Multi-core Interference-sensitive WCET Analysis Leveraging Runtime Resource Capacity Enforcement

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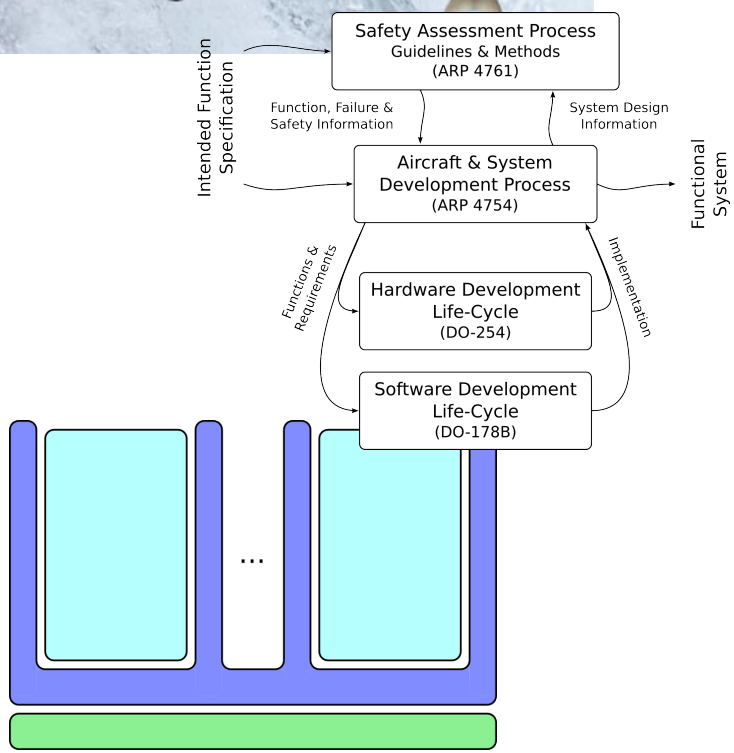
Background

Problem Areas

Multi-core Processors in ...

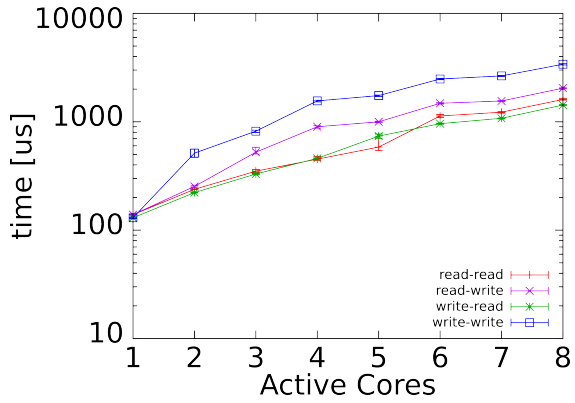
1. Real-time systems
   - → Temporal correctness
   - → Execution time guarantees
2. Safety-critical systems
   - → Certification requirements
   - → Documentation and traceability
3. Avionic systems
   - → Partitioning
   - → Incremental development
   - → Mixed-critical systems
   - → Commercial Off-The-Shelf (COTS) components



Problem Definition

Challenges

- Mutual interferences between processor cores due to the use of shared resources
  - → Timing analysis?
  - → Execution time guarantees?
- COTS components
  - → No hardware modifications possible

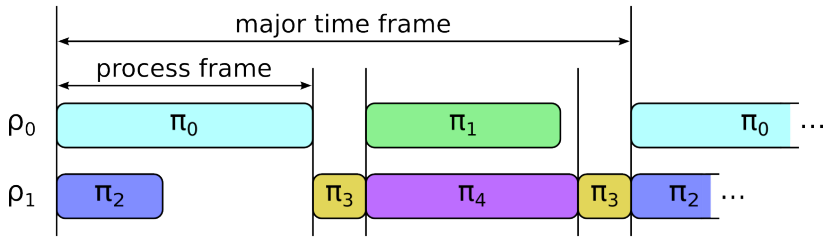


Contributions

1. Resource capacity enforcement approach
2. interference-sensitive Worst-Case Execution Time (isWCET) analysis, supporting

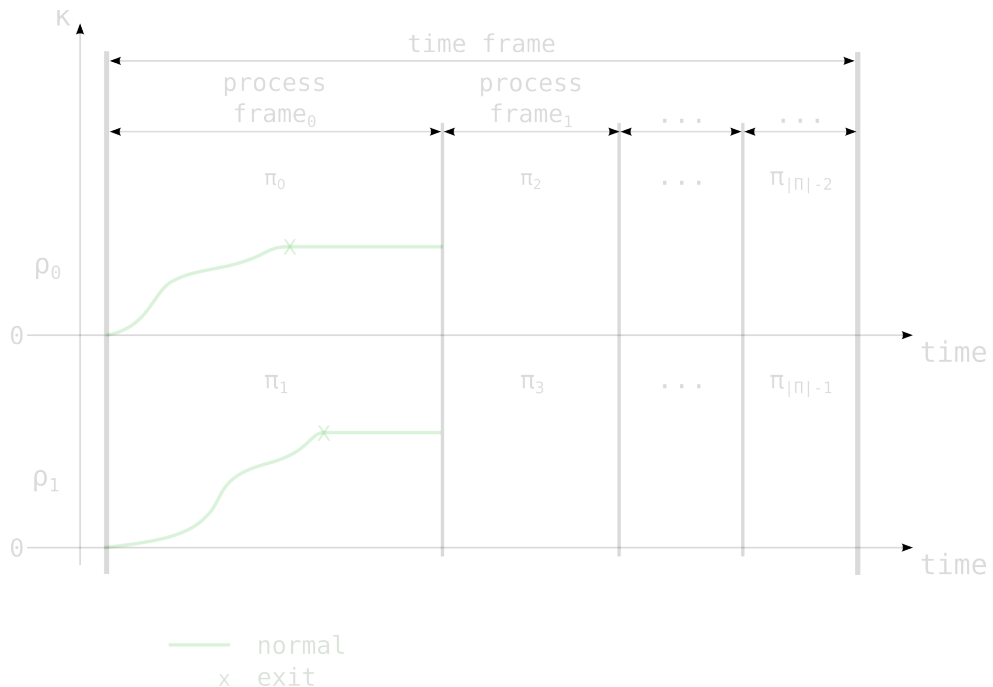
Resource Capacity Enforcement

Processor Time

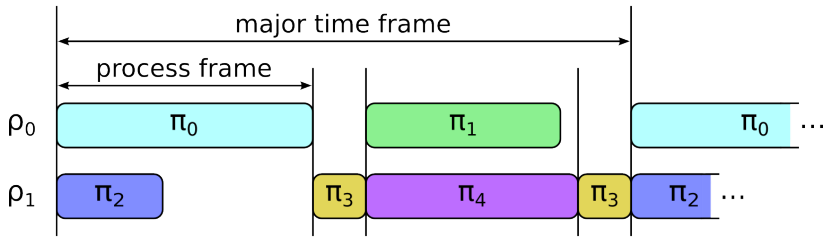


ρ_i... Processing Element
π_i... Process/Partition

Resource Usage



Processor Time



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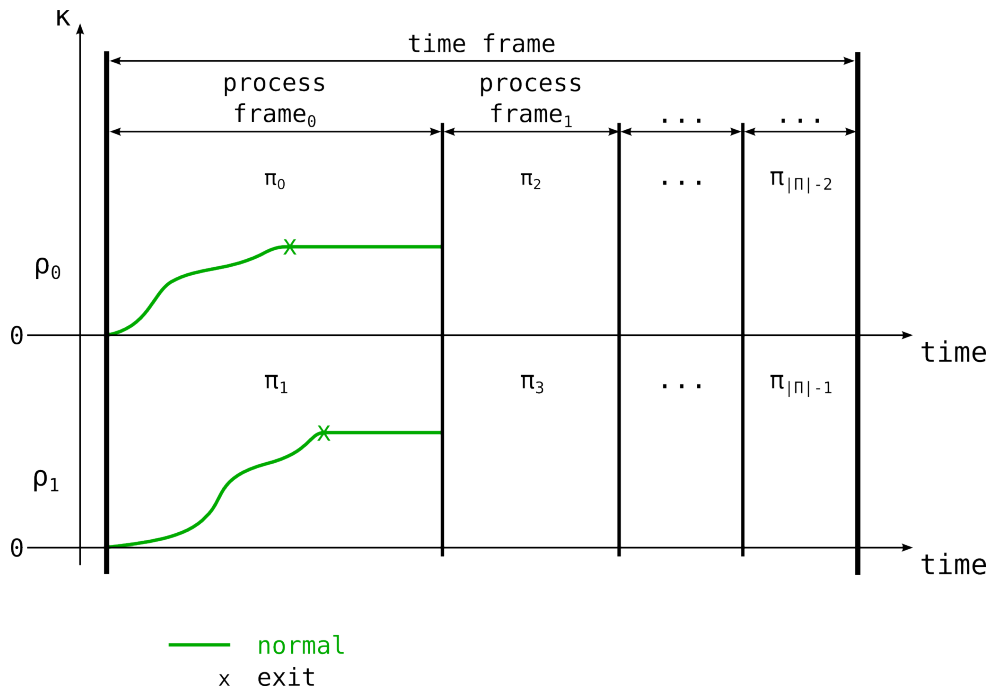
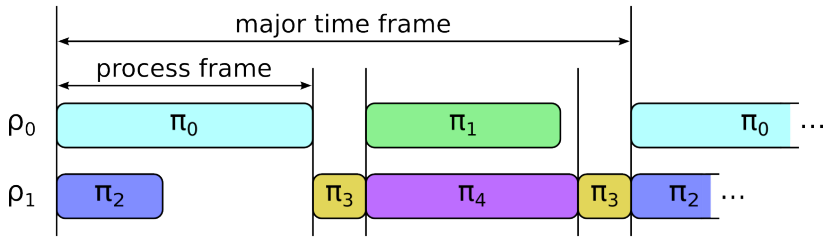


Processor Time



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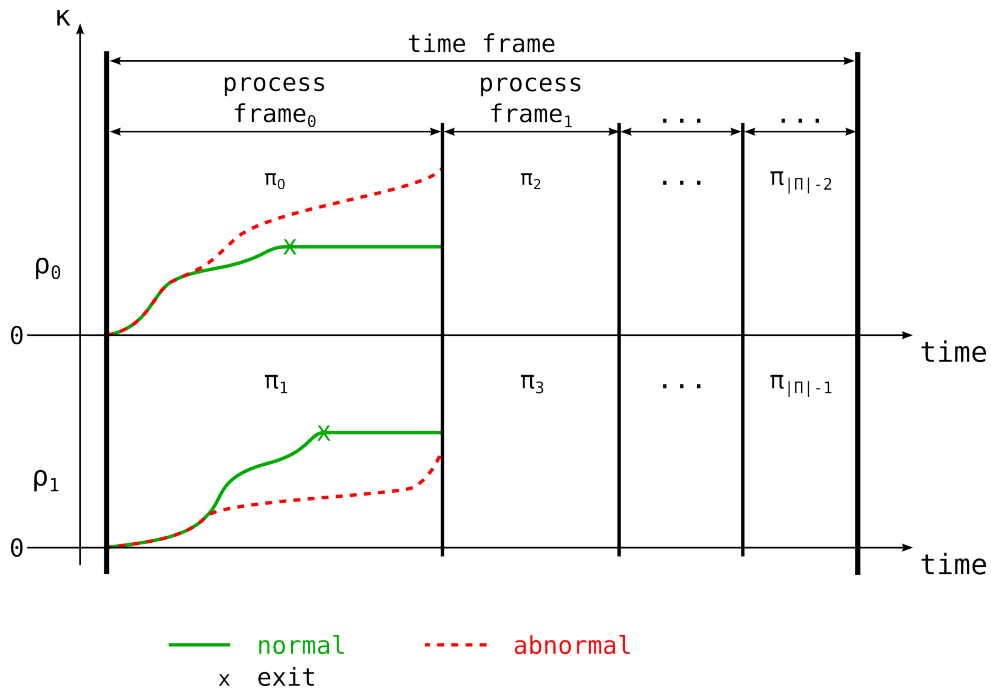
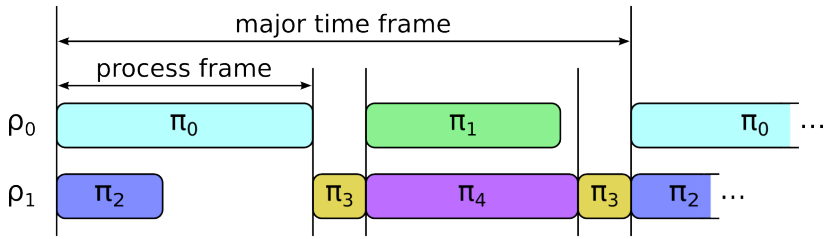


Processor Time



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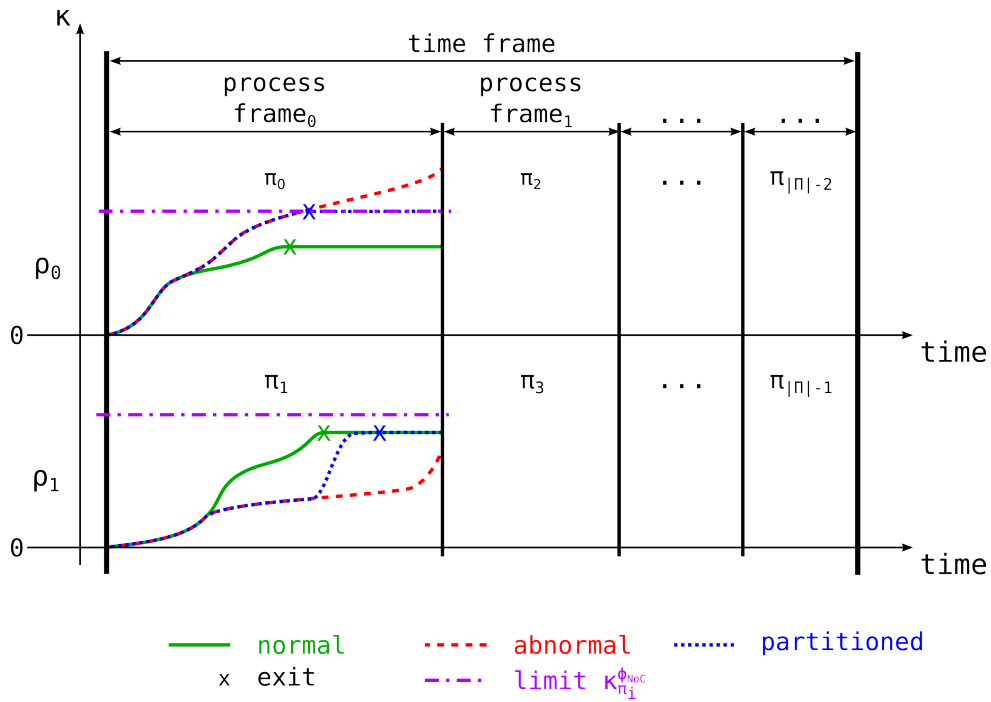
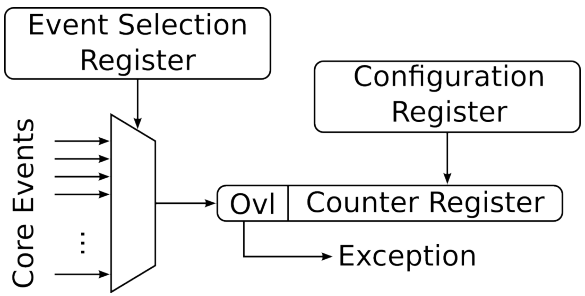
Resource Usage



Runtime Monitoring

- Goal: quantify resource usage
- Resource representation: bus interface request
- Monitoring: processor Performance Monitor Counter (PMC)



- Limit: PMC overflow exception

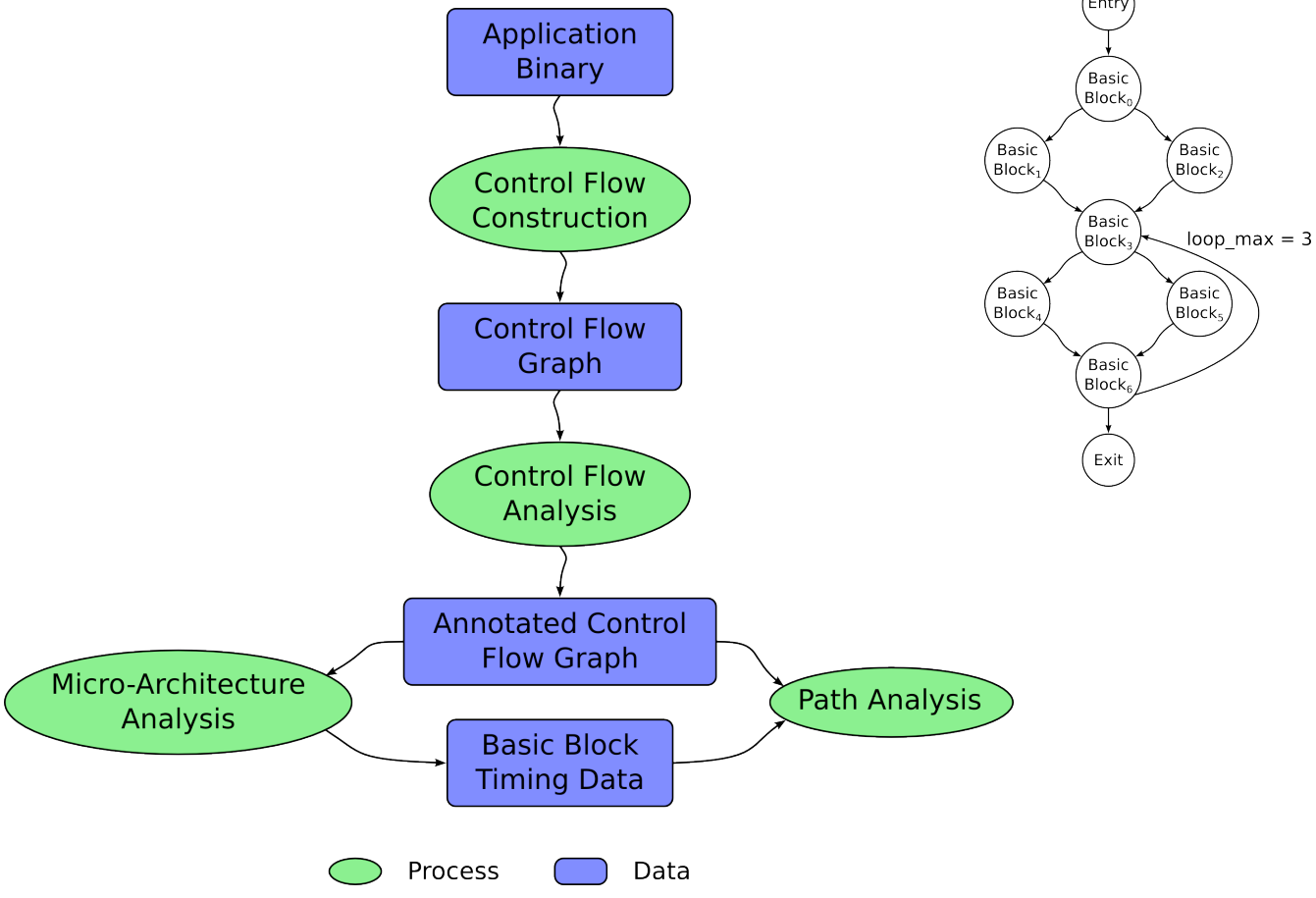
Suspension

- Goal: prevent further resource requests
- Implementation
  - Operating system callback for PMC overflow
  - Suspension of processor execution

WCET Analysis

State of the Art (Single-core)

Architecture



Methods

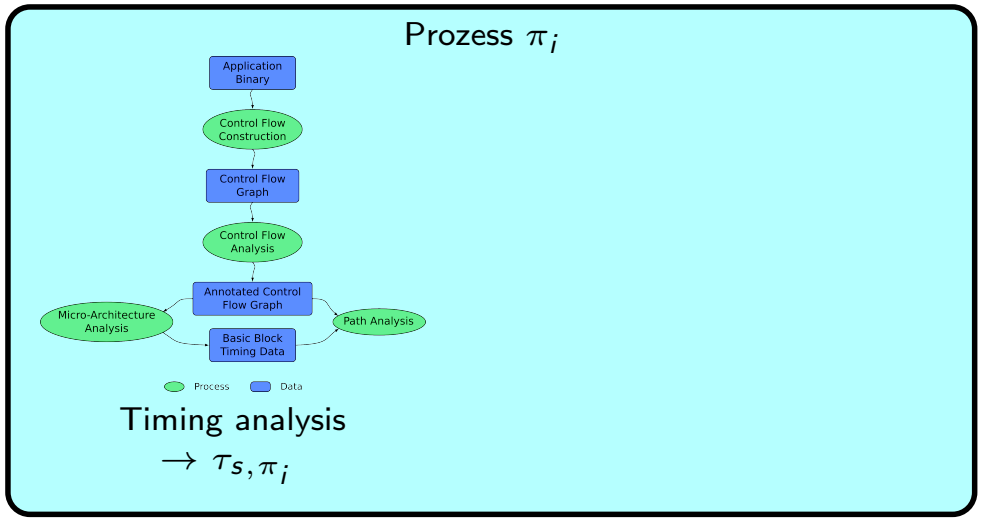
- Static, measurement-based, hybrid

Multi-core - isWCET

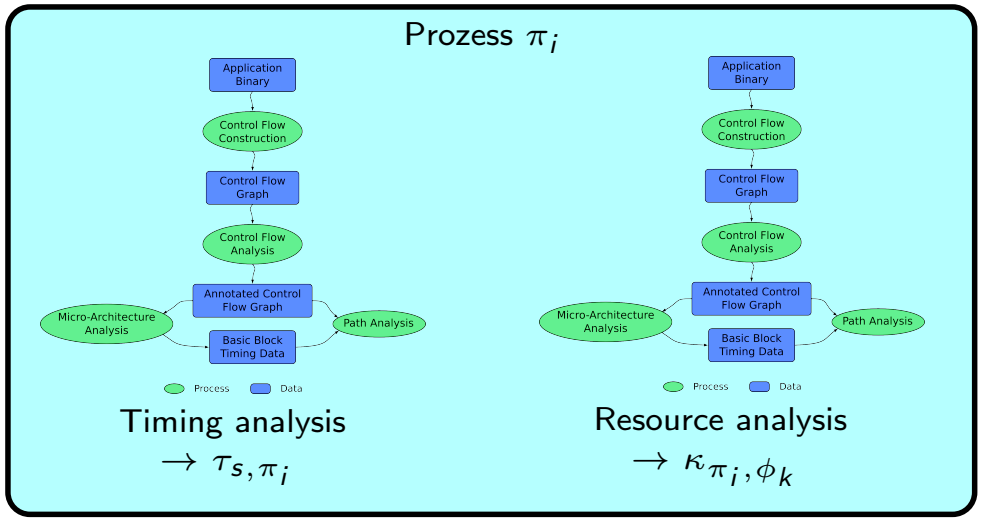
Idea

- Separate core-local and interference analyses
- Separation of timing and resource analyses

Core-local Analysis

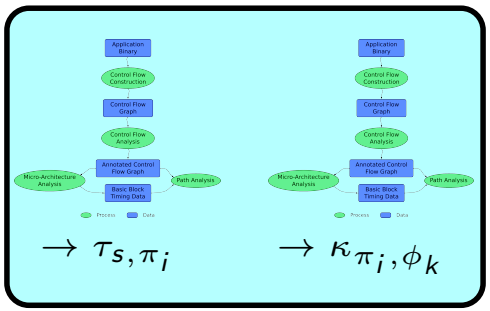


Core-local Analysis



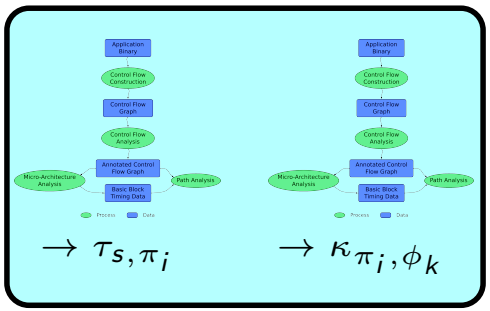
Multi-core - isWCET

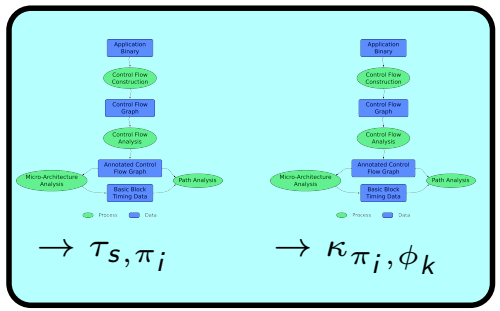
Core-local Analysis



Multi-core - isWCET

Core-local Analysis





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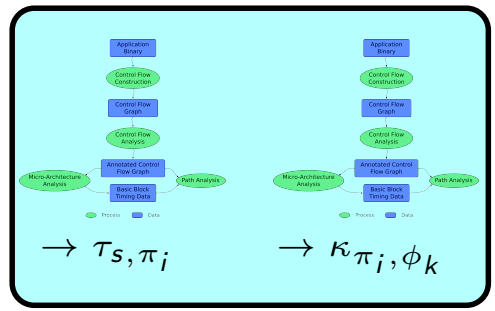

Multi-core - isWCET

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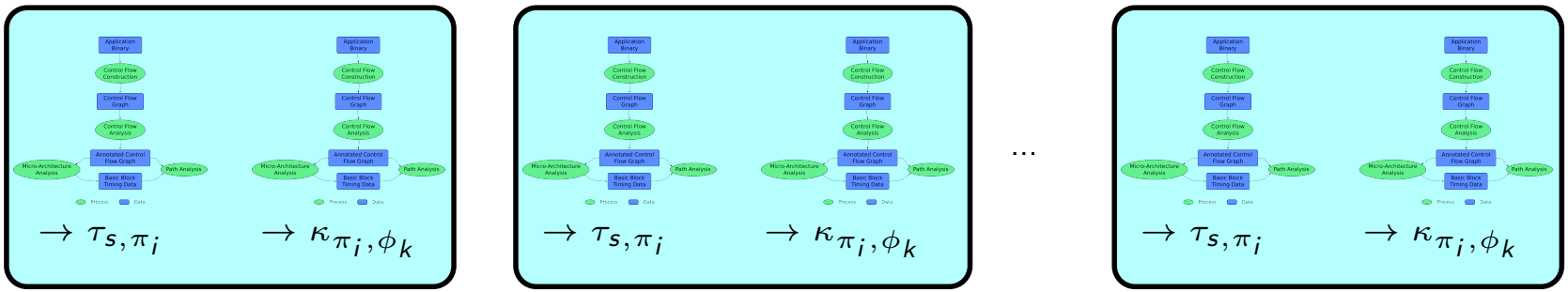
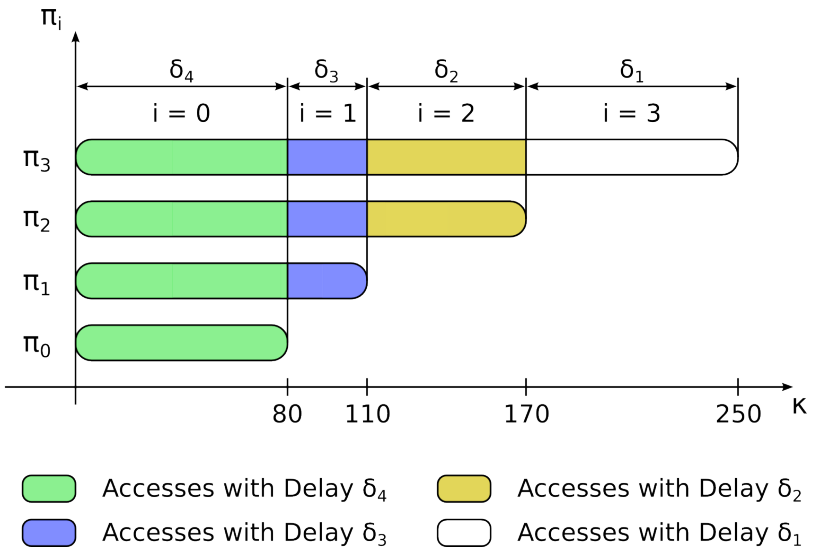
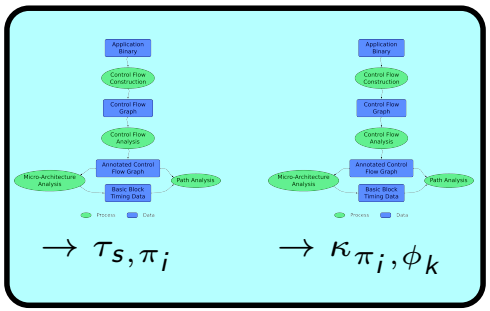


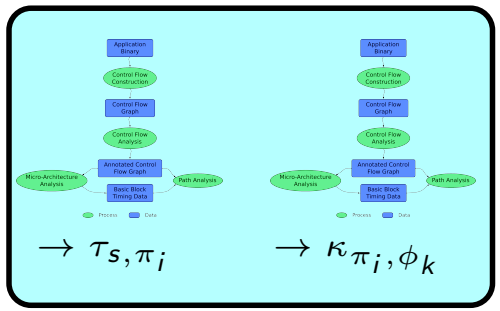
Interference Analysis



Multi-core - isWCET

Core-local Analysis





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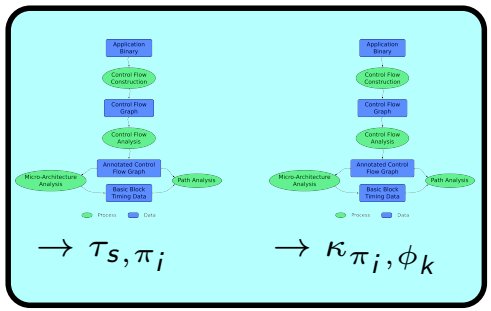

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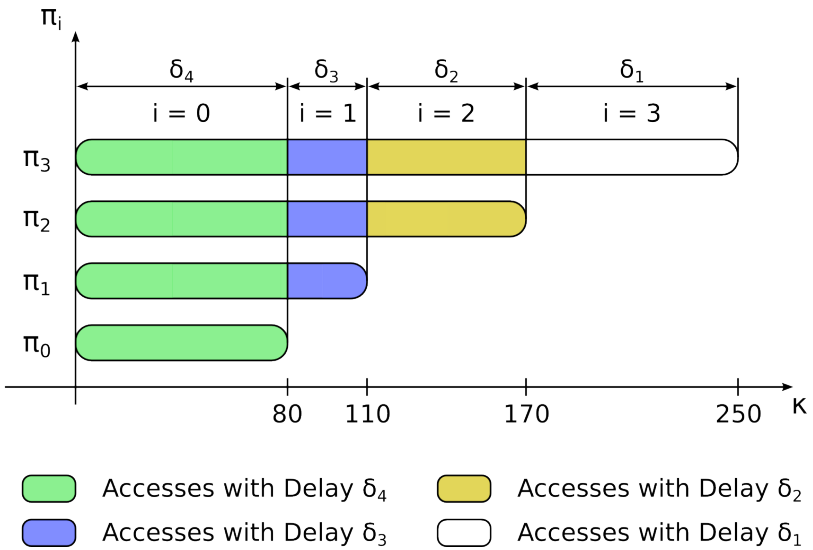


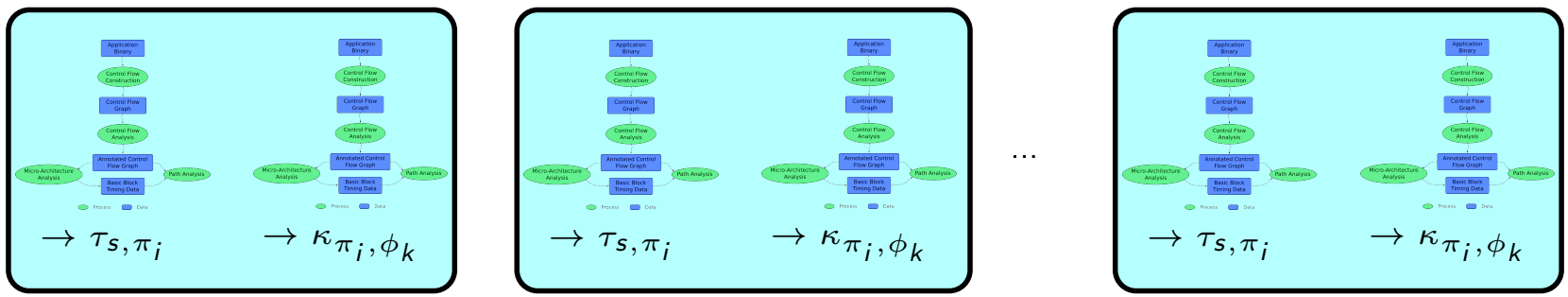
$$\begin{aligned}\tau_{int}(\pi_3, \phi_k) = \quad & \delta_4 \cdot 80 \\ & +\delta_3 \cdot 30 \\ & +\delta_2 \cdot 60 \\ & +\delta_1 \cdot 80\end{aligned}$$

Multi-core - isWCET

Idea

- Separate core-local and interference analyses
- Separation of timing and resource analyses

Core-local Analysis

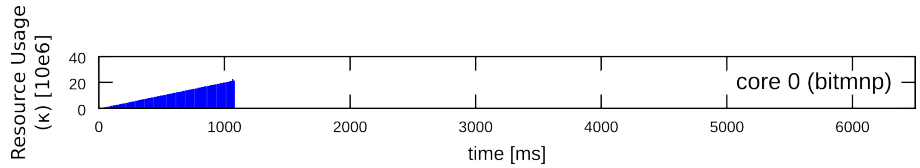


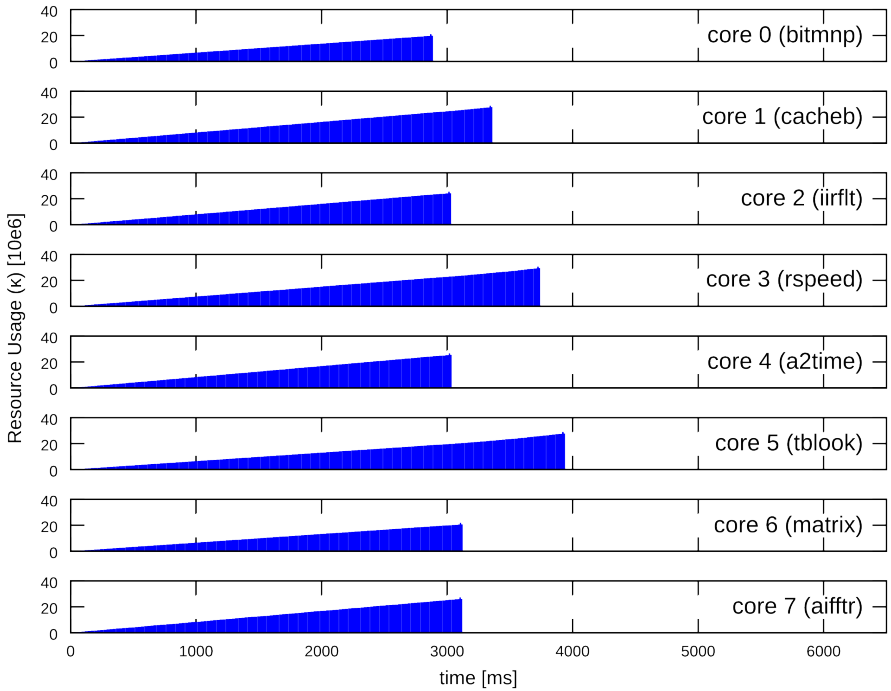
Interference Analysis

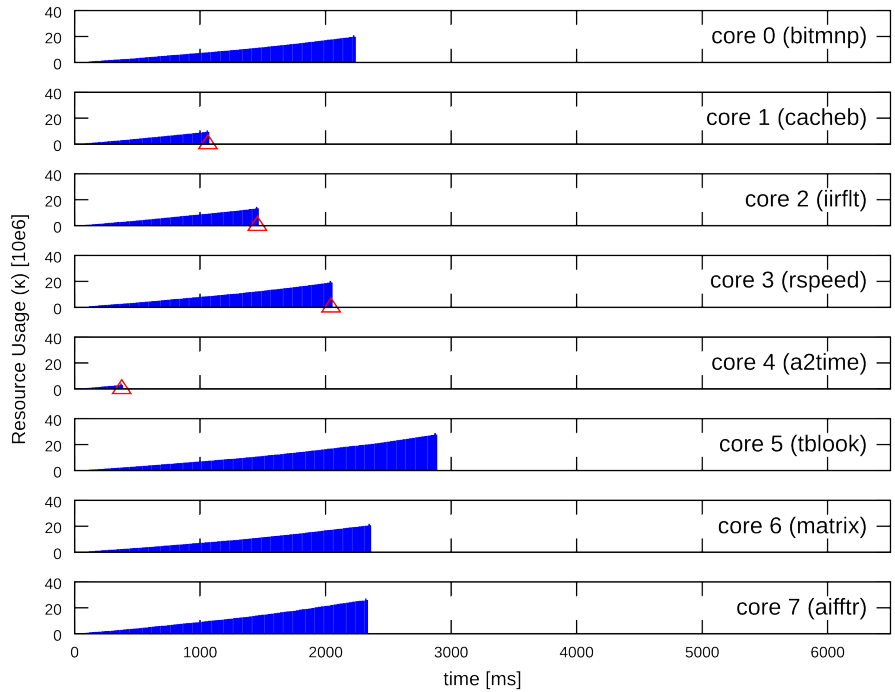
$$\tau_{is}\left(\pi_x\right) = \delta_{|\Pi_{||}|} \cdot \kappa_{\pi_0}^{\phi_k} + \sum_{i=1}^{x} \left(\delta_{|\Pi_{||}|-i} \cdot \left(\kappa_{\pi_i}^{\phi_k} - \kappa_{\pi_{i-1}}^{\phi_k} \right) \right) + \tau_s\left(\pi_x\right)$$

Evaluation

Functional Behaviour







Core-local Analyses

benchmark	analysed		observed		deviation	
	$\tau_s(\pi_x)$ [ms]	$\kappa_{\pi_i}^{\phi_k}$ [10^6]	ET [ms]	RA [10^6]	ET [%]	RA [%]
a2time	103	2.4	71	1.7	45.6	42.4
matrix	232	4.7	230	4.3	0.8	11.3
cacheb	391	9.5	371	8.3	5.5	13.9
iirflt	420	11.3	369	8.1	13.9	40.0
rspeed	600	15.4	445	9.3	34.7	65.6
aifftr	1304	31.3	87	2.2	1403.2	1344.6
tblook	1363	31.4	1131	23.1	20.5	35.7
bitmnp	1546	33.1	1106	21.8	39.7	51.8

Core-local Analyses

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isWCET

benchmark	τ_{max} [ms]	τ_{is} [ms]	reduction [%]
a2time	2109	2109	0.0
matrix	4212	3775	10.4
cacheb	8346	6843	18.0
iirflt	9883	7647	22.6
rspeed	13513	9413	30.3
aifftr	27528	13355	51.5
tblook	27700	13433	51.5
bitmnp	29291	13673	53.3

Core-local Analyses

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Summary

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Problems

- Multi-core shared resource interference
- Timing analysis
- COTS components

Contributions

- Temporal partitioning
  - Transparent application isolation
  - Platform and operating system independent
- isWCET analysis
  - Improvements in multi-core WCET bounds over "standard" maximum contention approach (53.3%)
  - Avoiding resource privatisation
  - Enabling incremental analysis
  - Adaptable to established timing analysis methods

Questions