Extensible Modeling Languages and Precision Timed Infrastructures for Cyber-Physical Systems

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Key contributors and collaborators related to the PRET project

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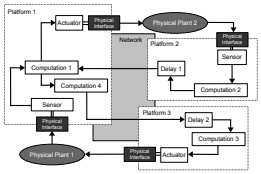
Jeff Jensen	Hiren Patel	Michael Zimmer	

Agenda

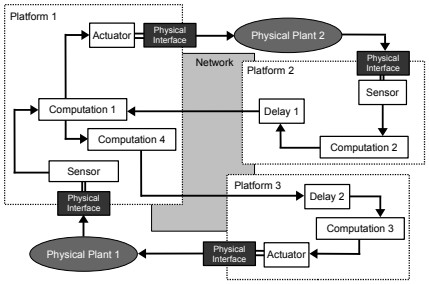
Part I
Cyber-Physical Systems



Part II
Modelyze -
a host language for equation-based languages

Part III
Precision Timed Infrastructure –
making time an engineering abstraction

Part I
Cyber-Physical Systems



Complex Cyber-Physical Systems (CPSs)

Industrial Robots

Power Plants

Aircraft

Modeling, Simulating, and Running Cyber-Physical Systems

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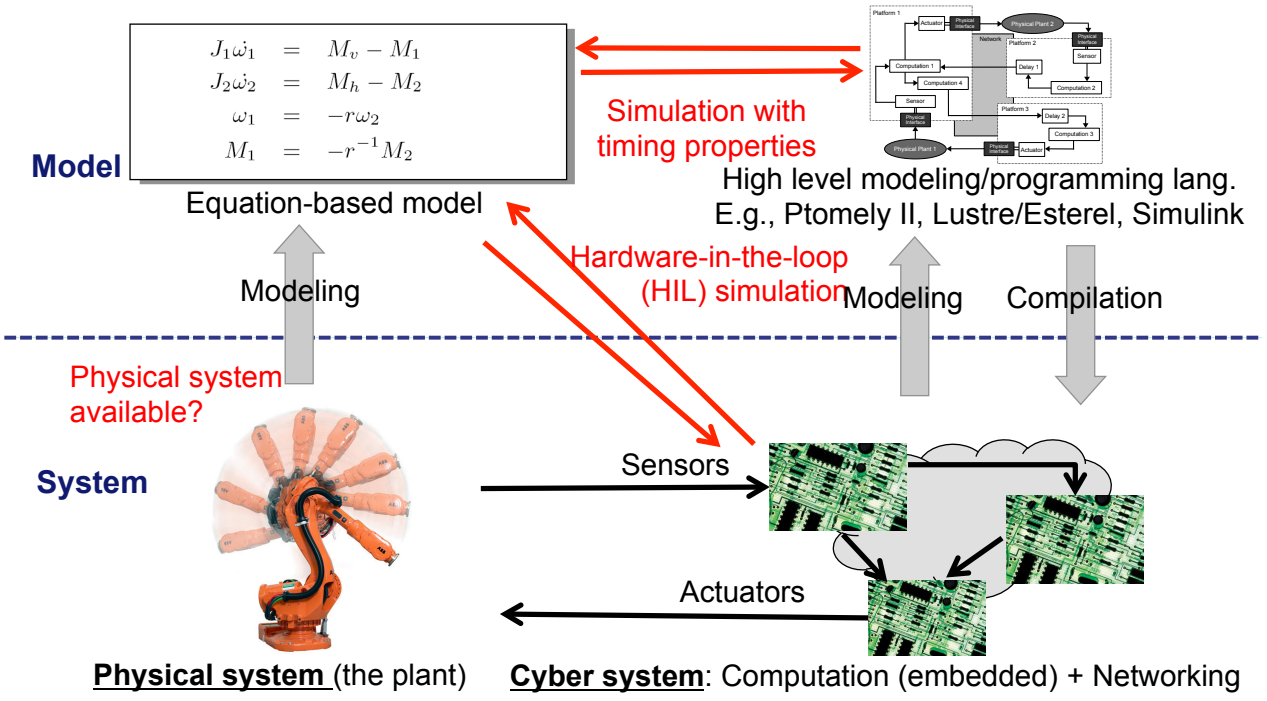

Part I
Cyber-Physical Systems

Part II
Modelyze - a host language for equation-based languages

Part III
Precision Timed Infrastructure - making time an engineering abstraction

Modeling, Simulating, and Running Cyber-Physical Systems

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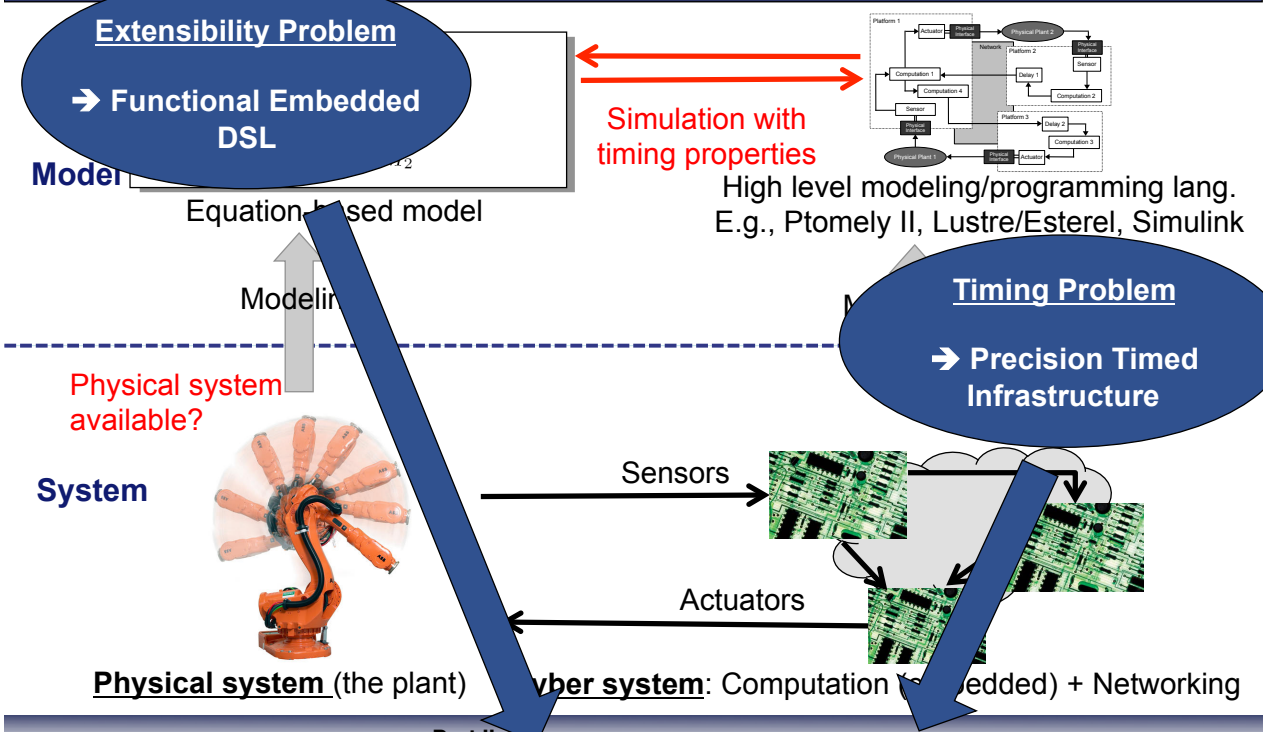
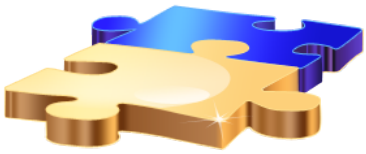


Part I
Cyber-Physical Systems

Part II
Modelyze - a host language for equation-based languages

Part III
Precision Timed Infrastructure - making time an engineering abstraction

Part II
Modelyze
a host language for equation-based languages



In collaboration with

Jeremy G. Siek
University of Colorado at Boulder

Problem: Expressiveness and Extensibility

Cannot express all modeling or analysis needs.
Limited to what the modeling language can provide.

Language versions: A, v1.0 → A, v1.1 → A, v2.0 → A, v2.2

Standard library versions: L, v1.0 → L, v1.1 → L, v2.0 → L, v2.2

Modelica: A new language definition approximately every second year

What is Modelyze?

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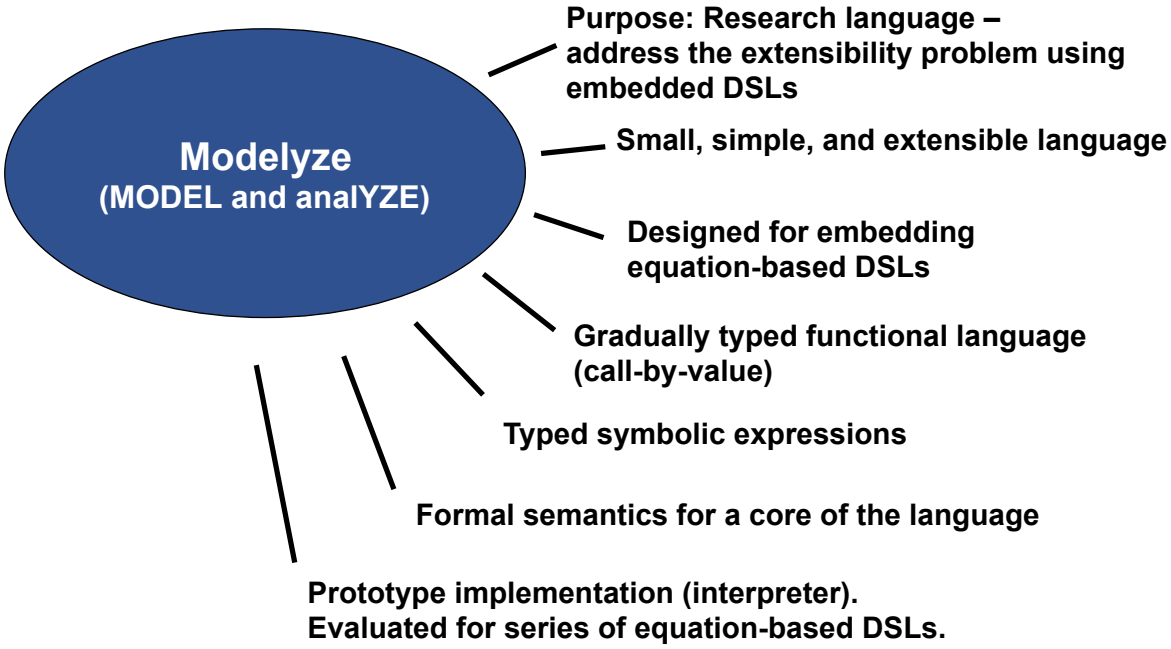

Process Overview

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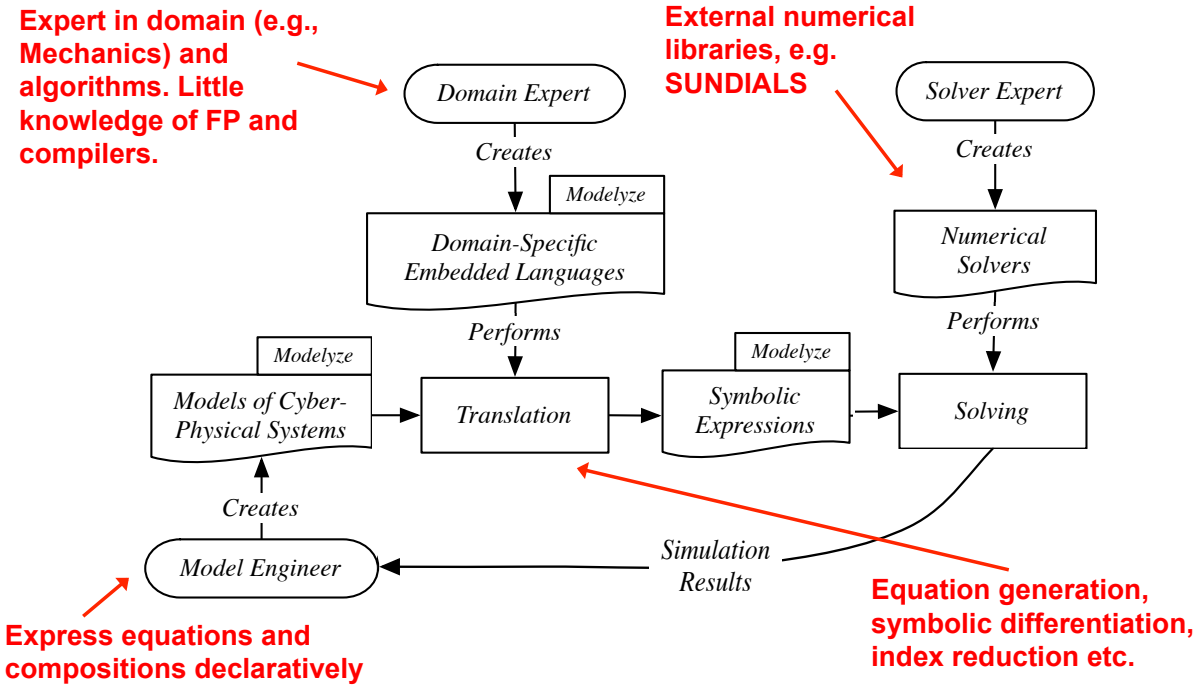

Challenges and Contributions

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1. Provide seamless integration between host language and embedded DSL

Performed together with type checking.

Symbol Lifting Analysis

2. Make it easy to transform and analyze equations (domain expert)

Pattern matching on symbolic expressions

Gradual Typing + Typed Symbolic Expressions

3. Provide domain specific errors (model engineer)

Static type checking

Process Overview

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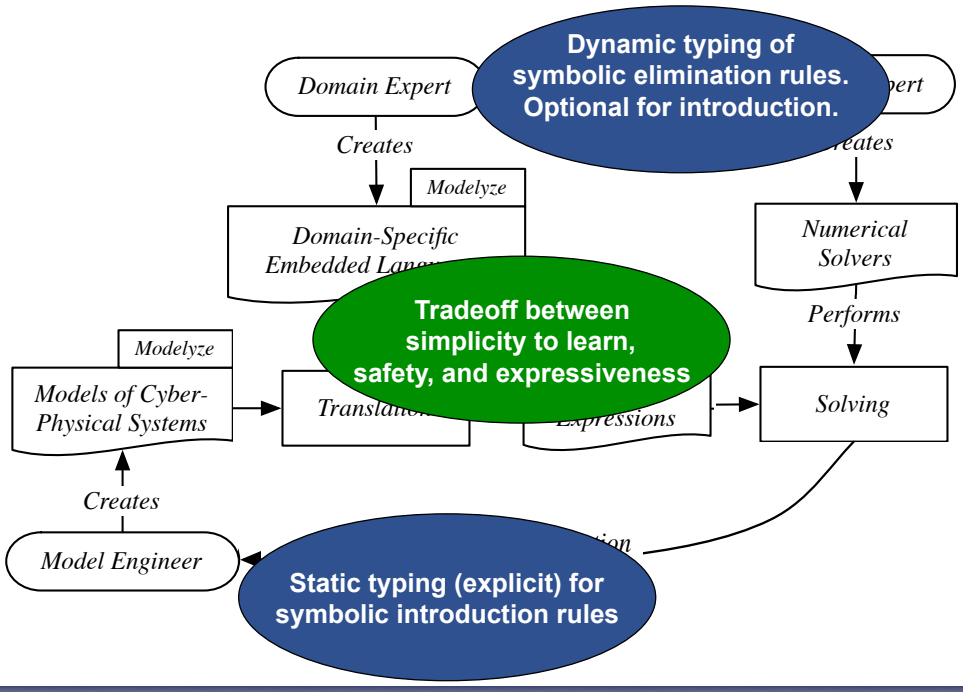

Related Work

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Implementing DSLs

Compiler construction

- JastAdd (Ekman & Hedin, 2007)
- MetaModelica (Pop & Fritzson, 2006)

Preprocessing and template metaprogramming

- C++ Templates (Veldhuizen, 1995)
- Template Haskell (Sheard & Peyton Jones, 2002)
- Stratego/XP (Bravenboer et al., 2008)

Embedded DSLs

- Haskel DSELs, e.g., Fran (Ellito & Hudak, 1997), Lava (Bjesse et al. 1998), and Paradise(Augustsson, 2008)
- FHM (Nilsson et al., 2003)
- Pure embedding (Higher-order functions, polymorphism, lazy evaluation, type classes) (Hudak, 1998)

Combining Dynamic and Static Typing

- Gradual Typing (Siek & Taha, 2007)
- Soft Typing (Cartwright & Fagan, 1991)
- Dynamic type with typecase (Abadi et al., 1991)
- Typed Scheme, Racket (Tobin-Hochstadt, Felleisen, 2008)
- Thorn, like types (Wrigstad et al., 2010)

Representing Code and Data type

- Dynamic languages LISP, Mathematica
- MetaML <T> (Taha & Sheard, 2000)
- GADT (Peyton Jones et al.,2006; Xi et al., 2003; Cheney & Ralf, 2003)
- Open Data types (Löh & Hinze, 2006)
- Pattern Calculus (Jay, 2009)

Pendulum Example

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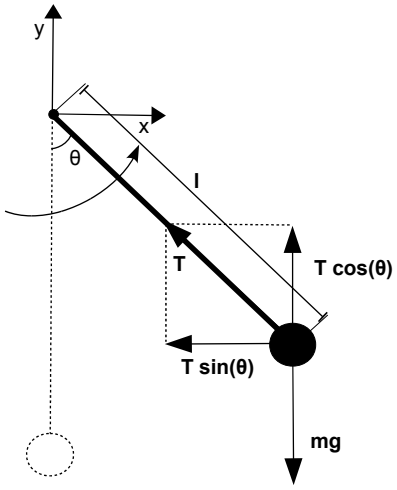

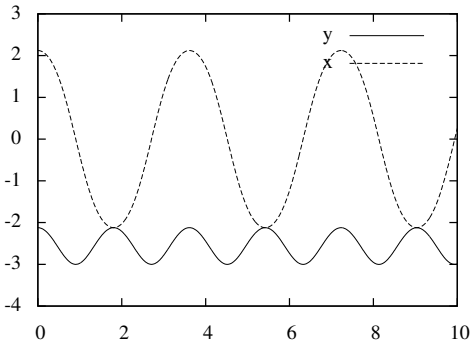

$$-T \cdot \frac{x}{l} = m\ddot{x}$$

$$-T \cdot \frac{y}{l} - mg = m\ddot{y}$$

$$x^2 + y^2 = l^2$$

$$x(0) = l \sin(\theta_s)$$

$$y(0) = -l \cos(\theta_s)$$

Differential-Algebraic equations

Algebraic constraint

Initial values

Declarative Mathematical Model

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Using function abstraction to define the model

Unknowns are given types but not bound to values

Equations and initial values are defined declaratively, just as the mathematical equations

```
def Pendulum(m:Real,l:Real,angle:Real) = {
    def x,y,T:Real;
    init x (l*sin(angle));
    init y (-l*cos(angle));

    -T*x/l = m*x'';
    -T*y/l - m*g = m*y'';
    x^2 + y^2 = l^2;
}
```

$$-T \cdot \frac{x}{l} = m\ddot{x} \qquad x(0) = l\sin(\theta_s)$$
$$-T \cdot \frac{y}{l} - mg = m\ddot{y} \qquad y(0) = -l\cos(\theta_s)$$
$$x^2 + y^2 = l^2$$

Declarative Mathematical Model

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Which parts are part of the host language (Modelyze)?

Unknowns are internally represented as typed symbols

```
def Pendulum(m:Real,l:Real,angle:Real) = {
    def x,y,T:Real;
    init x (l*sin(angle));
    init y (-l*cos(angle));

    -T*x/l = m*x'';
    -T*y/l - m*g = m*y'';
    x^2 + y^2 = l^2;
}
```

$s:\tau$

Fresh (unique) symbol

Tagged with a type

Variable `x` is bound to fresh symbol of type `<Real>`

$<\tau>$ ← Symbolic type

Release the user from annotation burden

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Symbols cannot be bound to values, so `x^2` would crash at runtime

```
def Pendulum(m:Real,l:Real,angle:Real) = {
    def x,y,T:Real;
    init x (l*sin(angle));
    init y (-l*cos(angle));

    -T*x/l = m*x'';
    -T*y/l - m*g = m*y'';
    x^2 + y^2 = l^2;
}
```

Use quasi-quoting to mix symbolic expressions and program code?

Using MetaML syntax `< >` for quotation and `~` for anti-quoting (escape)

```
<~x^2 + ~y^2 = ~((fun t -> <t>)l^2)>;
```

Heavy annotation burden for the end-user

Symbol Lifting Analysis (SLA)

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Symbol Lifting Analysis (SLA): During type checking, lift expressions that cannot be safely evaluated at runtime into symbolic expressions (data).

$$\Gamma \vdash_L e \rightsquigarrow e' : \tau$$

Rewritten to prefix curried form

```
((() x) l)
```

where

```
(/):Real-> Real -> Real
x:<Real>
l:Real
```

```
def Pendulum(m:Real,l:Real,angle:Real) = {
    def x,y,T:Real;
    init x (l*sin(angle));
    init y (-l*cos(angle));

    -T*x/l = m*x'';
    -T*y/l - m*g = m*y'';
    x^2 + y^2 = l^2;
}
```

```
(((lift(/):Real-Real->Real) @ x) @ (lift l:Real))
```

Resulting type `<Real>`

Division cannot be performed, lift expression to type `<Real-> Real -> Real>`.

Term `lift e:T` wraps `e` and results in type `<T>`

Term `e1@e2` is a symbolic application, represented as a tuple.

Symbols used to construct equation systems

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```
def Pendulum(m:Real,l:Real,angle:Real) -> Equations = {
    def x,y,T:Real;
    init x (l*sin(angle));
    init y (-l*cos(angle));

    -T*x/l = m*x'';
    -T*y/l - m*g = m*y'';
    x^2 + y^2 = l^2;
}
```

Symbolic data type

Type of **Pendulum** : Real -> Real -> Real -> Equations

Typed symbol used as constructors

```
type Equations
def (=) : Real -> Real -> Equations
def (;) : Equations -> Equations -> Equations
```

Data types are open with no exhaustive checking for patterns

```
def der : Real -> Real
def (')  = der
def init : Real -> Real -> Equations
```


Pattern Matching on Symbolic Expressions

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Dynamic symbolic type **<?>**

Accumulator Sets of symbolic type **<Real>**

Query for all unknowns in a model instance

```
def getUnknowns(exp:<?>, acc:(Set <Real>)) -> (Set <Real>) = {
    match exp with
    | e1 e2 -> getUnknowns(e2,getUnknowns(e1,acc))
    | sym:Real -> Set.add exp acc
    | _ -> acc
}
```

Uniform data structure, no boilplate code (matching on symbolic applications)

Match all symbols of type **<Real>** i.e., unknowns in the model.

```
getUnknowns(Pendulum(5,3,45*pi/180),Set.empty)
```

Returns a set with 3 symbols (representing **x**, **y**, and **T**).

Static Error Checking at the DSL Level

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Syntactically correct model (host syntax)

Static type error instead of dynamic error during translation/pattern matching.

```
def ModifiedPendulum(m:Real,l:Real,angle:Real) = {
    def x,y,T:Real;
    init x (l*sin(angle));
    init y;                    //Error 1: Missing initial value

    -T*der/l = m*x'';          //Error 2: der used incorrectly
    -T*y/l - m*g = m*y'';
    x^2 + y^2 = l^2;
}
```

Still challenging to provide meaningful error messages.
"Expected type `<Real>` but found `<Real->Real>`"

Mechatronic Control Example

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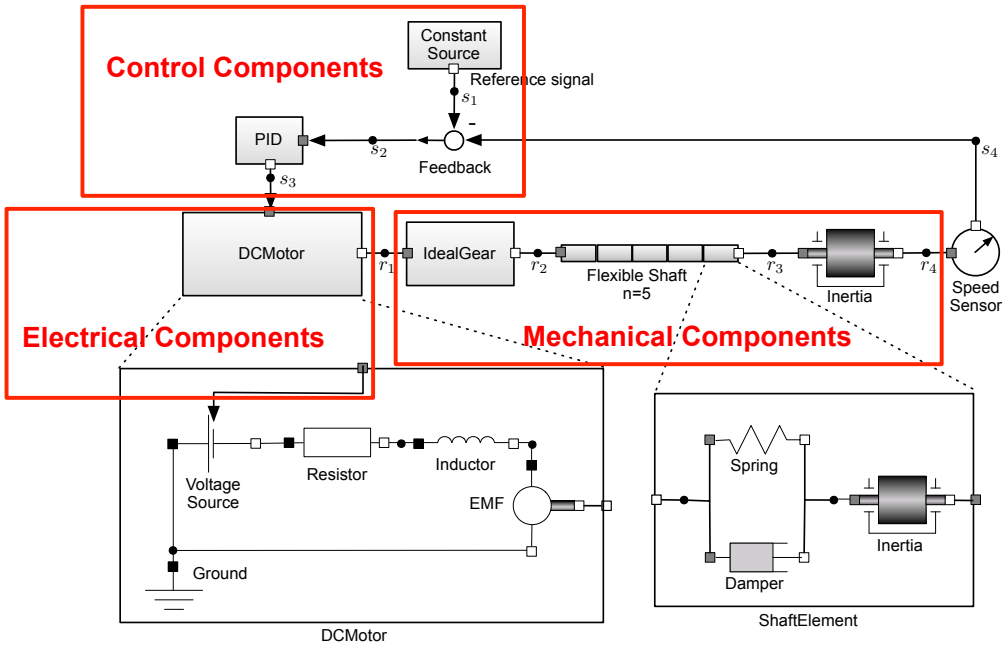

Mechatronic Control Example

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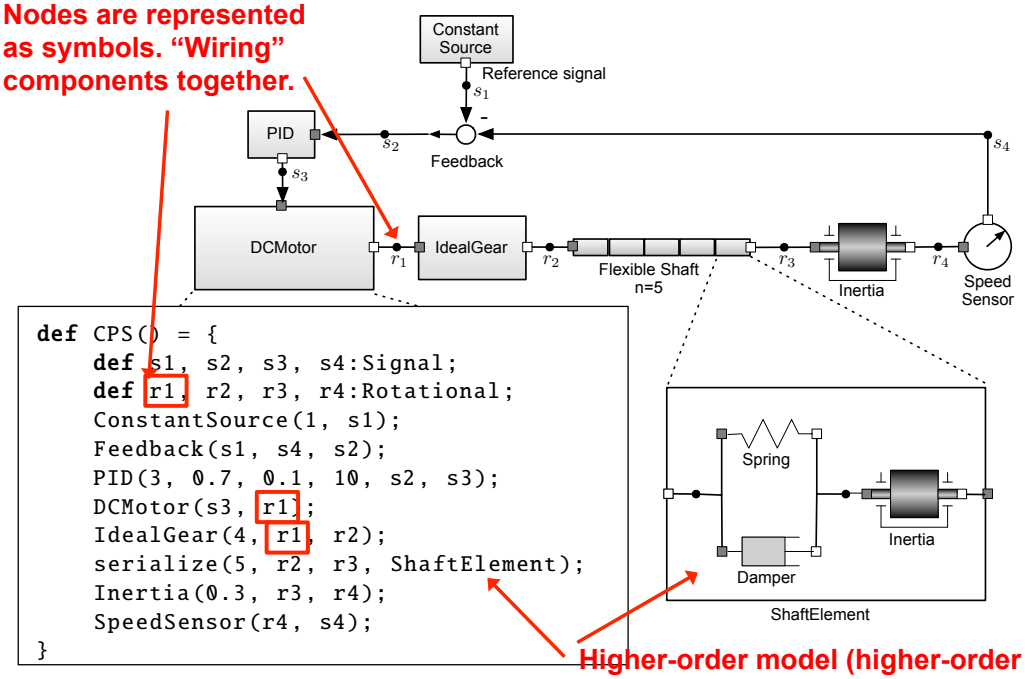
Nodes are represented as symbols. "Wiring" components together.




```
def CPS() = {
    def s1, s2, s3, s4:Signal;
    def r1, r2, r3, r4:Rotational;
    ConstantSource(1, s1);
    Feedback(s1, s4, s2);
    PID(3, 0.7, 0.1, 10, s2, s3);
    DCMotor(s3, r1);
    IdealGear(4, r1, r2);
    serialize(5, r2, r3, ShaftElement);
    Inertia(0.3, r3, r4);
    SpeedSensor(r4, s4);
}
```

Higher-order model (higher-order function)

Mechatronic Control Example

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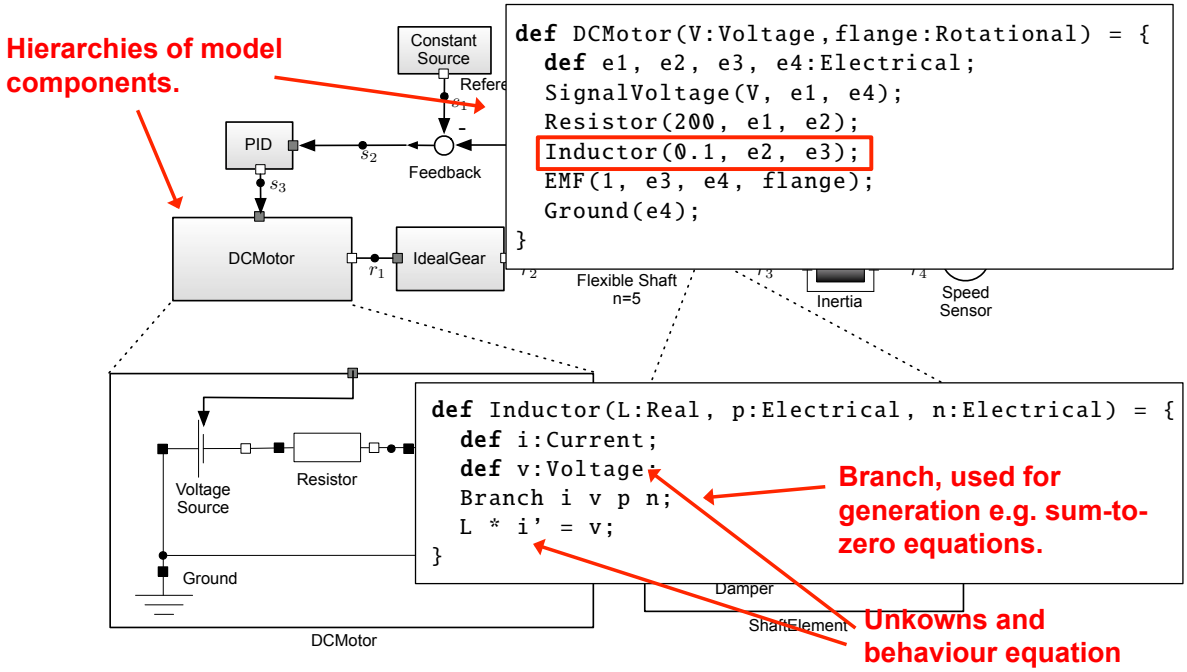
Hierarchies of model components.




```
def DCMotor(V:Voltage,flange:Rotational) = {
  def e1, e2, e3, e4:Electrical;
  SignalVoltage(V, e1, e4);
  Resistor(200, e1, e2);
  Inductor(0.1, e2, e3);
  EMF(1, e3, e4, flange);
  Ground(e4);
}
```

```
def Inductor(L:Real, p:Electrical, n:Electrical) = {
  def i:Current;
  def v:Voltage;
  Branch i v p n;
  L * i' = v;
}
```

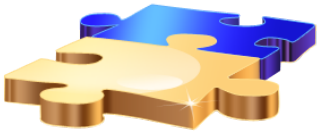
Branch, used for generation e.g. sum-to-zero equations.

Unkowns and behaviour equation

Conclusions

Main takeaway points (Modelyze)

A simple research language – host language for embedding equation-based DSLs



Symbol lifting analysis (SLA) is used to release the annotation burden from the user

Typed symbols with gradual typing is used for pattern matching and DSL-level error reporting

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Part II
Precision Timed Infrastructure
Making Time an Engineering Abstraction

Key contributors and collaborators related to the PRET project

Edward A. Lee	**Isaac Liu**	**Jan Reineke**	Jia Zou
Steven A. Edwards	Slobadon Matic	Sanjit Seshia	Sungjun Kim
Jeff Jensen	Hiren Patel	Michael Zimmer	

A Story…

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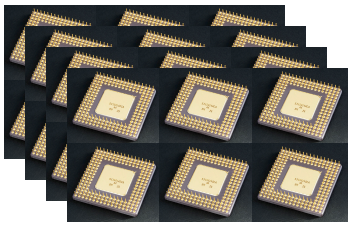
Fly-by-wire technology controlled by software.

Safety critical ➔
Rigorous validation and certification

Success?



They have to purchase and store microprocessors for at least 50 years production and maintenance…

Why?

Apparently, the software does not specify the behaviour that has been validated and certified!

What is PRET?

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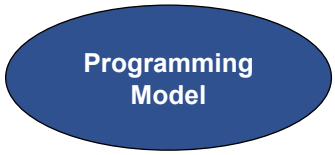
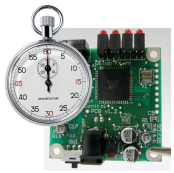
Timing is not part of the software semantics

Correct execution of programs (e.g., in C, C++, C#, Java, Scala, Haskell, OCaml) has nothing to do with how long time things takes to execute.

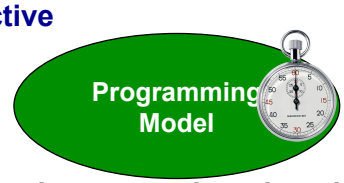
Traditional Approach



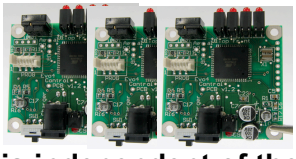


Timing Dependent on the Hardware Platform

Our Objective



Make time an engineering abstraction within the programming model



Timing is independent of the hardware platform (within certain constraints)

What is PRET?

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

PRET Infrastructure

- **PRET Language (Language timing semantics)**
- **PRET Compiler (Timing aware compilation)**
- **PRET Machine (Computer Architecture)**

What do precision, predictable, and repeatable timing mean?

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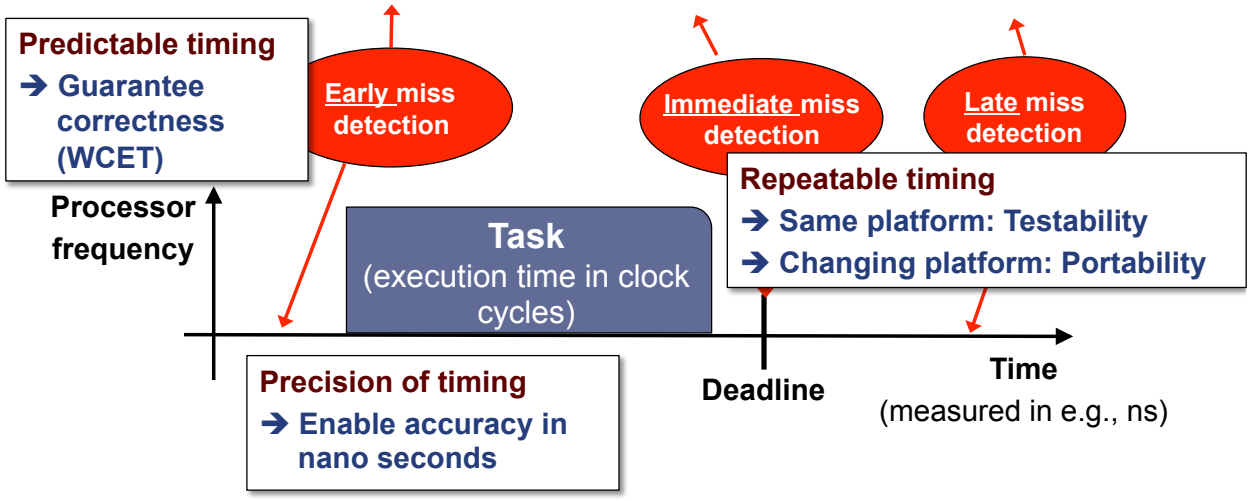
Focus on cyber-physical systems with real-time constraints

	Hard task	Firm task	Soft task
Missed deadline	Catastrophic consequence	Result is useless, but causes no damage	Result has still some utility



Instruction set architecture (ISA)

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Rethink the ISA

Timing has to be a *correctness* property not only a *performance* (quality) property

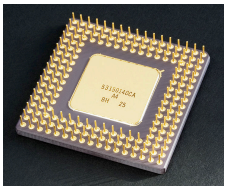

Photo by Andrew Dunn, 2005

PRET Machine

- **Repeatable and predictable execution time (instructions)**
- **Repeatable memory access time**
- **Timing instructions for handling missed deadline detection**

Related Work

Java Optimized Processor (JOP) (Schoeberl, 2008)

ARPRET (Andalam et al., 2009)

ARMv4 ISA extended with timing constructs

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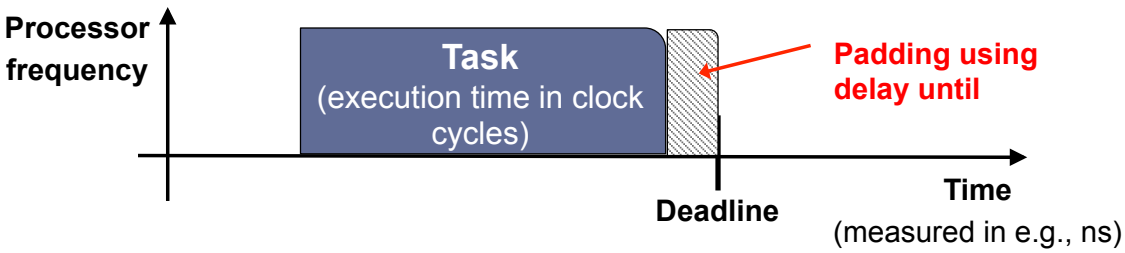
Best effort (with padding)

New instruction *get time* (gt)

```
gt      r1, r2      ; get time (ns)
  -- Code block --
adds    r2, r2, #500  ; add 500 ns
adc     r1, r1, #0    ; add with carry (time in 2 32-bit reg)
du      r1, r2      ; delay until 500ns have elapsed
```

New instruction *delay until* (du)

We do not detect missed deadlines!



ARMv4 ISA extended with timing constructs

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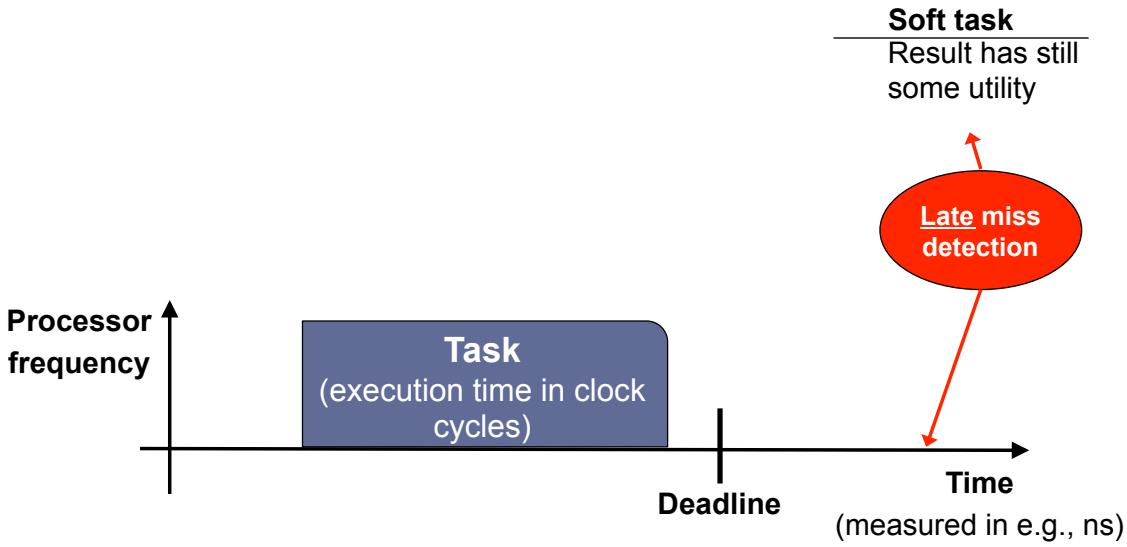
Late miss detection



ARMv4 ISA extended with timing constructs

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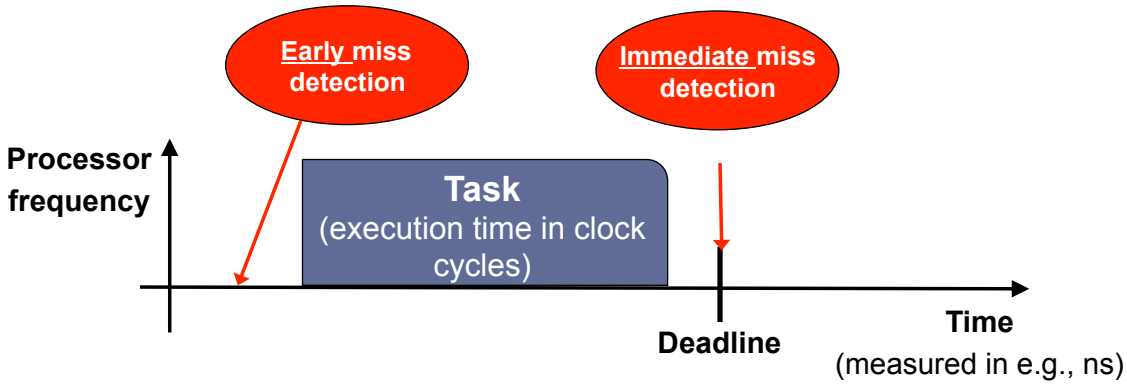
Early and immediate miss detection

Not handled at the ISA level

Needs static timing analysis!

Handled using timing exceptions
New instructions:
ee - Exception on Expire
de - Deactivate Exception



We need implementations that deliver repeatable timing

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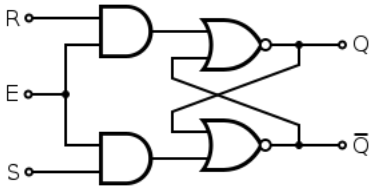
The good news

Fortunately, electronics technology delivers highly reliable and precise timing



The bad news…

The chip architectures introduces highly non-deterministic behavior (e.g., using caches, pipelines etc.).

We need to rethink the microarchitecture

- **Pipelining**
- **Memory hierarchies**
- **I/O (DMA, interupts)**
- **Power management**
- **On-chip communication**
- **Reseource sharing (e.g., in multicore)**

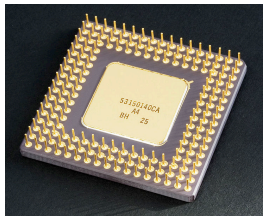


Photo by Andrew Dunn, 2005

Our Current PRET Architecture

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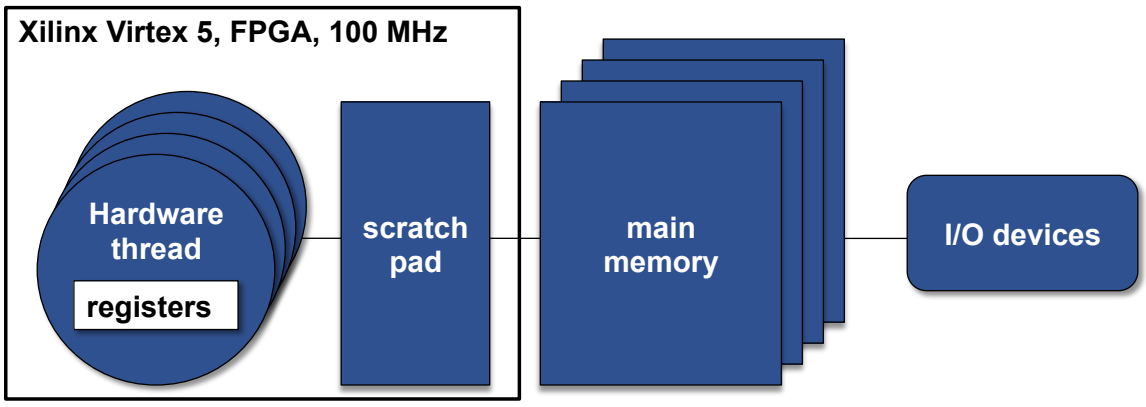
PTARM, a soft core on Xilinx Virtex 5 FPGA



Thread-interleaved Pipeline

4 threads, 5 stage pipeline

Scratchpad shared among threads

1 thread cycle for load/store

DRAM main memory, separate banks per thread

Load 4 thread cycle
Store 1-2 thread cycles
(1 thread cycle = 4 processor cycles)

Timing Aware Compilation (Work-in-progress)

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Modeling Language

Simulink, Ptolemy, Modelica, Other DSLs

Programming Language

Real-time Concurrent C (Gehani and Ramamritham, 1991)

PRET-C (Andalam et al., 2009)

WCC (Falk and Lokuciejewski, 2010)

Assembly Language

Timing Aware Compilation (Work-in-progress)

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Modeling Language

Simulink, Ptolemy, Modelica, Other DSLs

Programming Language

Extended with timing semantics

Java, ptC, Haskell, C/C++

Intermediate Language

Expose timing constructs and WCET

PRETIL

Abstracting away the memory allocation (scratchpad)

Assembly Language

PRET ISA

Some of the main challenges

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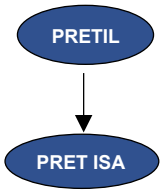
Relating real-time to execution-time

Execution time in clock cycles – oscillators not precise enough

➔ IEEE1588 clock synchronization (needs WCET margin)



Compiling with execution time

```
runfor(10ms){
  <code1>
}
```

(1) Estimate WCET of ASM program
(2) WCET-aware compilation to minimize WCET

Scratchpad allocation is now a compiler problem

➔ Optimization problem with timing constraints. Options:
(1) For a given frequency, optimize (average case) performance
(2) Find lowest frequency fulfilling constraints

Making time independent of the hardware

For the same ISA, different platform parameters affect timing (Scratchpad size, clock frequency, memory latency, etc.)

➔ Compiler generates a certificate – checked at load time

Part I
Cyber-Physical Systems

Part II
Modelyze - a host language for equation-based languages

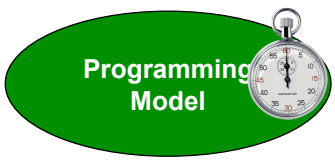
Part III
Precision Timed Infrastructure - making time an engineering abstraction

Conclusions

Main takeaway points (PRET)

Time is a correctness factor – not just a performance (quality) factor

Today, timing behavior is a property of the *realizations* of a software system



The PRET approach aims at making time an engineering abstraction *within* the *programming model*

Thank you for listening!