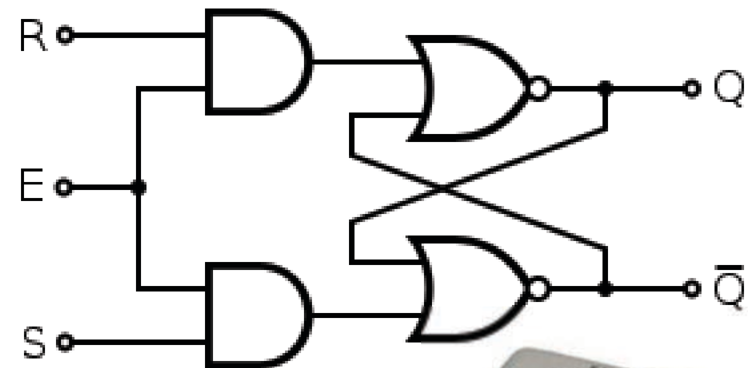
```
1  void foo(int32_t x) {
2          if (x > 1000) {
3                  x = 1000;
4          }
5          if (x > 0) {
6                  x = x + 1000;
7                  if (x < 0) {
8                          panic();
9                  }
10         }
11 }
```

We can develop ***absolute confidence*** *in the software, in that only a* ***hardware failure*** *is an excuse.*

But not with regards to timing!!

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]);
}
```

PRET Machines – Giving Programs the Capabilities their Hardware Already Has.

- **PRE**cision-**T**imed processors = **PRET**
- **P**redictable, **RE**peatable **T**iming = **PRET**
- **P**erformance *with* **RE**peatable **T**iming = **PRET**

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

Computing

+

With time

= PRET

Major Challenges

and existence proofs that they can be met

- Pipelines
  - fine-grain multithreading
- Memory hierarchy
  - memory controllers with controllable latency
- I/O
  - threaded interrupts, with bounded effects on timing

PRET Publications

PRET ISA Realizations:

- PRET1, Sparc-based
  - [Lickly et al., CASES, 2008]
- PTARM, ARM-based
  - [Liu et al., ICCD, 2012]
- FlexPRET, RISC-V-based
  - [Zimmer et al., RTAS, 2014]

PRET Applications:

- *Control systems*
  - *[Bui et al., RTCSA 2010]*
- *Computational fluid dynamics*
  - *[Liu et al., FCCM, 2012]*

PRET for Security:

- *Eliminating side-channel attacks*
  - *[Lie & McGrogan, Report 2009]*

PRET Memory Systems:

- *DRAM controller*
  - *[Reineke et al., CODES+ISSS 2011]*
- *Scratchpad managment*
  - *[Kim et al., RTAS, 2014]*
- *Mixed criticality DRAM controller*
  - *[Kim et al., RTAS 2015]*

PRET Principle:

- *The case for PRET*
  - *[Edwards & Lee, DAC 2007]*
- *PRET ISA extensions*
  - *[Edwards at al., ICCD 2009]*
- *Temporal isolation*
  - *[Bui et al., DAC, 2011]*
- *Design challenges*
  - *[Broman et al., ESLsyn, 2013]*
- *Cyber-physical systems*
  - *[Lee., Sensors, 2015]*

Major Challenges, Yes, but Leading to Major Opportunities

- Improved determinism
- Better testability
- Reduced energy consumption
- Reduced overdesign (cost, weight)
- Improved confidence and safety
- Substitutable hardware

Three Generations of PRET Machines at Berkeley

- PRET1, Sparc-based (simulation only)
  - [Lickly et al., CASES, 2008]

- PTARM, ARM-based (FPGA implementation)
  - [Liu et al., ICCD, 2012]

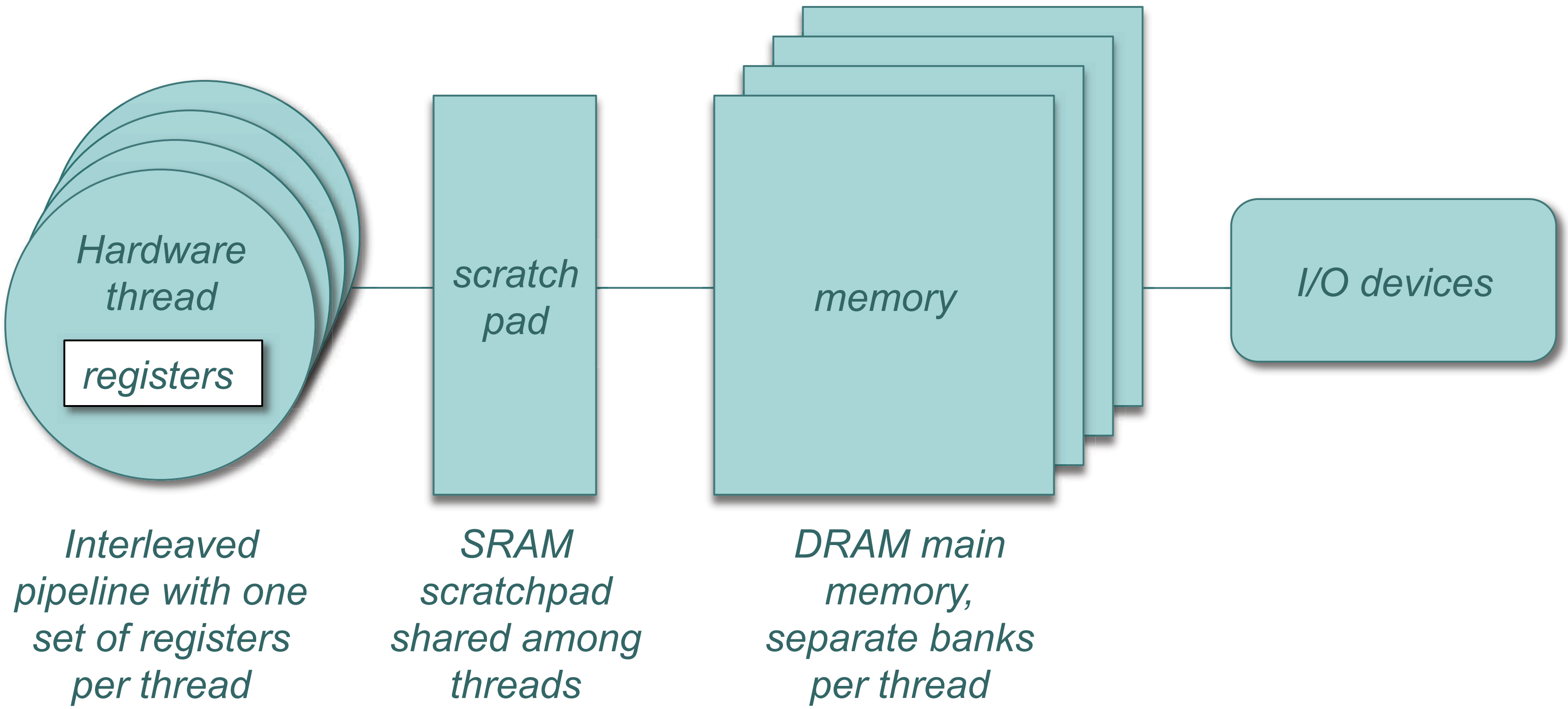
- FlexPRET, RISC-V-based (FPGA + simulation)
  - [Zimmer et al., RTAS, 2014]

Our Second Generation PRET

PTArm, a soft core on a
Xilinx Virtex 5 FPGA (2012)

Note inverted memory compared to multicore!

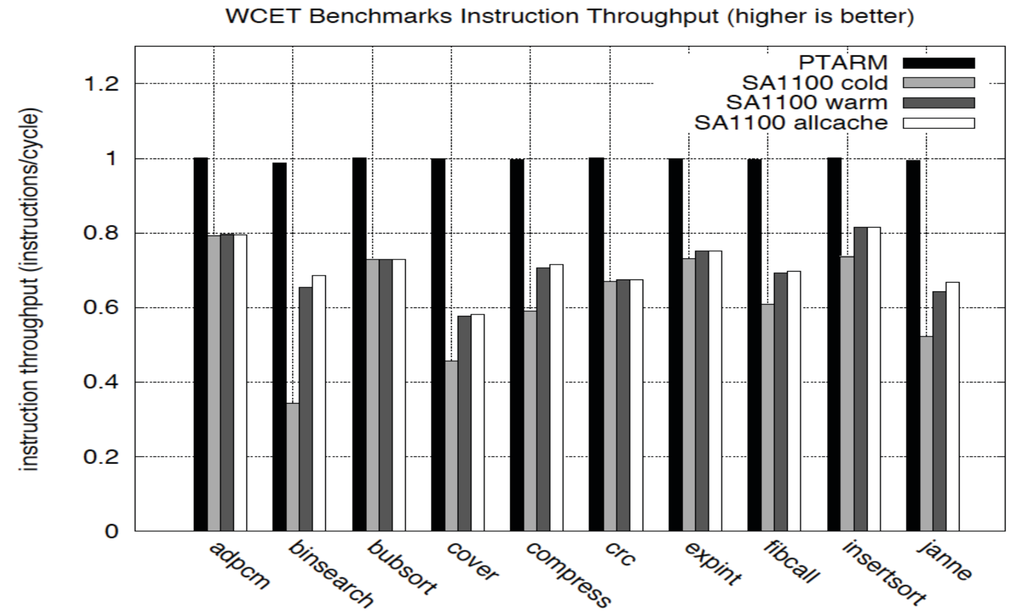
Fast, close memory is shared, slow remote memory is private!

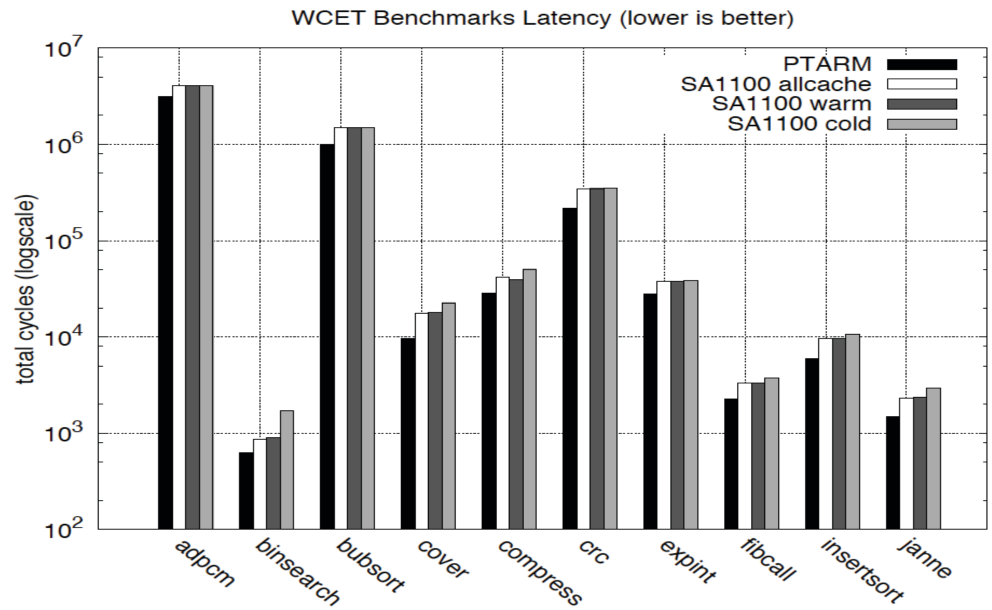


Performance Cost?

Not really!

In microarchitecture design, the PRET project has shown that you do not need to sacrifice performance to get control over timing.

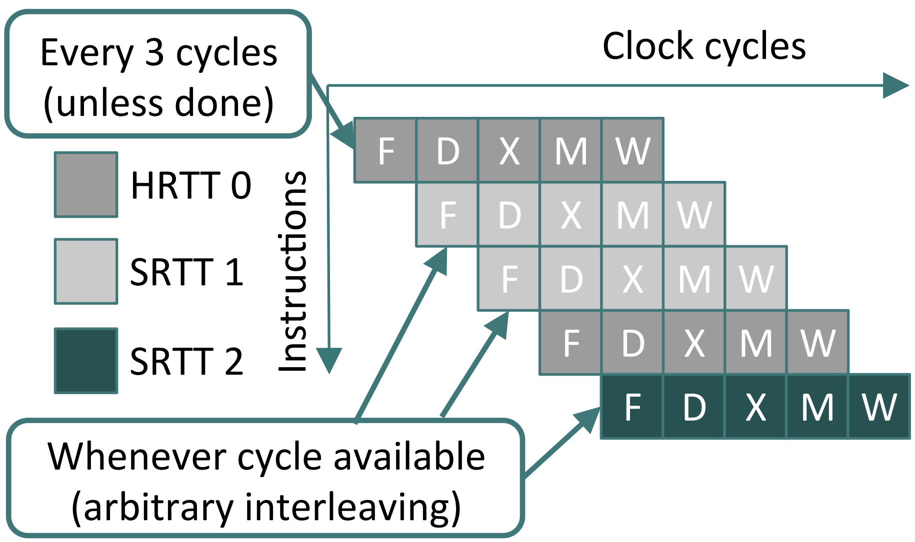


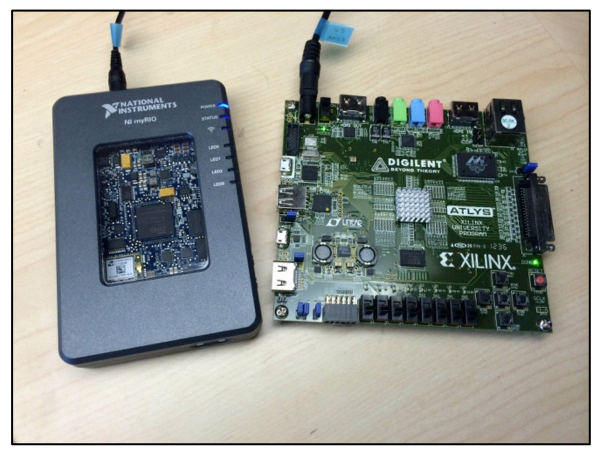


[Isaac Liu, PhD Thesis, May, 2012]

Our Third-Generation PRET:
Open-Source FlexPRET (Zimmer et al., 2014)

- 32-bit, 5-stage thread interleaved pipeline, RISC-V ISA
  - **Hard real-time HW threads**:
    scheduled at constant rate for isolation and predictability
  - **Soft real-time HW threads**:
    share all available cycles (e.g. HW thread sleeping) for efficiency
- Deployed on Xilinx FPGA (area comparable to Microblaze)

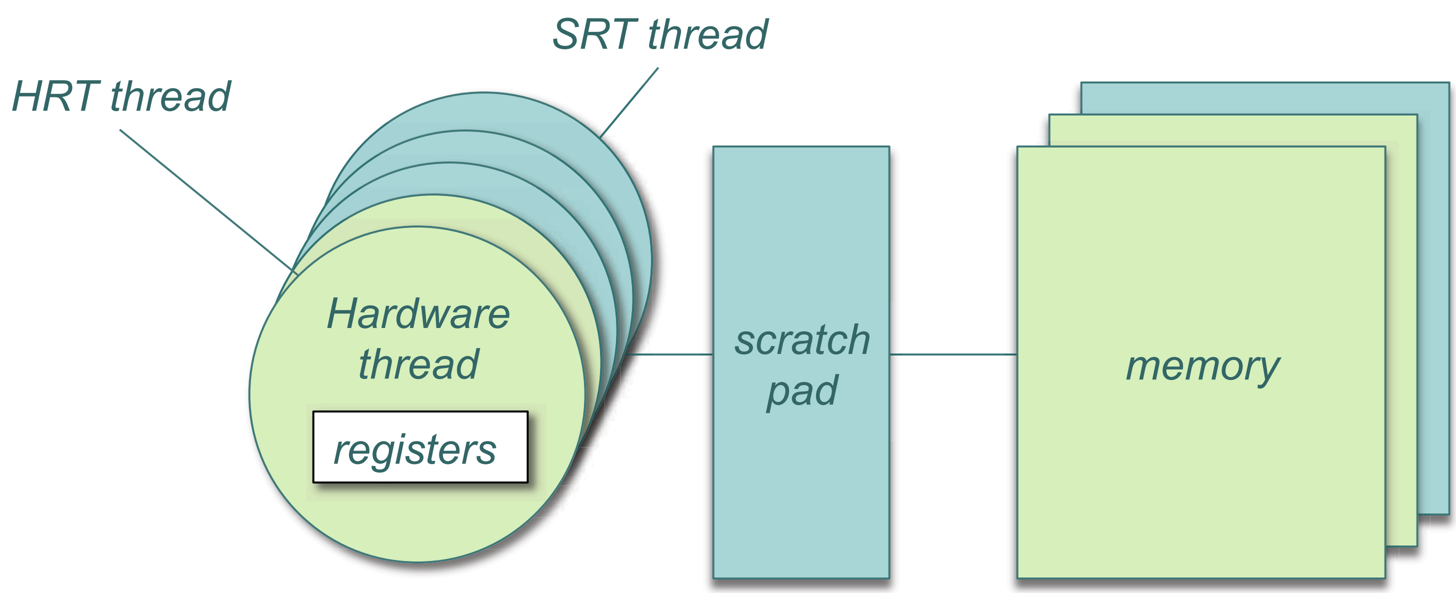




Digilent Atlys (Spartan 6) and NI myRIO (Zync)

FlexPRET

Hard-Real-Time (HRT) Threads
Interleaved with Soft-Real-Time (SRT) Threads



HRT threads have **deterministic timing.** SRT threads share available cycles

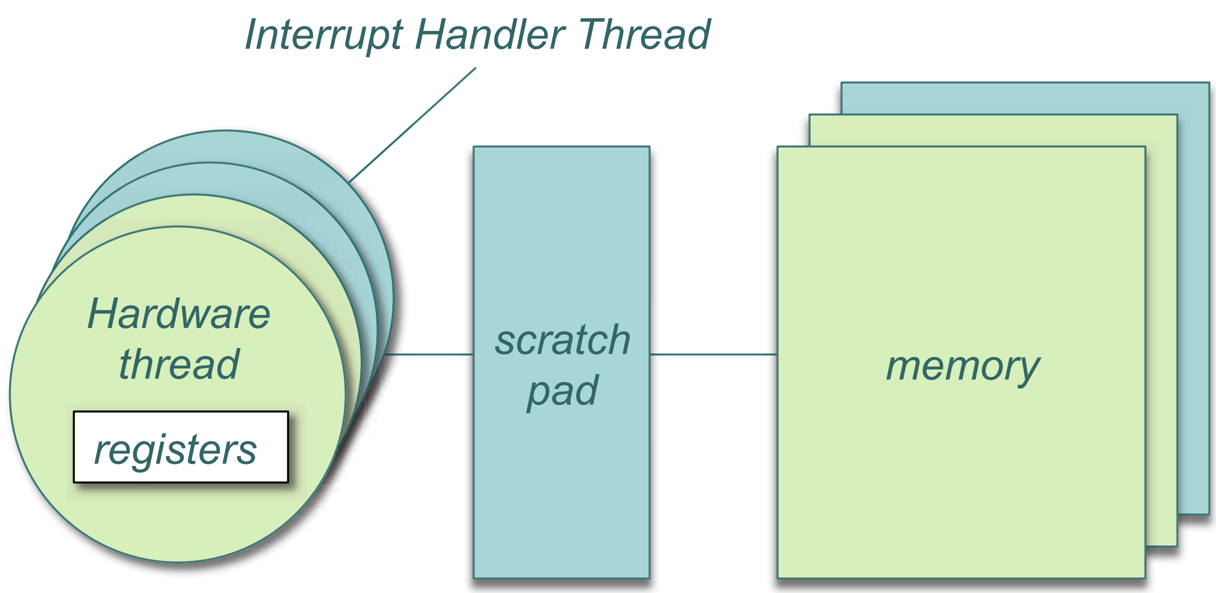
SRAM scratchpad shared among threads

DRAM main memory provides **deterministic latency** for HRT threads. Conventional behavior for the rest.

Michael Zimmer

FlexPRET I/O

Interrupt-Driven I/O is notorious for disrupting timing



Interrupts have
no effect on HRT threads, and
bounded effect on SRT threads!

Michael Zimmer

FlexPRET Shows:

- Not only is there no performance cost for appropriate workloads, but there is also no performance cost for inappropriate workloads!
- Pipelining, memory hierarchy, and interrupt-driven I/O can all be done without losing timing determinacy!

Software

Example of one sort of mechanism we can achieve (with some difficulty!) today:

```
tryin (500ms) {
   // Code block
} catch {
    panic();
}
```

```
jmp_buf  buf;

if ( !setjmp(buf) ){
  set_time r1, 500ms
  exception_on_expire r1, 0
  // Code block
  deactivate_exception 0
} else {
    panic();
}


exception_handler_0 () {
     longjmp(buf)
}
```

Pseudocode showing how to do this today.

If the code block takes longer than 500ms to run, then the panic() procedure will be invoked.

But then we would like to verify that panic() is never invoked!

Extending an ISA with Timing Semantics

[V1] Best effort:

```
set_time r1, 1s
// Code block
delay_until r1
```

[V2] Late miss detection

```
set_time r1, 1s
// Code block
branch_expired r1, <target>
delay_until r1
```

[V3] Immediate miss detection

```
set_time r1, 1s
exception_on_expire r1, 1
// Code block
deactivate_exception 1
delay_until r1
```

[V4] Exact execution:

```
set_time r1, 1s
// Code block
MTFD r1
```

But Wait…

The whole point of an ISA is that the same program does the same thing on multiple hardware realizations.

Isn’t this incompatible with deterministic timing?

```
set_time r1, 1s
// Code block
MTFD r1
```

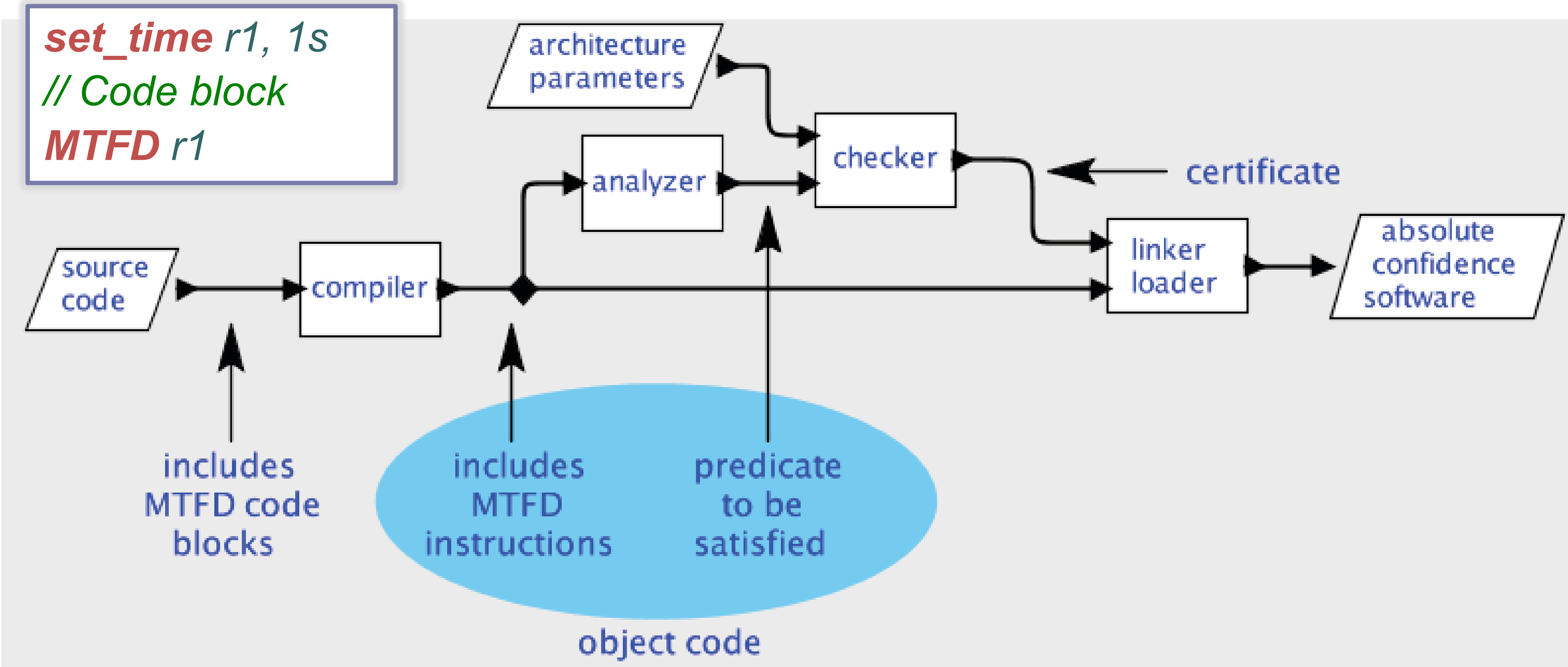
Parametric PRET Architectures

ISA that admits a variety of implementations:

- Variable clock rates and energy profiles
- Variable number of cycles per instruction
- Latency of memory access varying by address
- Varying sizes of memory regions
- …

A given program may meet deadlines on only some realizations of the same parametric PRET ISA.

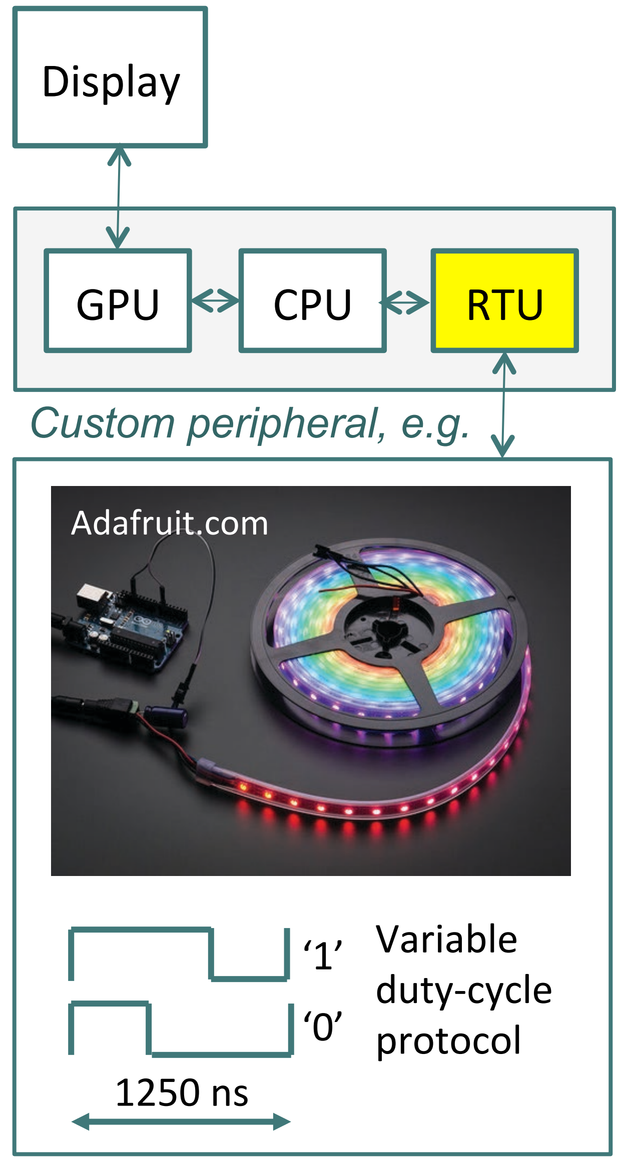
Realizing the MTFD instruction on a Parametric PRET machine



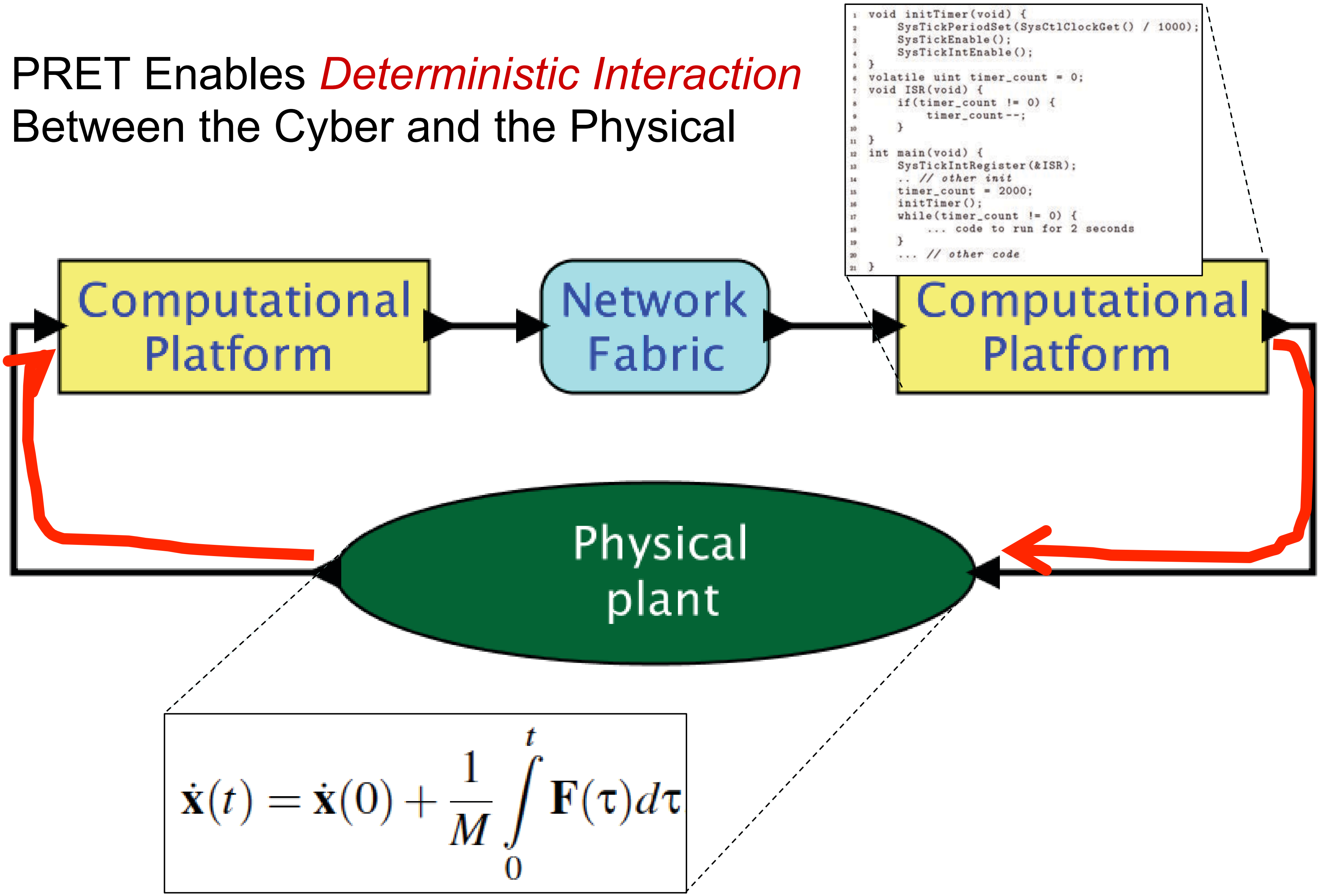
The goal is to make software that will run correctly on many implementations of the ISA, and that correctness can be checked for each implementation.

How to Make PRET Widespread? Real-Time Units (RTUs)

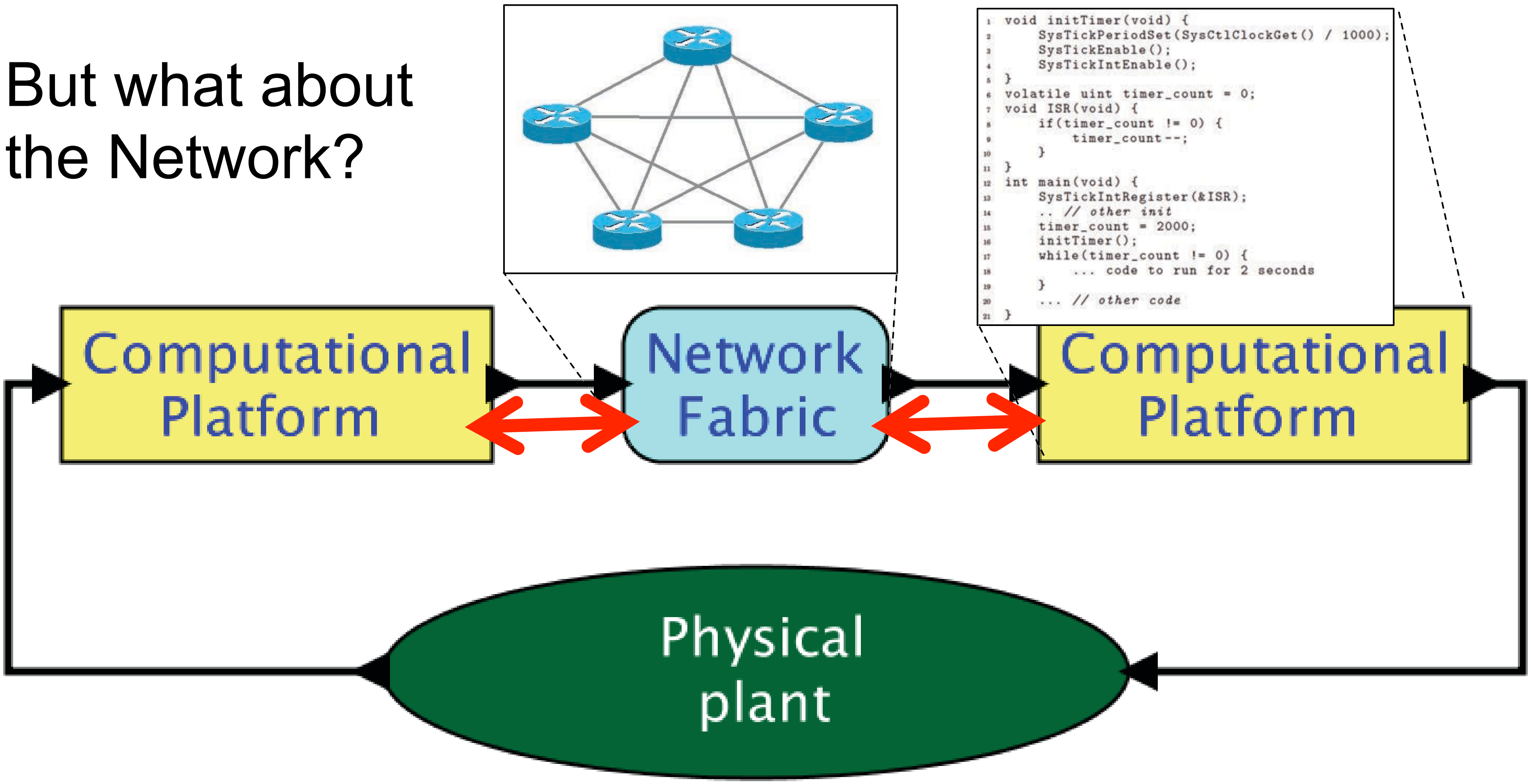
- Offload timing-critical functions to the RTU
  - Compare with dedicated hardware
- Software peripherals
  - Bit-banging for custom protocols
- Software API: OpenRT?
  - Richer interface for smart sensors/actuators



PRET Enables *Deterministic Interaction* Between the Cyber and the Physical



But what about the Network?



We have also developed *deterministic models* for distributed real-time software, using a technique called PTIDES.

PTIDES: Programming Temporally Integrated Distributed Embedded Systems

See

http://chess.eecs.berkeley.edu/ptides

(or invite me back next year)

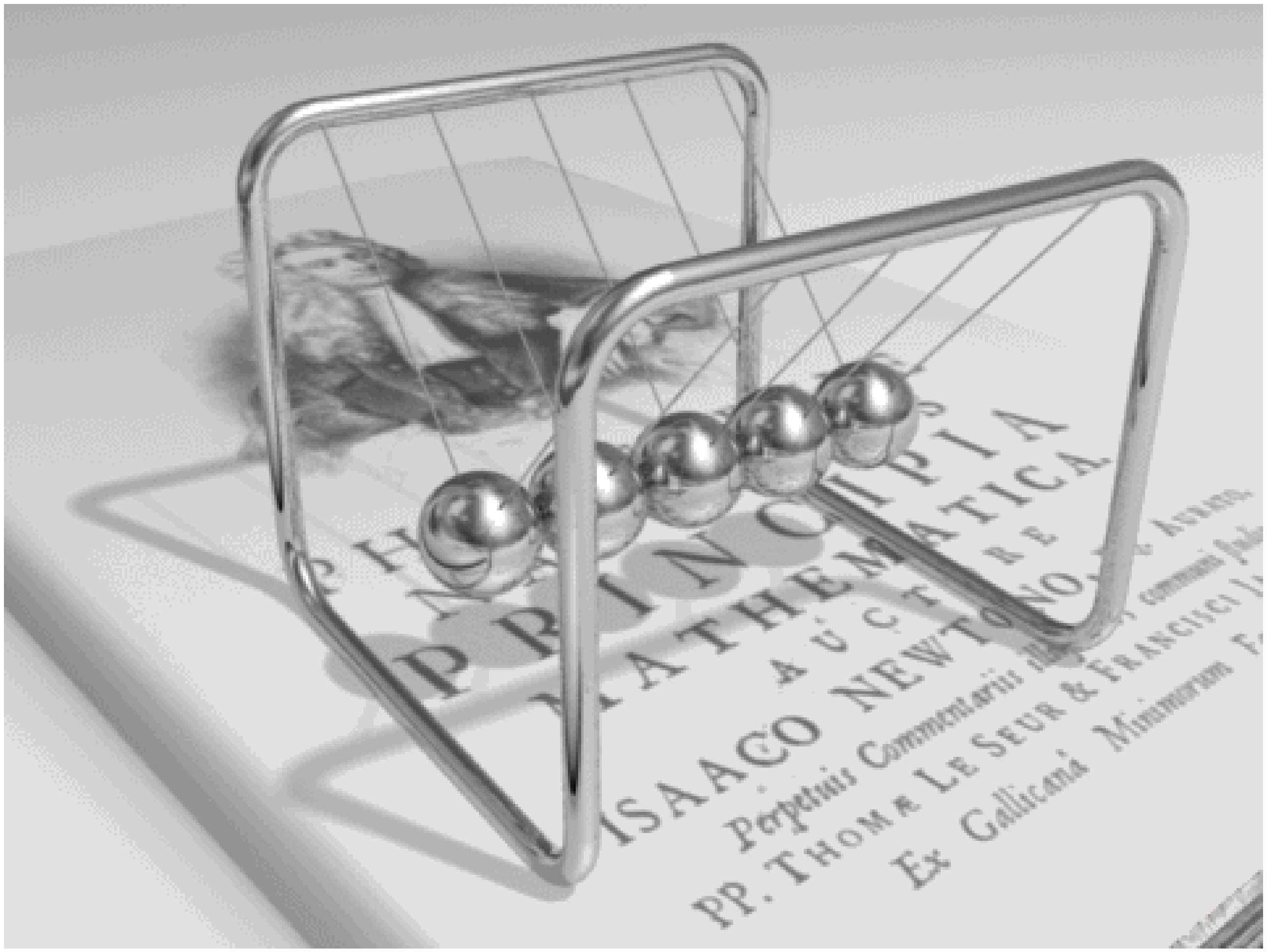
One Last Comment… Model Fidelity

- In *science*, a good model matches well the behavior of the physical world.
- In *engineering*, a good physical implementation matches well the behavior of the model.

In engineering, model fidelity is a two-way street!

For a model to be useful, it is necessary (but not sufficient) to be able to be able to construct a faithful physical realization.

A Model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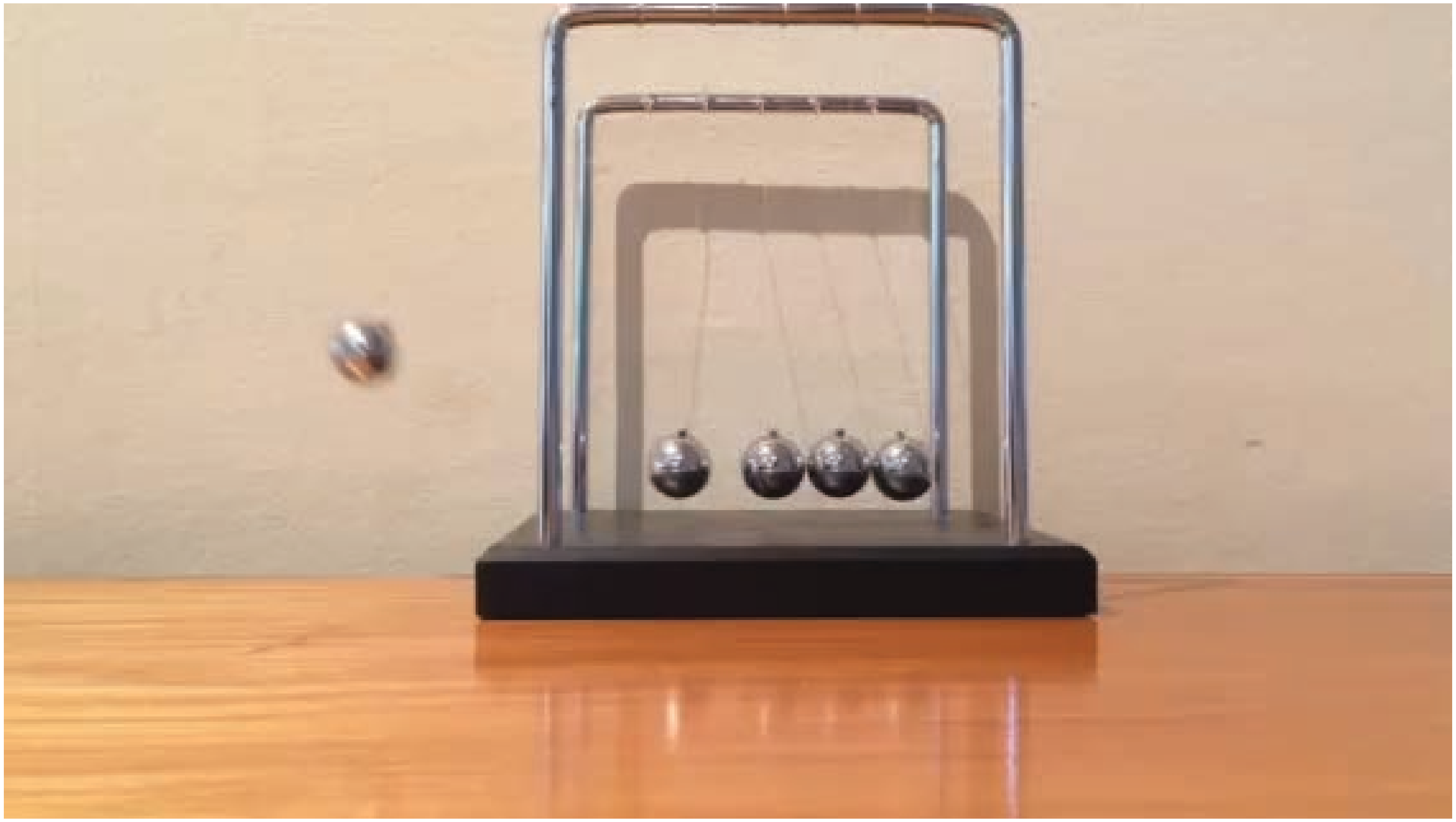
Ex Gallicanâ Minimorum

A Physical Realization



Model Fidelity

- To a *scientist*, the model is flawed.
- To an *engineer*, the physical realization is flawed.

I'm an engineer…

Determinism?

For a model to be useful, it is necessary (but not sufficient) to be able to be able to construct a faithful physical realization.

- The real world is highly unpredictable.
- So, are deterministic models useful?
  - Is synchronous digital logic useful?
  - Are ISAs useful?
  - Single-threaded imperative programs?
  - Differential equations?

Determinism?

Deterministic models do not eliminate the need for for robust, fault-tolerant designs.

In fact, they *enable* such designs, because they make it much clearer what it means to have a fault!

Determinism

According to Google:

de·ter·min·ism

/dəˈtərməˌnizəm/

noun PHILOSOPHY

the doctrine that all events, including human action, are ultimately determined by causes external to the will. Some philosophers have taken determinism to imply that individual human beings have no free will and cannot be held morally responsible for their actions.

Translations, word origin, and more definitions

PRET enables a programming model with *deterministic* timing.

http://chess.eecs.berkeley.edu/pret

PRET Publications

PRET ISA Realizations:

- PRET1, Sparc-based
  - [Lickly et al., CASES, 2008]
- PTARM, ARM-based
  - [Liu et al., ICCD, 2012]
- FlexPRET, RISC-V-based
  - [Zimmer et al., RTAS, 2014]

PRET Applications:

- *Control systems*
  - *[Bui et al., RTCSA 2010]*
- *Computational fluid dynamics*
  - *[Liu et al., FCCM, 2012]*

PRET for Security:

- *Eliminating side-channel attacks*
  - *[Lie & McGrogan, Report 2009]*

PRET Memory Systems:

- *DRAM controller*
  - *[Reineke et al., CODES+ISSS 2011]*
- *Scratchpad managment*
  - *[Kim et al., RTAS, 2014]*
- *Mixed criticality DRAM controller*
  - *[Kim et al., RTAS 2015]*

PRET Principle:

- *The case for PRET*
  - *[Edwards & Lee, DAC 2007]*
- *PRET ISA extensions*
  - *[Edwards at al., ICCD 2009]*
- *Temporal isolation*
  - *[Bui et al., DAC, 2011]*
- *Design challenges*
  - *[Broman et al., ESLsyn, 2013]*
- *Cyber-physical systems*
  - *[Lee., Sensors, 2015]*

Teşekkür ederim

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- *David Broman*
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- *Jan Reineke*
- *Michael Zimmer*

Today, timing behavior in computers emerges from the physical realization.

Tomorrow, timing behavior will be part of the programming their hardware realizations.

See: Lee, "The Past, Present, and Future of Cyber-Physical Systems: A Focus on Models," Sensors, 15(3), February, 2015. (Open Access)

Raffaello Sanzio da Urbino – The Athens School *Image: Wikimedia Commons*