Contract-Based Integration of Cyber-Physical Analyses

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October 14, 2014
14th International Conference on Embedded Software

Carnegie Mellon · institute for SOFTWARE RESEARCH · Software Engineering Institute

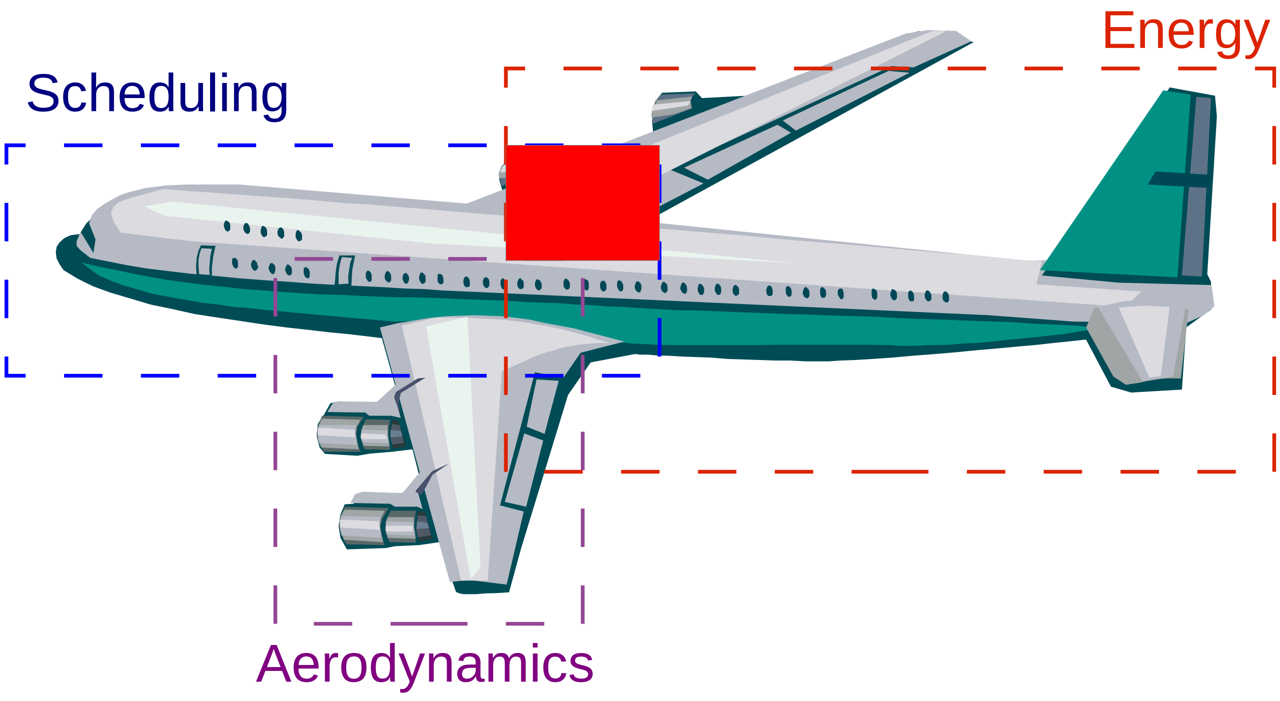
This material is based upon work funded and supported by the Department of Defense under Contract No. FA8721-05-C-0003 with Carnegie Mellon University for the operation of the Software Engineering Institute, a federally funded research and development center.

DM-0001714

Outline

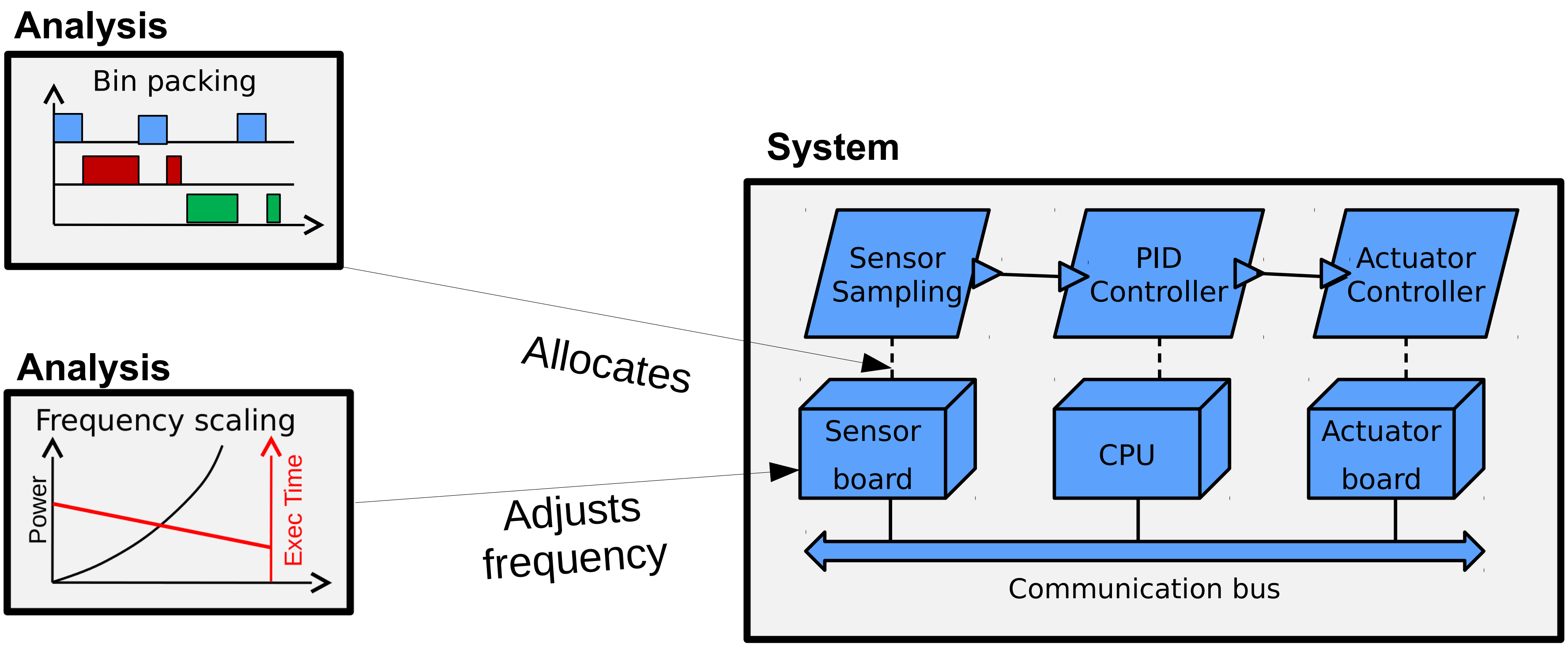
- Analysis integration problem
- Analysis contracts approach
  - Specification
  - Verification
- Experimental results

Model integration in CPS



- Subtle mismatches between technical domains
- Lead to costly fixes or failures

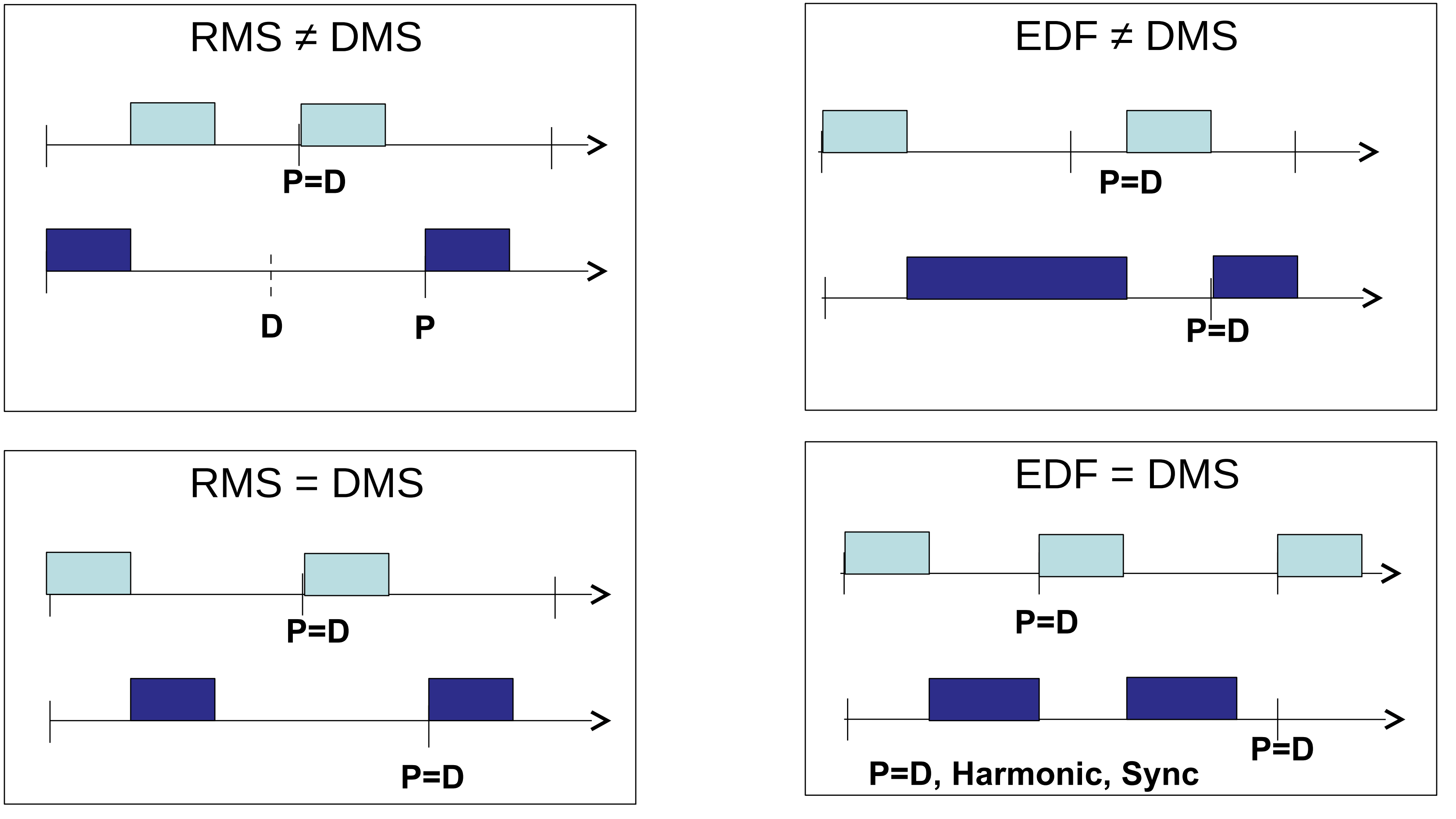
Analytic aspect of integration



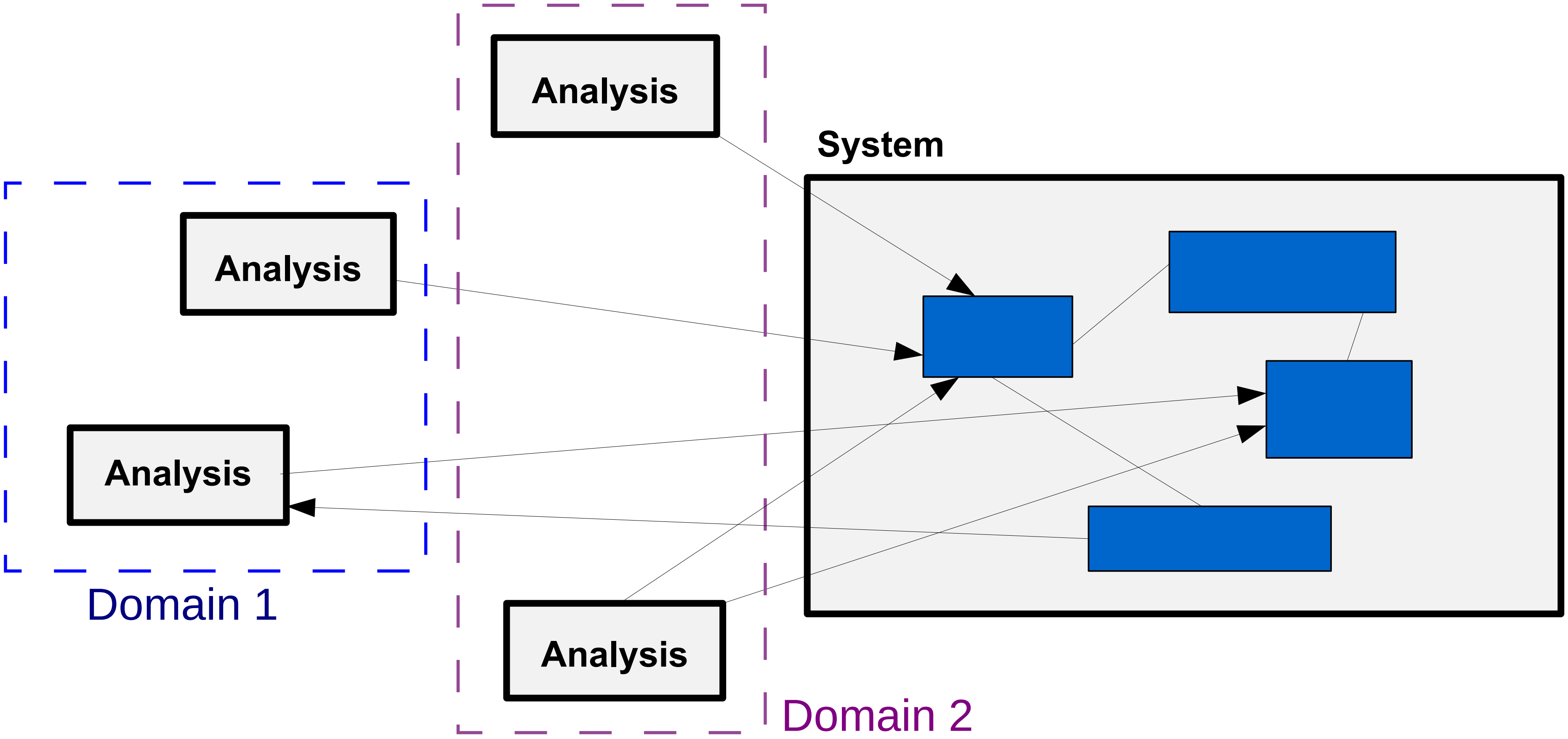
- Frequency scaling is applicable *only* when:
  - used after Bin packing
  - the system is behaviorally deadline-monotonic
- Otherwise, frequency scaling may render the system unschedulable

Frequency scaling assumption

- Behavioral equivalence to deadline-monotonic scheduling



Analysis integration problem



- Out-of-order execution
- Invalidation of assumptions

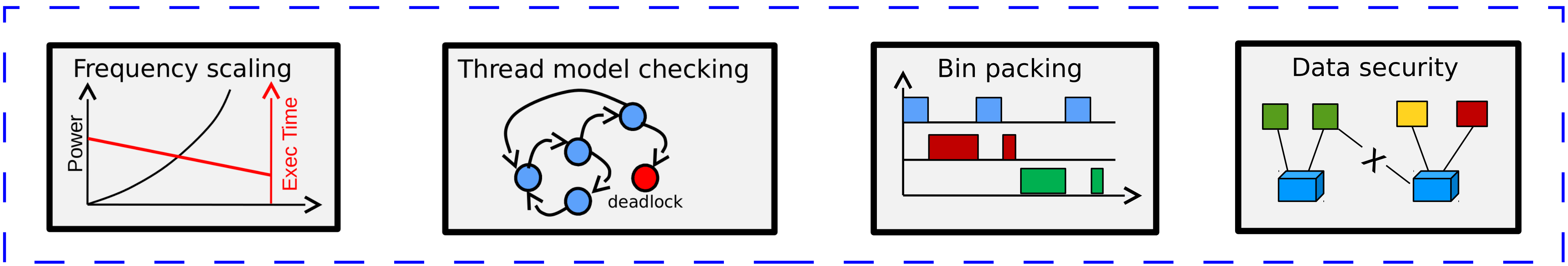
Existing solutions

- Assume-guarantee component composition does not handle analytic integration of tools [1][2].
- Architectural views tackle model consistency, not analytic tool consistency [3][4]
- Meta-level AADL languages do not allow domain-specific semantics [5]
- Previous work on analysis contracts: single domain only, unsound and incomplete verification [6]

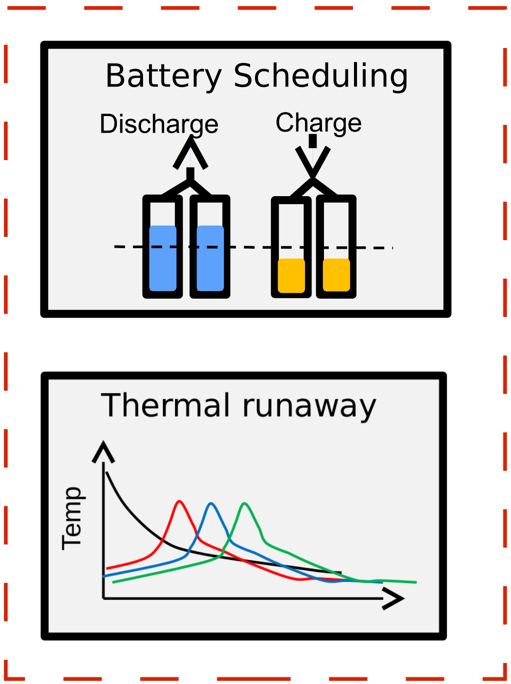
[1] Frehse et al. Assume-guarantee reasoning for hybrid I/O-automata by over-approximation of continuous interaction, 2004
[2] Sangiovanni-Vincentelli et al. Taming Dr. Frankenstein: contract-based design for cyber-physical systems, 2013
[3] Torngren et al. Integrating viewpoints in the development of mechatronic products, 2013
[4] Rajhans et al. Supporting heterogeneity in cyber-physical systems architectures, 2014
[5] Boddy et al. The FUSED meta-language and tools for complex system engineering, 2011
[6] Nam et al. Resource allocation contracts for open analytic runtime models, 2011

Running example

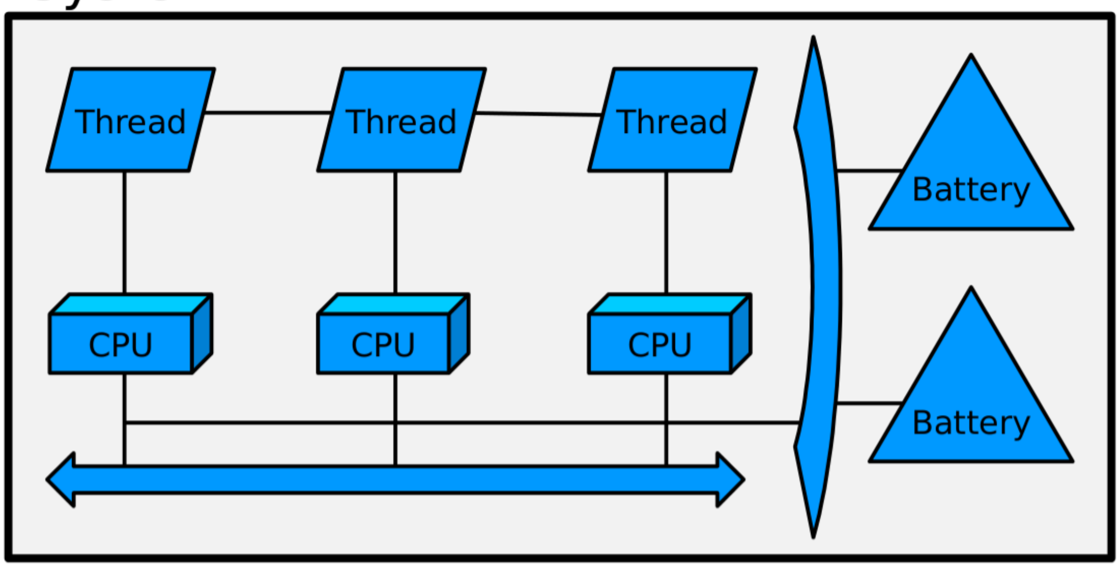
Scheduling



Battery



System



Outline

- Analysis integration problem
- **Analysis contracts approach**
  - Specification
  - Verification
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Analysis contracts approach

1. Formalize analysis domains
2. Specify dependencies, assumptions, and guarantees of analyses
3. Determine correct ordering of analyses
4. Verify assumptions and guarantees of analyses

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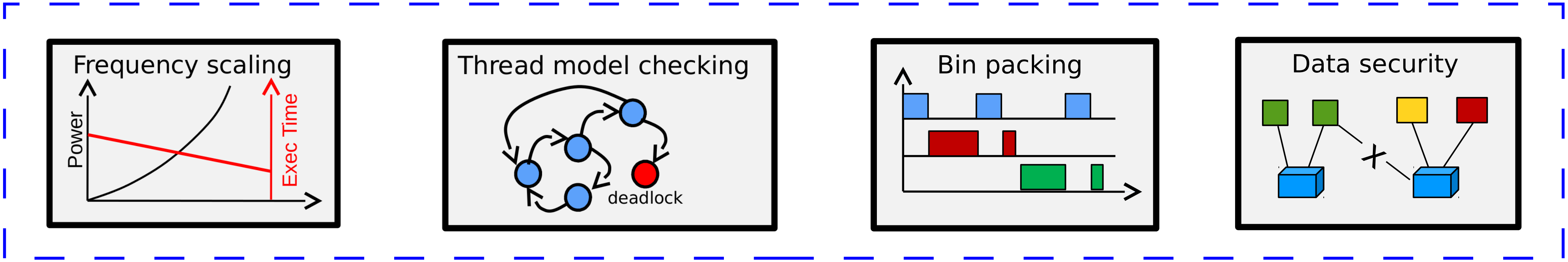
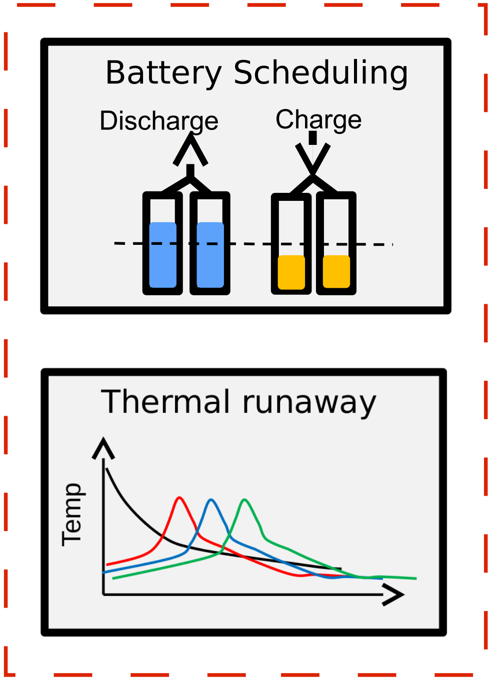
Running example

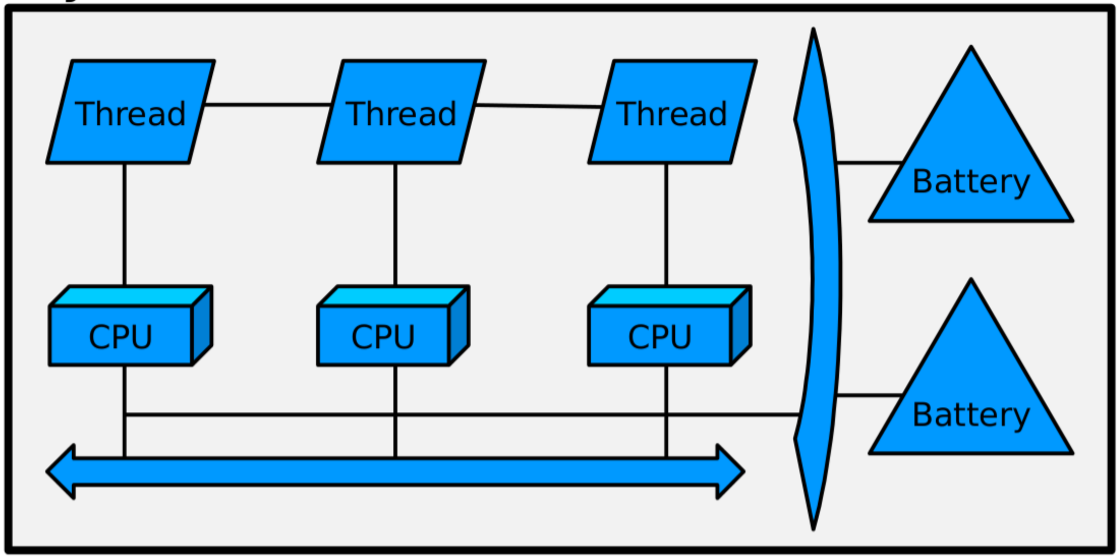
Scheduling



Battery

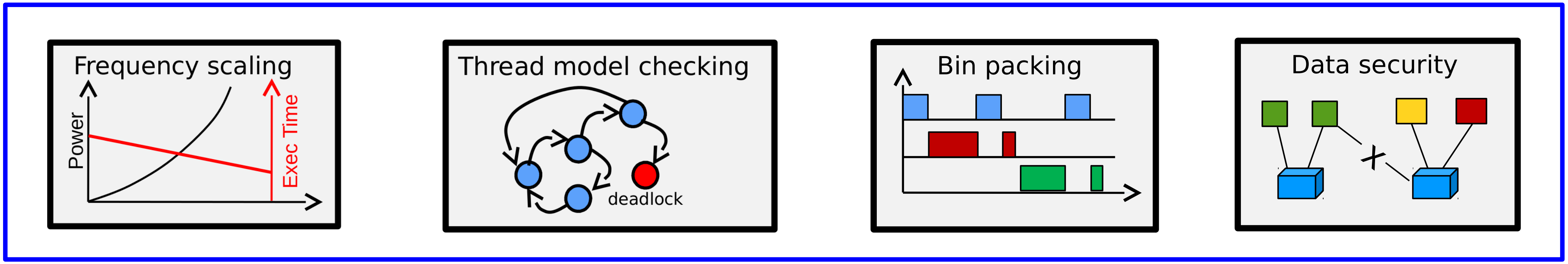


System

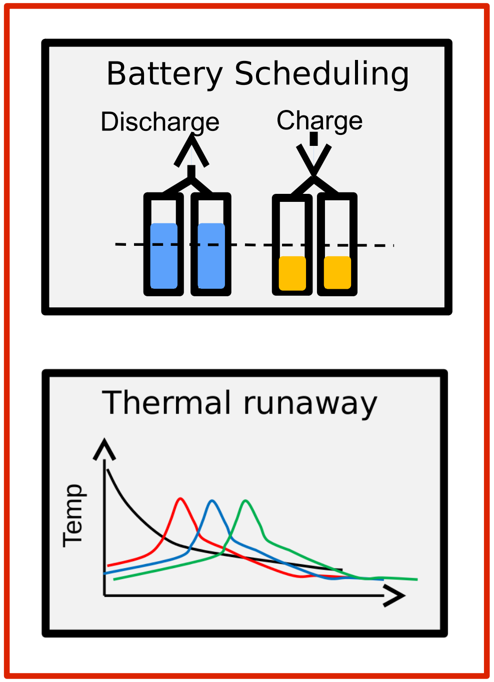


Running example

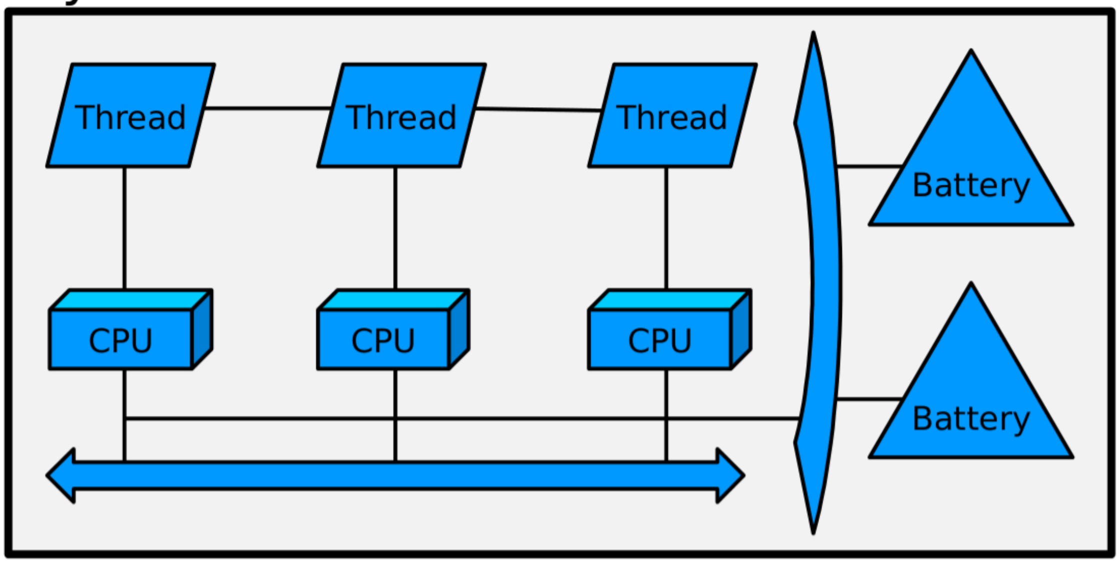
Scheduling domain $\boldsymbol{\sigma}_{\textbf{sched}}$



Battery domain $\boldsymbol{\sigma}_{\textbf{batt}}$



System



Verification domain

Domain **σ** is a many-sorted signature ($\mathcal{A}$, $\mathcal{S}$, $\mathcal{R}$, $\mathcal{T}$, $⟦\,⟧_{\boldsymbol{\sigma}}$):

- $\mathcal{A}$ **–** set of atoms: $\mathbb{B}$, $\mathbb{Z}$, *Threads*, *Batteries, SchedPol*
- $\mathcal{S}$ **–** static functions: *Period, Dline, CPUBind, Voltage*
- $\mathcal{R}$ **–** runtime functions C*anPrmpt*: *Threads x Threads* → $\mathbb{B}$
- $\mathcal{T}$ **–** execution semantics
  - set of sequences of $\mathcal{R}$ assignments
- $⟦\,⟧_{\boldsymbol{\sigma}}$ and $⟦\,⟧_{\mathbf{m}}$ **–** domain and model interpretations
  - $⟦\mathit{SchedPol}⟧_{\boldsymbol{\sigma}}$ = {RMS, DMS, EDF}
  - $⟦\mathrm{CPUBind}⟧_{\mathbf{m}}$ **=** { ($Ctrl_1$, CPU_1), (Ctrl_2, CPU_2), ... }

Analysis contract

- Given a domain **σ**, *analysis contract* **C** is a tuple (**I**, **O**, **A**, **G**)
  - Inputs $\mathbf{I} \subseteq \mathcal{A} \cup \mathcal{S}$
  - Outputs $\mathbf{O} \subseteq \mathcal{A} \cup \mathcal{S}$
  - Assumptions $\mathbf{A} \subseteq \mathcal{F}_{\boldsymbol{\sigma}}$
  - Guarantees $\mathbf{G} \subseteq \mathcal{F}_{\boldsymbol{\sigma}}$
- Where:
  - $\mathcal{F}_{\boldsymbol{\sigma}}$ ::= $\{\forall|\exists\}\ v_1..v_n \bullet \varphi \ \ | \ \ \{\forall|\exists\}\ v_1..v_n \bullet \varphi : \psi$
  - φ is a static predicate formula over $\mathcal{A}$ and $\mathcal{S}$
  - ψ is an LTL formula over $\mathcal{A}$, $\mathcal{S}$, and $\mathcal{R}$
  - E.g.: $\forall\ t_1, t_2$: *Threads* • $t_1 \neq t_2 \wedge$ *CPUBind*(t_1) = *CPUBind*(t_2) :

    G (*CanPrmpt*(t_1, t_2) ⇒ *Dline*(t_1) < *Dline*(t_2))

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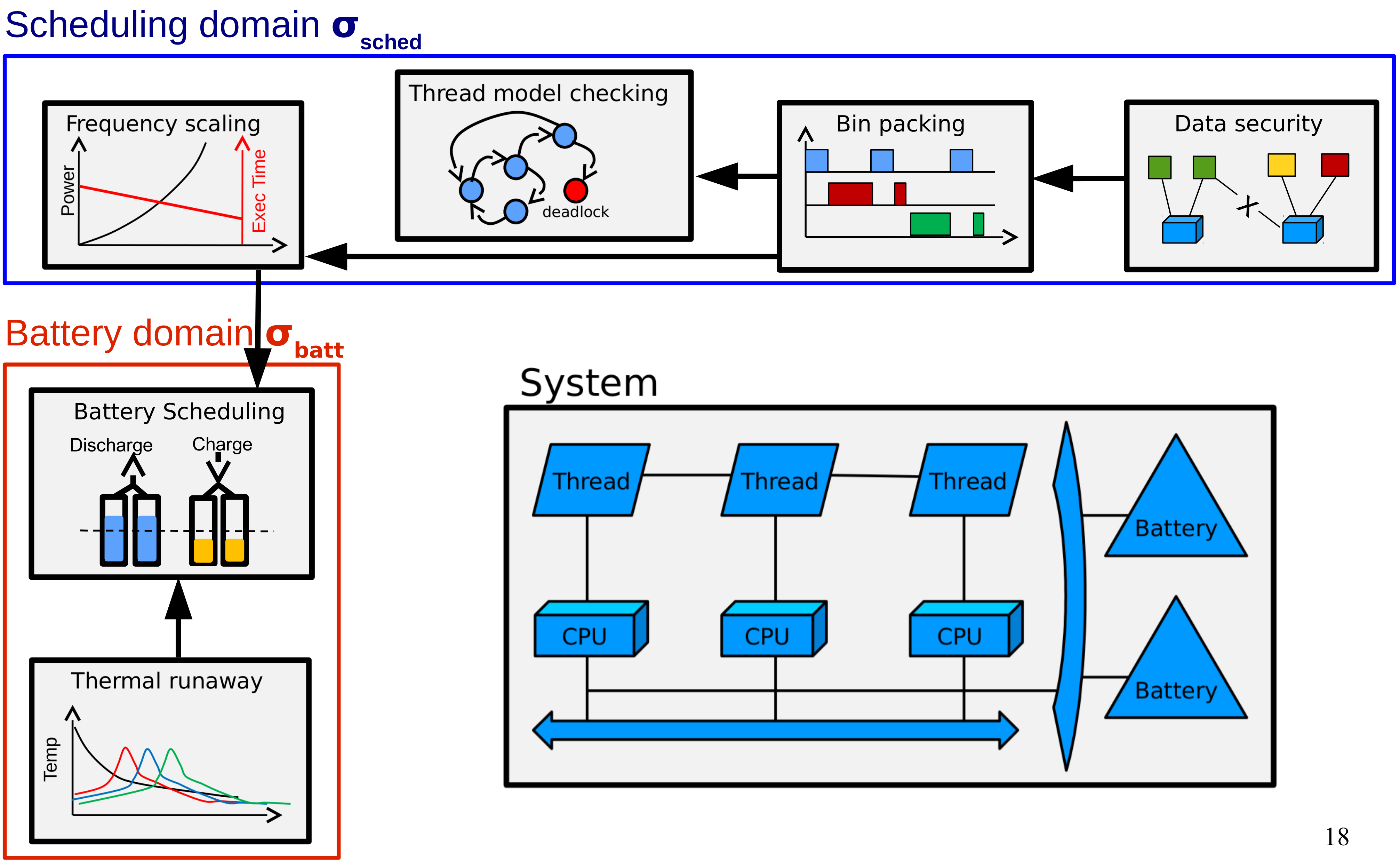


Assumption verification

- Goal:

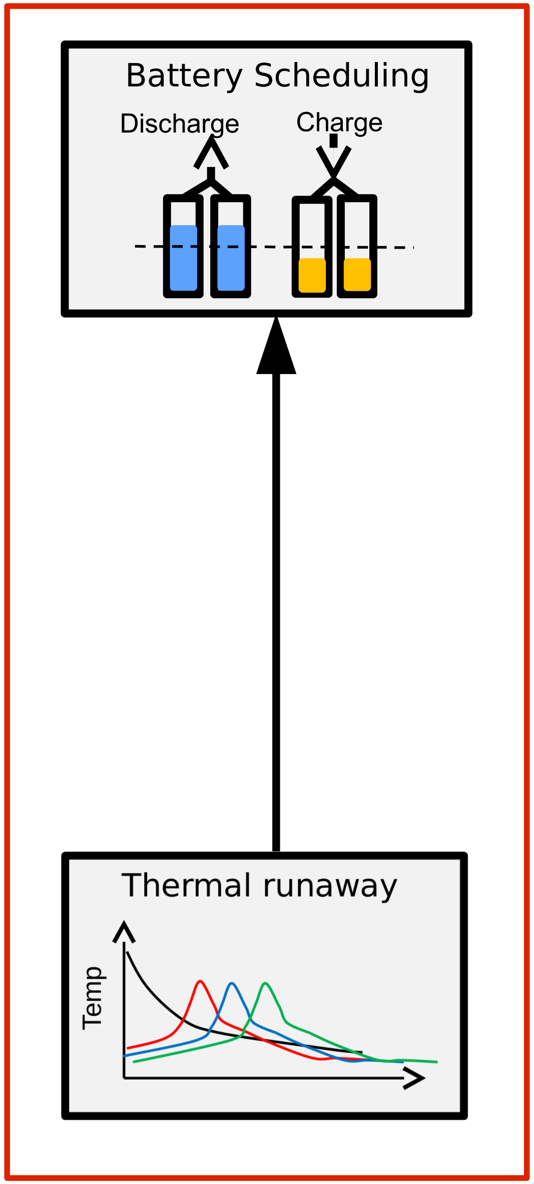
  $\forall\ t_1, t_2$: *Threads* • $t_1 \neq t_2 \wedge CPUBind(t_1) = CPUBind(t_2)$:

  $G\ (CanPrmpt(t_1, t_2) \Rightarrow Dline(t_1) < Dline(t_2))$

- SMT solver finds solutions for static fragment φ
  - $\forall\ t_1, t_2$:*Threads* | $t_1 \neq t_2 \wedge CPUBind(t_1) = CPUBind(t_2)$
- Model checking property ψ in a behavioral Promela model for each SMT solution:
  - $G\ (CanPrmpt(t_1, t_2) \Rightarrow Dline(t_1) < Dline(t_2))$

Battery modeling

Battery domain $\boldsymbol{\sigma}_{\mathbf{batt}}$

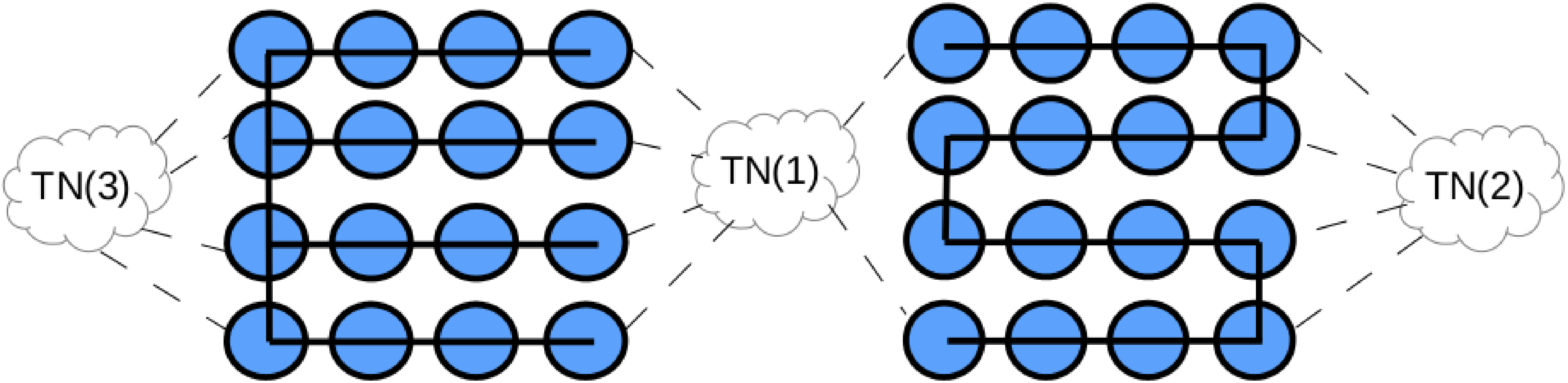


- Abstraction: circuits
- Selects a scheduler for cell connections
- Oblivious of heat: treats any configuration as acceptable heat-wise

- Restrictions on acceptable thermal configurations
- Guarantee: unacceptable ones don't occur

- Abstraction: geometry
- Simulates heat propagation
- Cannot scale to dynamic scheduling: simulates only fixed cell configurations

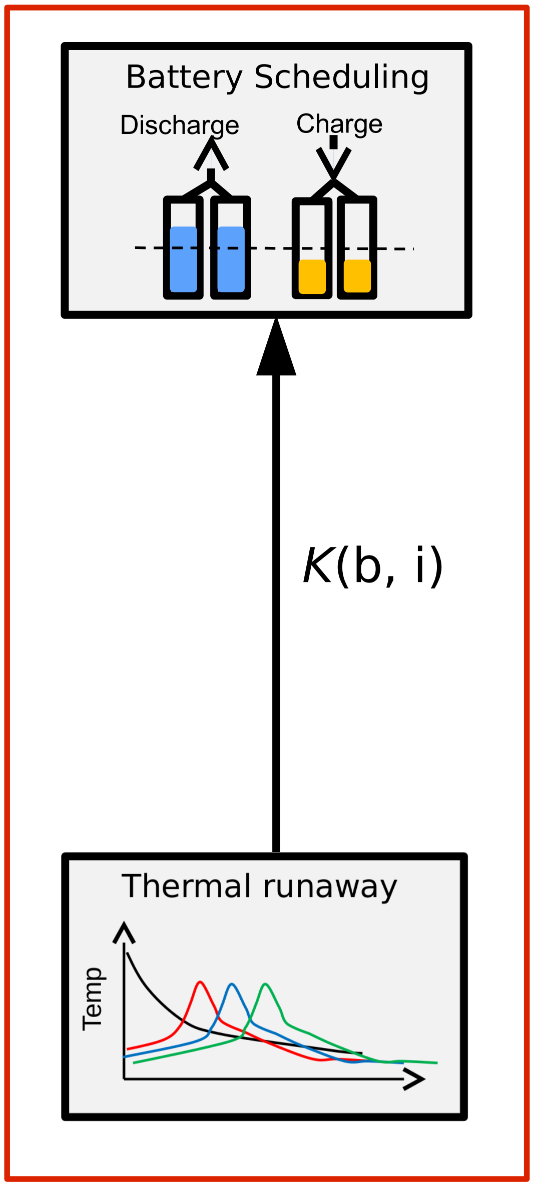
Battery scheduling guarantee



- ***G**: "Bad thermal configurations are not reachable"*
- *TN*(b, i) ∈ $\mathcal{R}$ – number of cells in b with i thermal neighbors
- *K*(b, i) ∈ $\mathcal{S}$ – experimental weight for *TN*(b, i)
- **G** = {∀ b: *Batteries* • G ($\sum_{i=0..3}$ *K*(b, i)**TN*(b, i)) ≥ 0}

Battery modeling

Battery domain σ_{batt}



Selects a battery scheduler

G: $\forall$ b: *Batteries* • G ($\sum_{i=0..3} K(b, i) * TN(b, i)$) ≥ 0

Verified with battery Promela/Spin model

Determines *K*(b, i) via simulation

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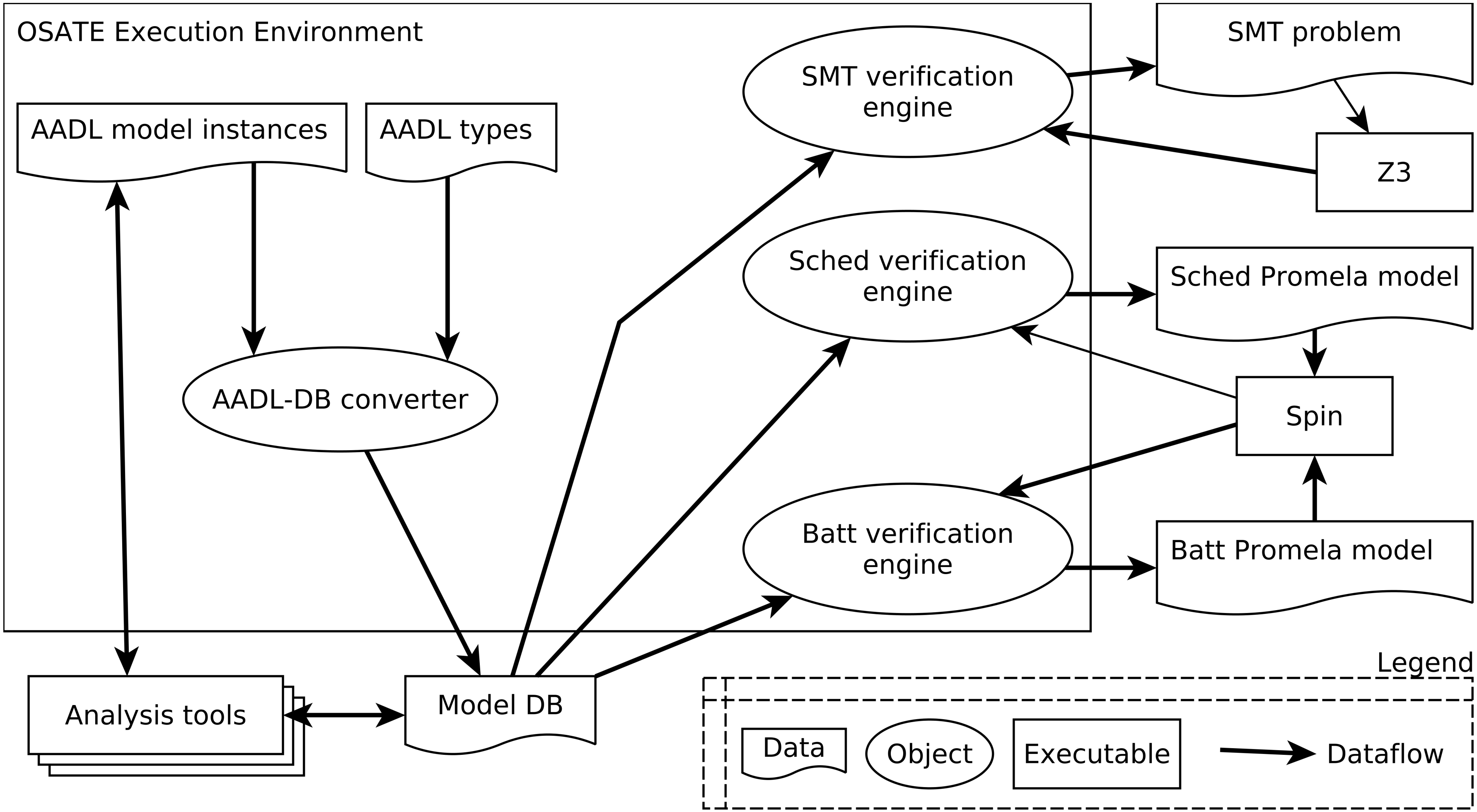
Framework implementation



Scalability evaluation

- SMT solving typically takes less than 0.1 second
- Spin model checking times:

σ_{sched}:

Threads	(R/D)MS time	EDF time
3	0.01	0.01
4	0.01	0.52
5	0.07	33.4
6	0.37	2290.0
7	2.18	Out Mem
8	12.4	Out Mem
9	71.2	Out Mem
10	421	Out Mem
11	Out Mem	Out Mem

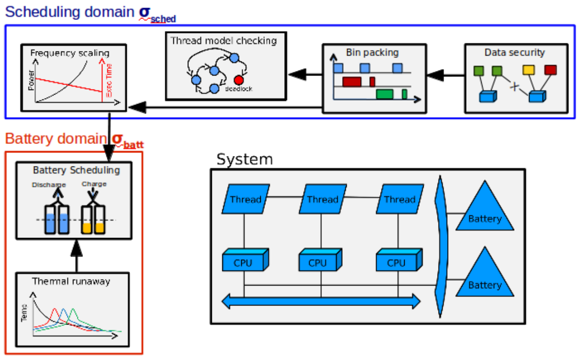
σ_{batt}:

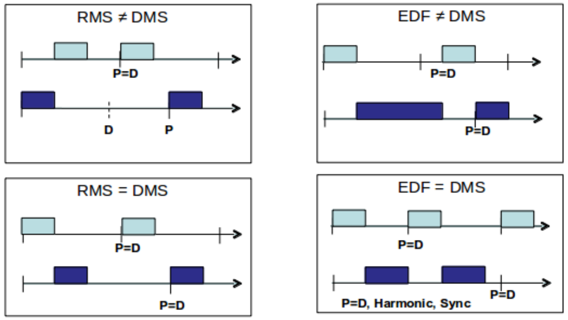
Cells	FGURR time	FGWRR time	GPWRR time
9	0.13	0.15	0.15
12	0.61	2.34	3.94
16	44	31.4	127
20	1060	619	Out Mem
25	Out Mem	Out Mem	Out Mem

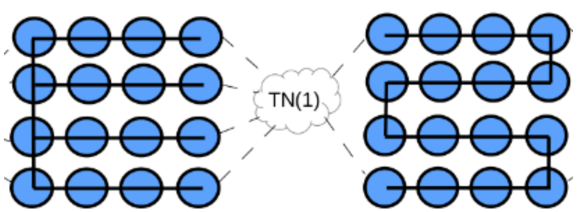
All times are in seconds

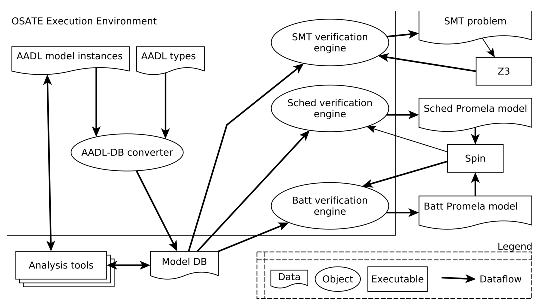
Summary

- Analysis integration is error-prone
  - Incorrect ordering
  - Violation of implicit assumptions
- Our solution:
  - Contract specification language
  - Contract verification algorithm
  - Framework implementation
- Effective, extensible, and scalable









Verification domain

- Domain **σ** is a many-sorted signature ($\mathcal{A}$, $\mathcal{S}$, $\mathcal{R}$, $\mathcal{T}$, $\{\!\![\ ]\!\!\}_\sigma$):
  - $\mathcal{A}$: set of sorts – system elements and standard sorts
    - E.g.: $\mathbb{B}$, $\mathbb{Z}$, *Threads*, *Batteries, SchedPol*
  - $\mathcal{S}$: $\mathcal{A}_i$ x ... x $\mathcal{A}_n \rightarrow \mathcal{A}_k$ – static functions that encode design properties
    - E.g.: *Period, Dline, CPUBind, Voltage*
  - $\mathcal{R}$: $\mathcal{A}_i$ x ... x $\mathcal{A}_n \rightarrow \mathcal{A}_k$ – runtime functions that encode dynamic properties
    - E.g.: *CanPrmpt*: *Threads* x *Threads* → $\mathbb{B}$
      TN: *Batteries* x $\mathbb{Z} \rightarrow \mathbb{Z}$

Verification domain

- Domain **σ** is a many-sorted signature ($\mathcal{A}$, $\mathcal{S}$, $\mathcal{R}$, $\mathcal{T}$, $⟦\,⟧_{\boldsymbol{\sigma}}$):
  - $\mathcal{T}$: execution semantics – set of sequences of $\mathcal{R}$ assignments
    - E.g.: thread scheduler state model for $\boldsymbol{\sigma}_{\mathbf{sched}}$
      battery state model for for $\boldsymbol{\sigma}_{\mathbf{batt}}$
  - $⟦\,⟧_{\boldsymbol{\sigma}}$: domain interpretation for $\mathcal{A}$ and $\mathcal{S}$
    - E.g.: $⟦\mathit{SchedPol}⟧_{\boldsymbol{\sigma}}$ = {RMS, DMS, EDF}
- Architectural model **m** is an interpretation $⟦\,⟧_{\mathbf{m}}$ of $\mathcal{A}$, $\mathcal{S}$, and $\mathcal{T}$
  - E.g.: $⟦\mathit{Threads}⟧_{\mathbf{m}}$ = { SensorSample, $Ctrl_1$, $Ctrl_2$ }
    $⟦CPUBind⟧_{\mathbf{m}}$ **=** { ($Ctrl_1$, CPU_1), ($Ctrl_2$, CPU_2), … }
  - $⟦\,⟧_{\boldsymbol{\sigma}} \cup ⟦\,⟧_{\mathbf{m}}$ is a full interpretation

Contracts

Security Analysis

- $An_{sec}.C: I = \{T, ThSecCl\}, O = \{NotColoc\}, A = \emptyset, G = \{g\}$
  - $g: \forall\, t_1, t_2 \cdot ThSecCl(t_1) \neq ThSecCl(t_2) \Rightarrow t_1 \in NotColoc(t_2)$

Multiprocessor scheduling: (Binpacking + scheduling)

- $An_{sched}.C: I = \{T, C, NotColoc, Per, WCET, Dline\}, O = \{CPUBind\}, A = \emptyset, G = \{g\}$
  - $g: \forall\, t_1, t_2 \cdot t_1 \in NotColoc(t_2) \Rightarrow CPUBind(t_1) \neq CPUBind(t_2)$

Frequency Scaling

- $An_{freqsc}.C: I = \{T, C, CPUBind, Dline\}, O = \{CPUFreq\}, G = \emptyset, A = \{a\}$
  - $a: \forall t_1, t_2 \cdot CPUBind(t_1) = CPUBind(t_2): G(CanPrmpt(t_1, t_2) \Rightarrow Dline(t_1) < Dline(t_2)$

Model checking periodic program (REK):

- $An_{rek}.C: I = \{T, C, Per, Dline, WCET, CPUBind\}, O = \{ThSafe\}, G = \emptyset, A = \{a_1, a_2\}$
- $a_1: \forall t \cdot Per(t) = Dline(t),\ \ a_2: \forall t_1, t_2 \cdot G(Canprmpt(t_1, t_2) \Rightarrow G\ \neg CanPrmpt(t_2, t_1))$

Thermal runaway:

- $An_{therm}.C: I = \{B, BatRows, BatCols, Voltage\}, O = \{K\}, A = \emptyset, G = \emptyset$

Battery Scheduling

- $An_{bsched}.C: I = \{B, BatRows, BatCols\}, O = \{BatConnSchedPol, HasReqLifetime, SeriqlReq, ParalRea\}, A = \emptyset, G = \{g\}$
- $g: G(K(0) \times TN(0) + K(1) \times TN(1) + K(2) \times TN(2) + K(3) \times TN(3) \geq 0)$