Symbiotic Job Scheduling on the IBM POWER8

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[2] *This work was done while Stijn Eyerman was at Ghent University*

Outline

Introduction

- Scheduling is important for manycore / manythread systems
  - Combinatorial amount of ways to schedule applications with different performance
- Scheduling for CMPs of SMT cores is challenging
  - Different levels of resource sharing
  - SMT performance very sensitive to co-runners
- Selecting the optimal schedule is an NP-hard problem
- Predicting the performance of a schedule is not trivial because of the high amount of resource sharing in SMTs

Introduction

Previous work on symbiotic scheduling

- Uses sampling to explore the space of possible schedules *(Snavely et al., ASPLOS'00)*
- Relies on novel hardware *(Eyerman et al, ASPLOS'10)*
- Performs an offline analysis with μ*benchmarks* to predict the interference between applications *(Zhang et al., MICRO'14)*

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Our symbiotic job scheduler

- Online model-based scheduling
- Without sampling schedules
- On a recent commercial processor

Introduction
Main contributions

- **Interference model**
  - Predicts the interference among threads on a SMT core
  - Based on CPI stacks
  - Considers contention in all the shared resources

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  - Considers contention in all the shared resources
- **Online scheduler**
  - Quickly explore the schedule space to select the optimal one
  - Quickly adapt to phase behavior
- **Implemented and evaluated on the IBM POWER8**
  - Average system throughput increase by 10.3% over a random scheduler and 4.7% over Linux

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Predicting Job Symbiosis

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  - Predicts the slowdown of the application on a schedule
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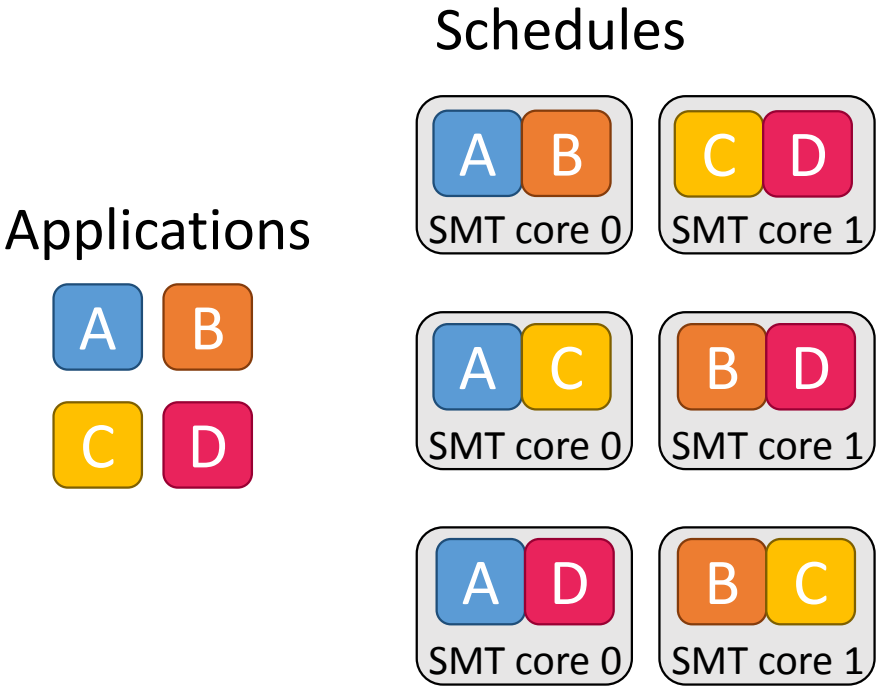

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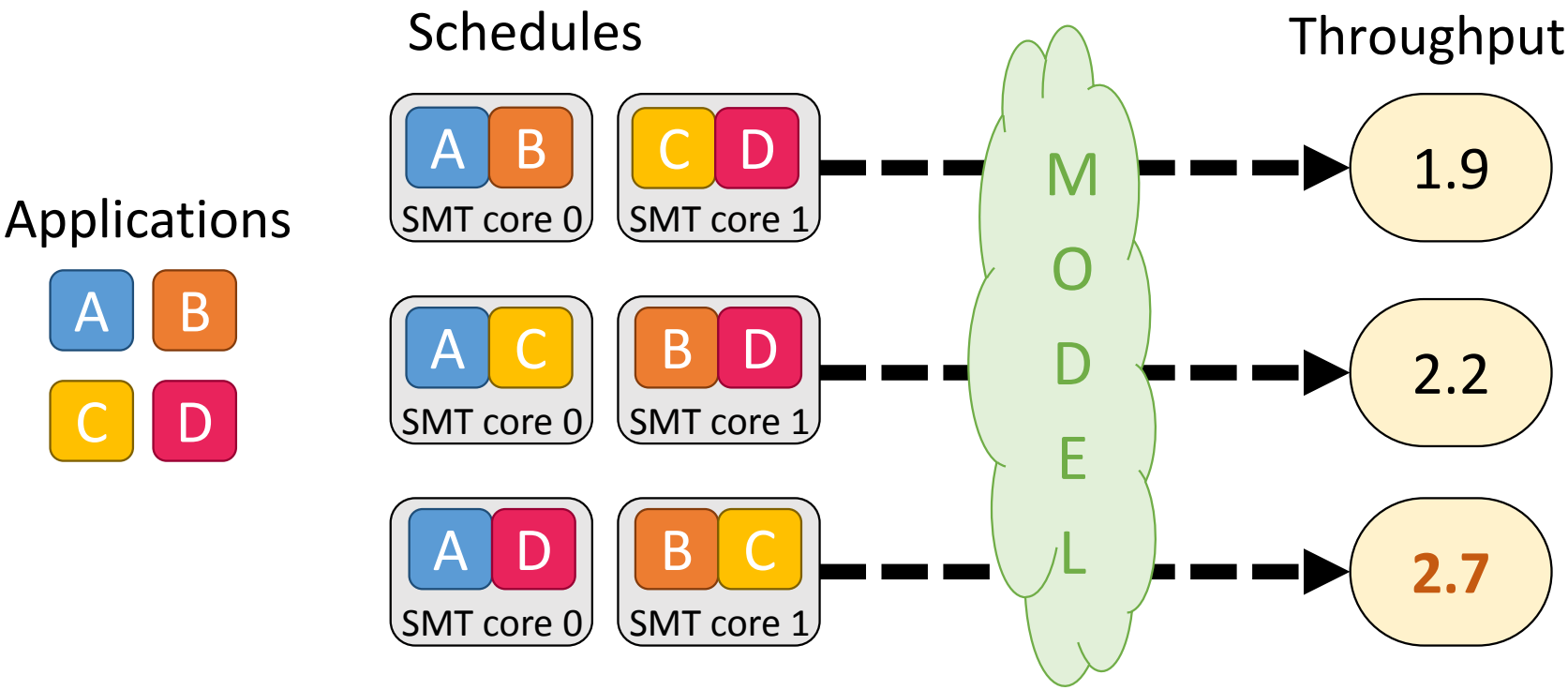
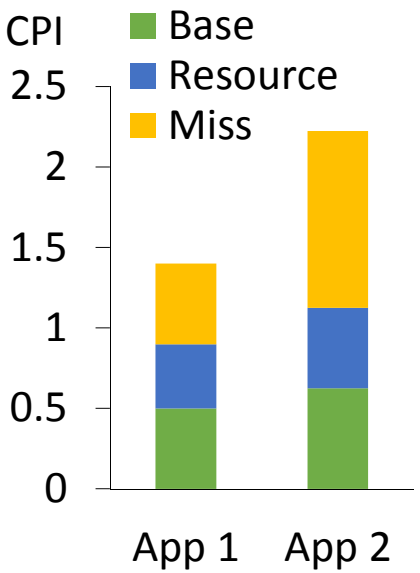


Interference model

- The proposed model leverages CPI stacks to predict job symbiosis



Measured single-threaded CPI stacks

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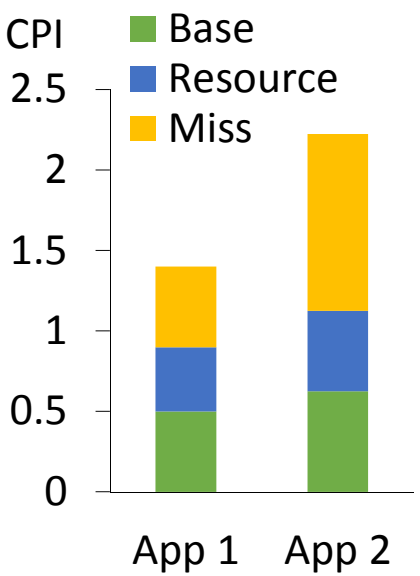

Measured single-threaded CPI stacks

CPI Stacks

Divide the execution cycles into various components:

- Base: cycles where instructions are completed
- Resource: no instruction completed due to resource stall
- Miss: no instruction completed due to miss event

Interference model

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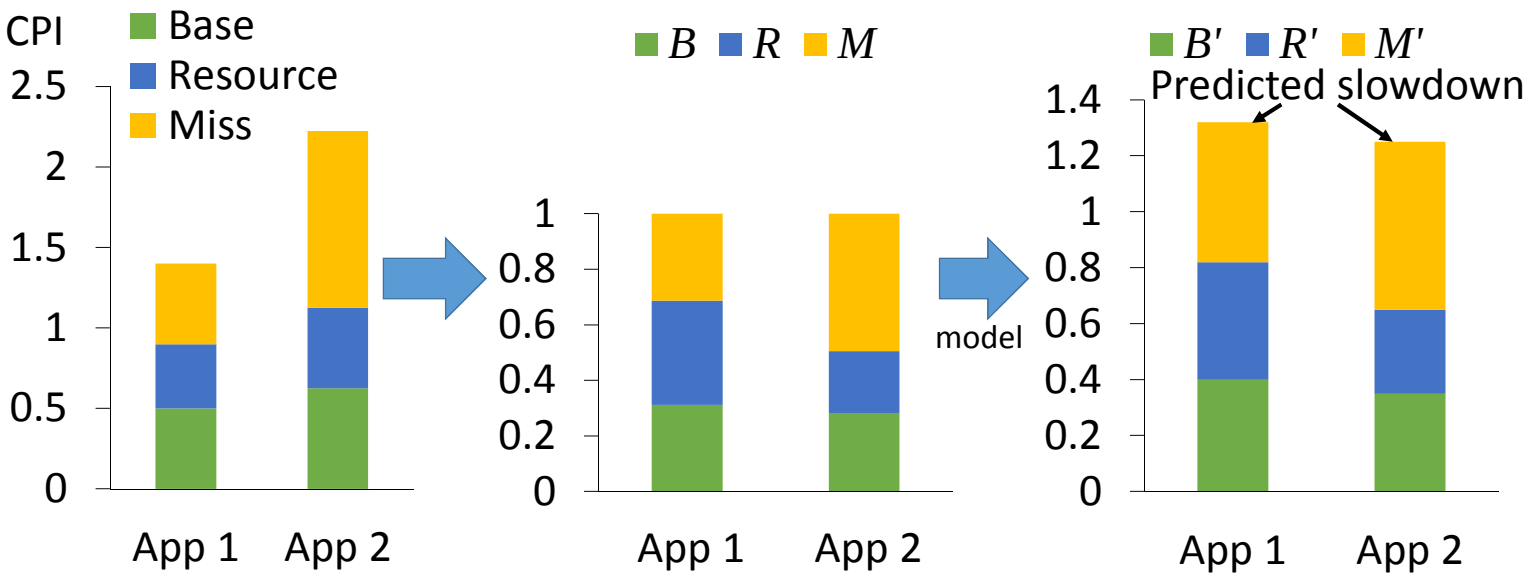
- Model: estimates the slowdown
  - Interprets the normalized CPI components as probabilities
  - Calculates the probability of interference



Model equation

Each component is modeled with the equation:

$$C'_j = \alpha_C + \beta_C C_j + \gamma_C \sum_{k \neq j} C_k + \delta_C C_j \sum_{k \neq j} C_k \quad (1)$$

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- C_j' identifies the SMT component of thread j

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- The meaningful parameters are determined using regression

Model construction and slowdown estimation

- Model parameters determined by linear regression
  - One-time offline training
    - Based on experimental data
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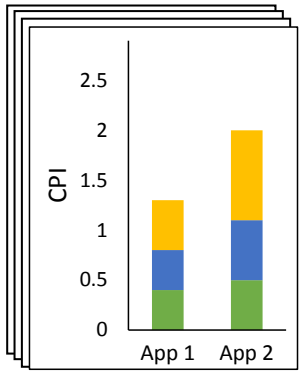

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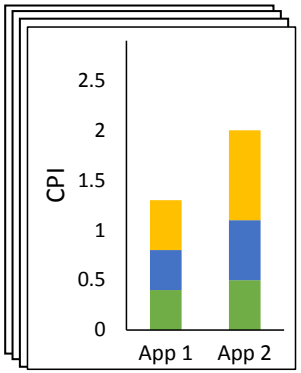

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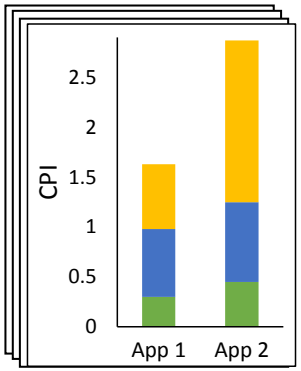

Measured SMT CPI stacks (Together)

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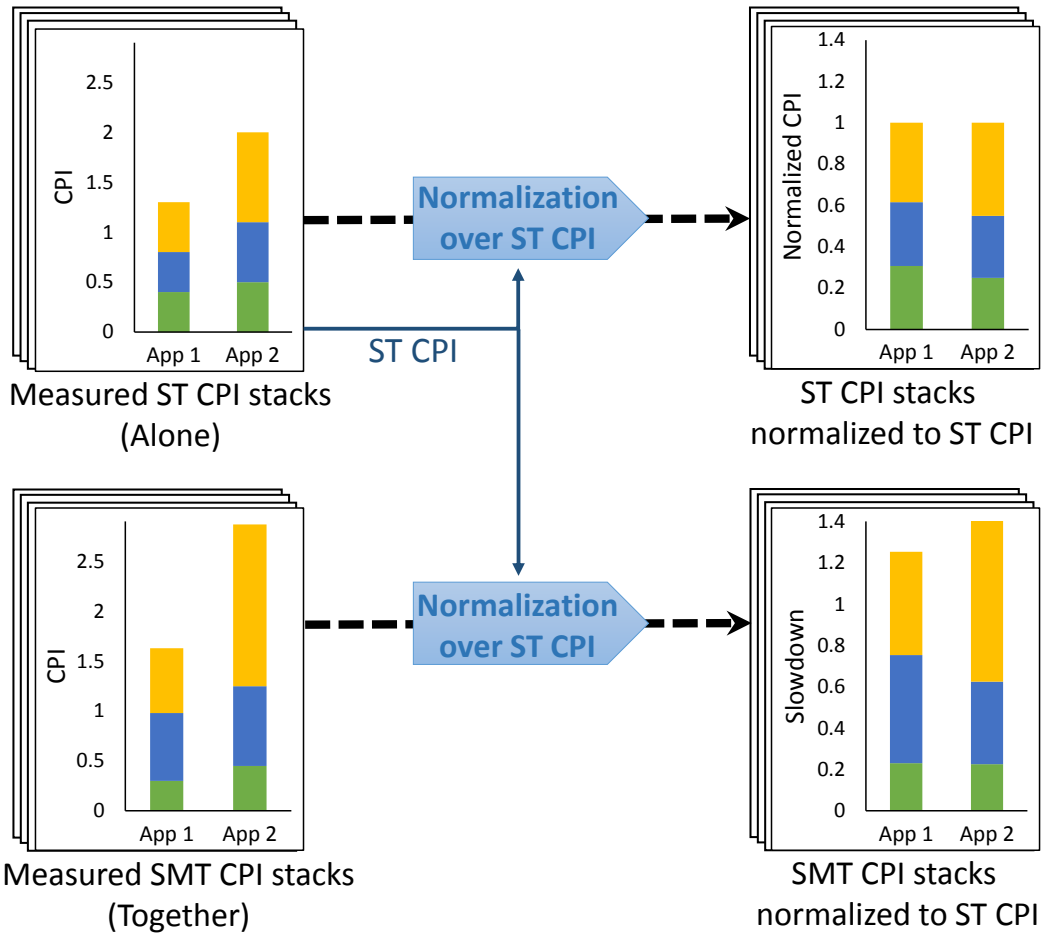

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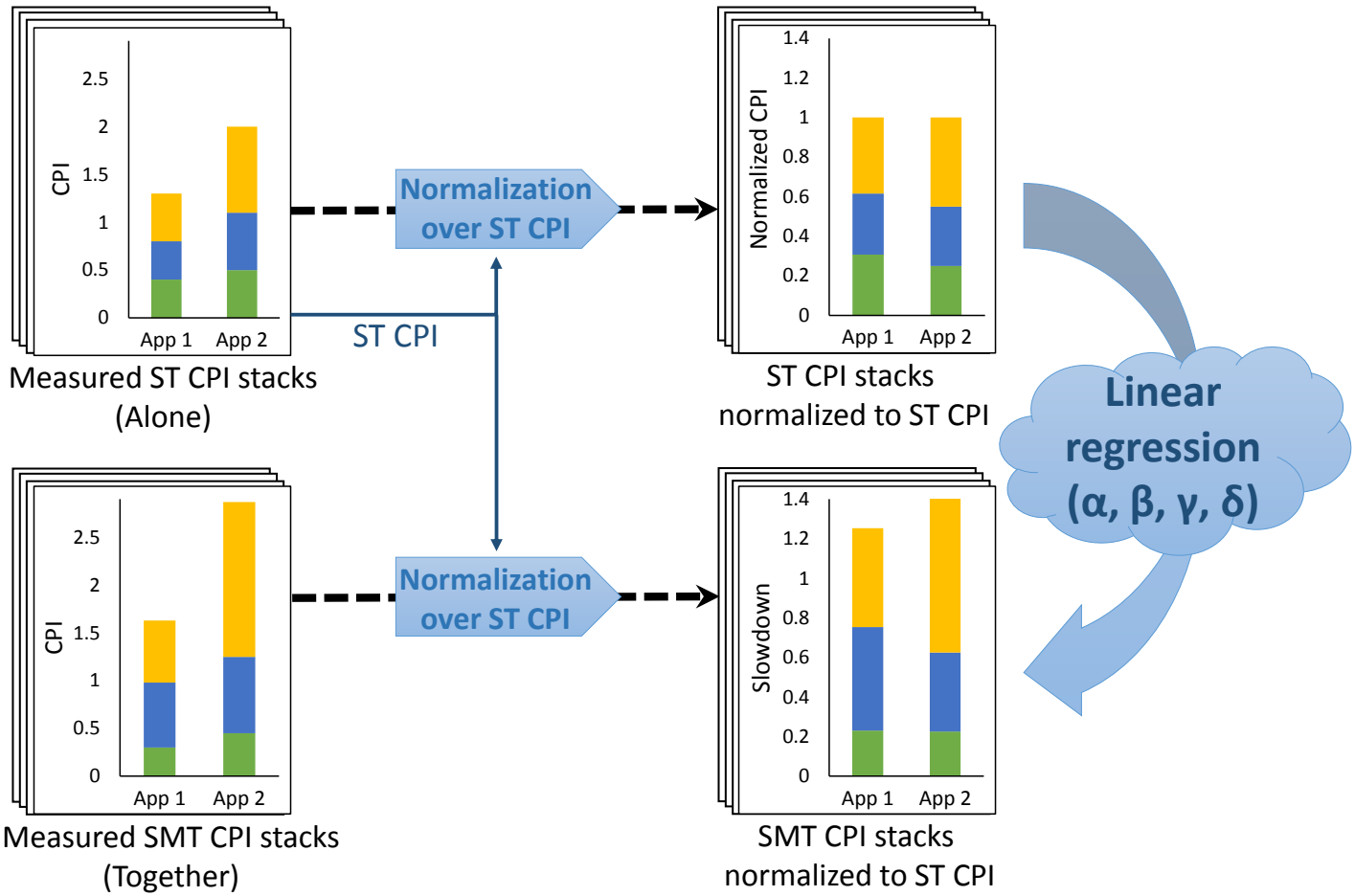
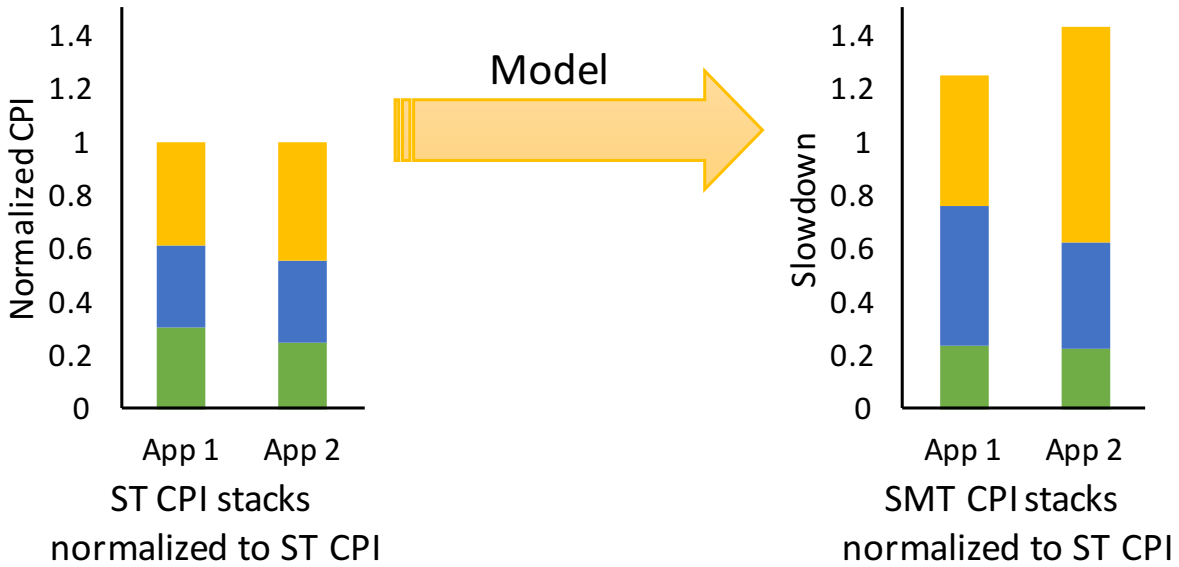


Obtaining ST CPI stacks in SMT mode



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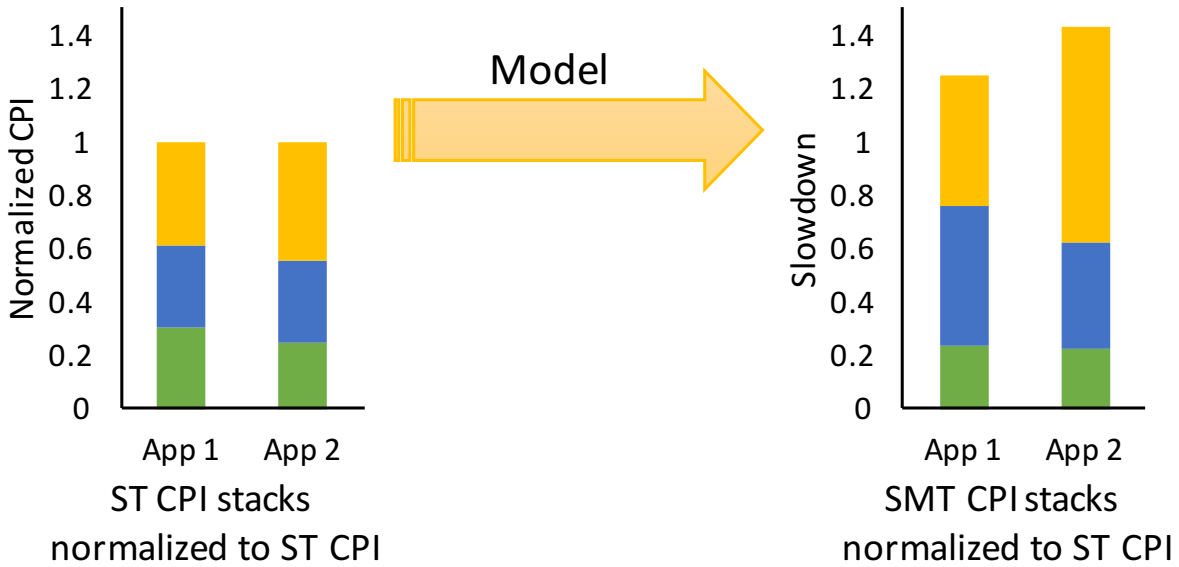

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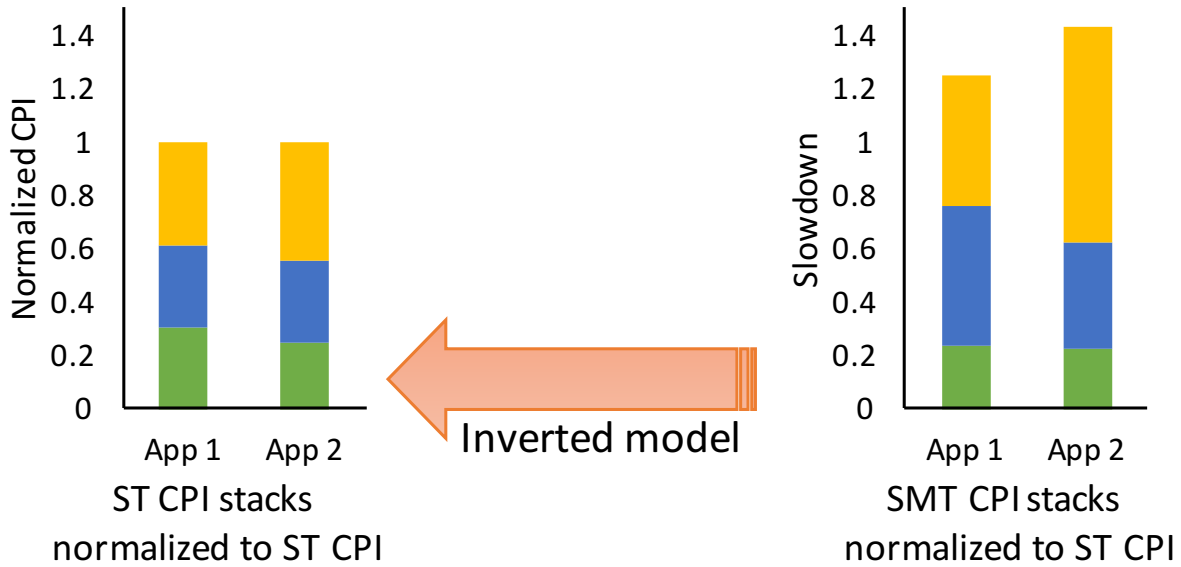

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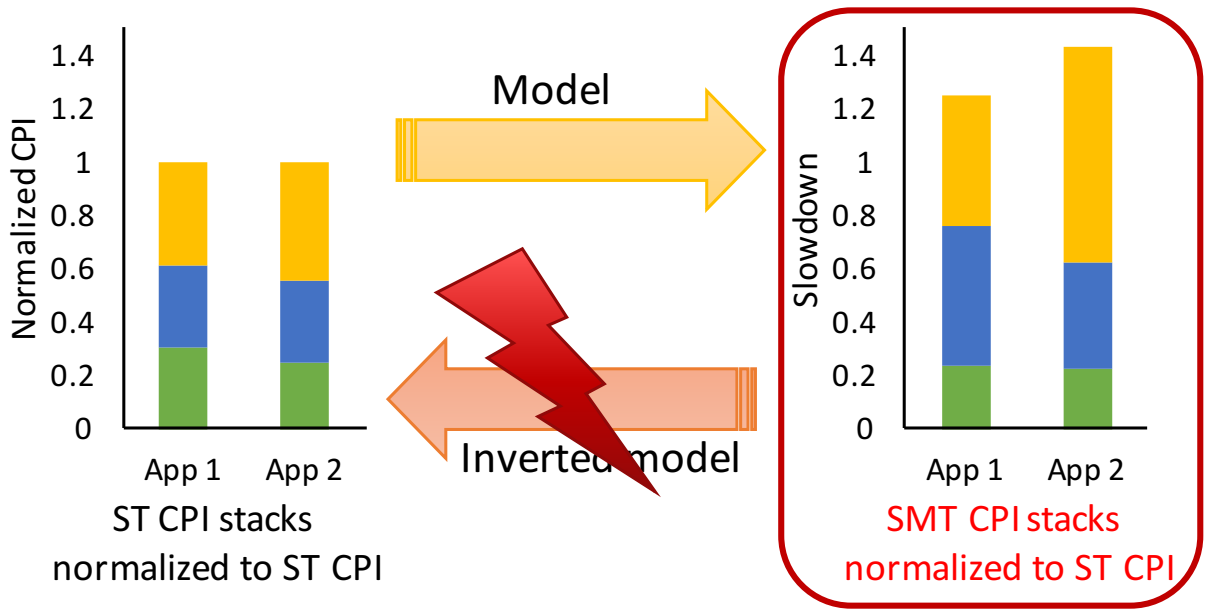
  - Specific hardware to collect ST CPI stacks online (Unavailable) ✗
- Measure the SMT CPI stacks and **invert the model** to obtain ST CPI stacks
  - Not trivial: ST CPI not available in SMT execution
  - Solved with an approximate approach



Outline

Reduction of the cycle stack components

- 45 events form the full CPI stack of the the IBM POWER8
- 6 thread-level counters are implemented (4 programmable)
  - Structural conflicts on some events that cannot be measured together
  - 19 time slices required to build the full CPI stack
- **Unacceptable for scheduling**
  - Obtaining an updated CPI stack is not possible
- Fortunately, the CPI stack model is build hierarchically
  - Top level with 5 components
  - The model accuracy is reduced, but it has lower complexity and use updated CPI stacks

Correction factor

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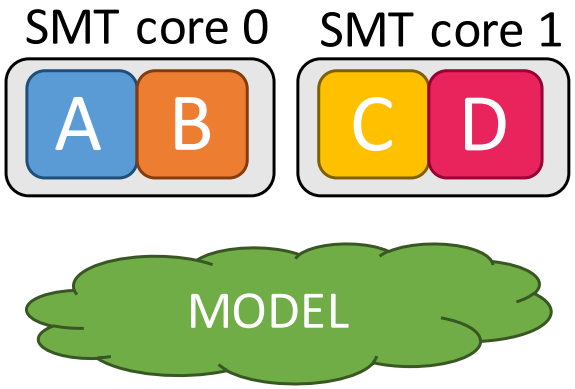
Schedule



Application \ Co-runner	A	B	C	D
A	-	1.0	1.0	1.0
B	1.0	-	1.0	1.0
C	1.0	1.0	-	1.0
D	1.0	1.0	1.0	-

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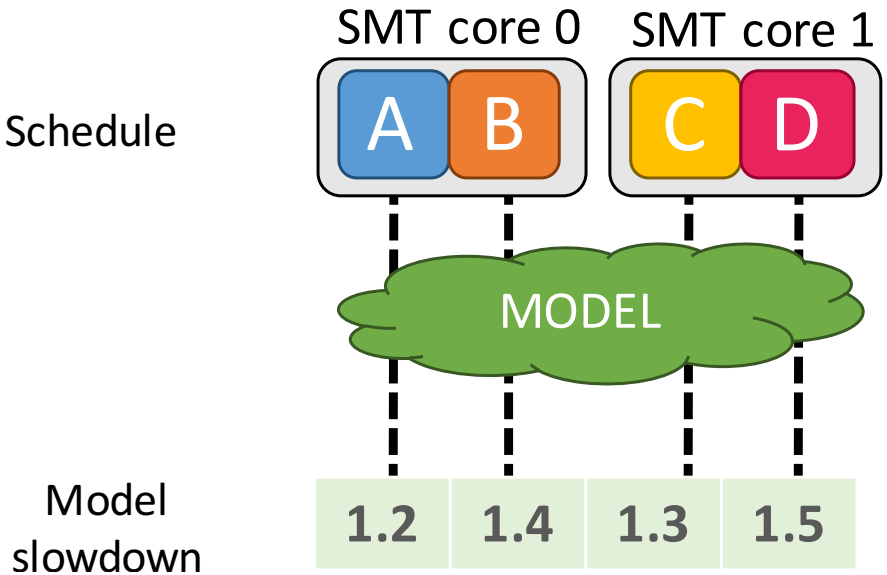

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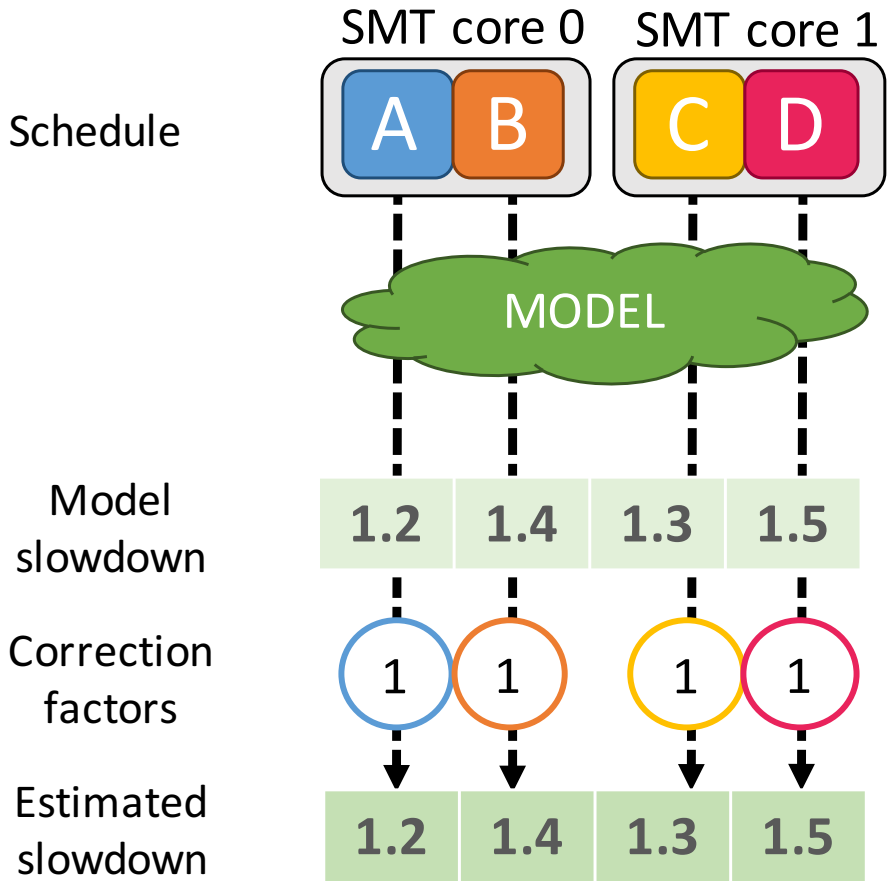

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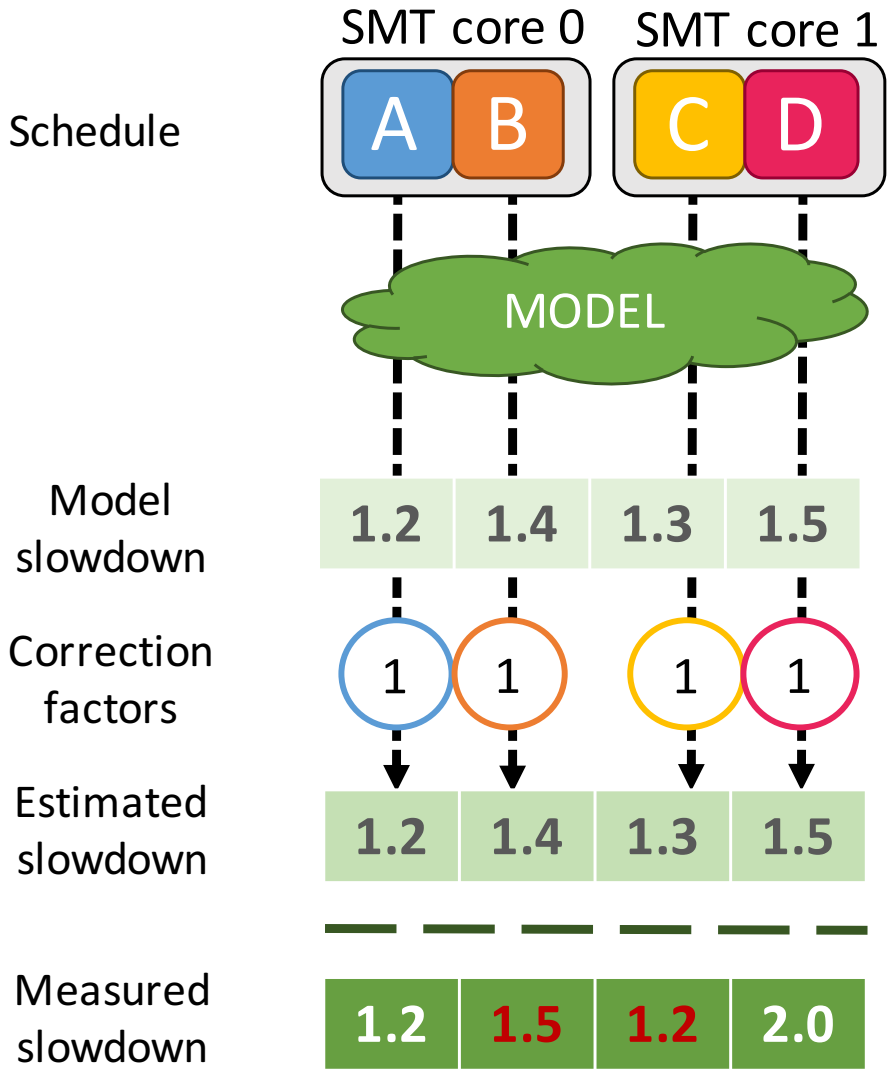

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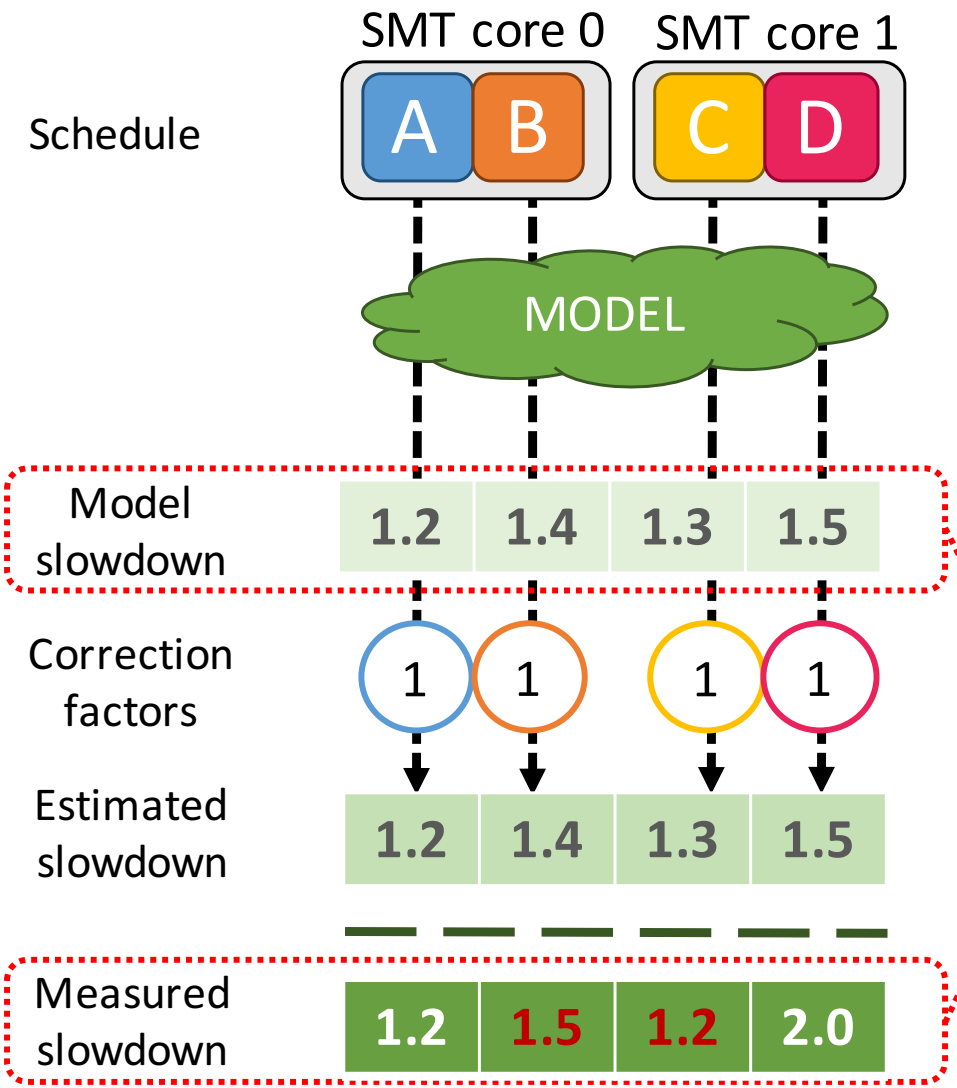

Co-runner

Application	A	B	C	D
A	-	1.0	1.0	1.0
B	1.1	-	1.0	1.0
C	1.0	1.0	-	0.9
D	1.0	1.0	1.0	-

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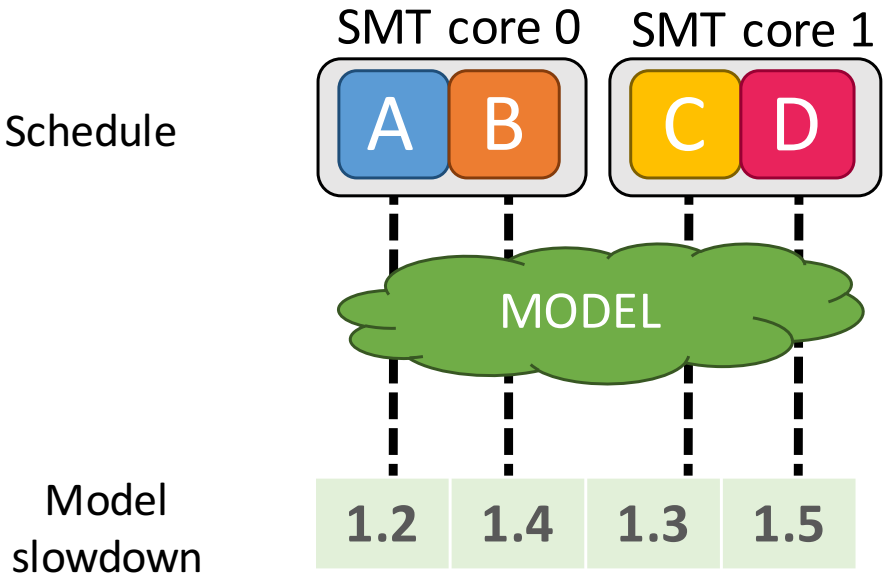

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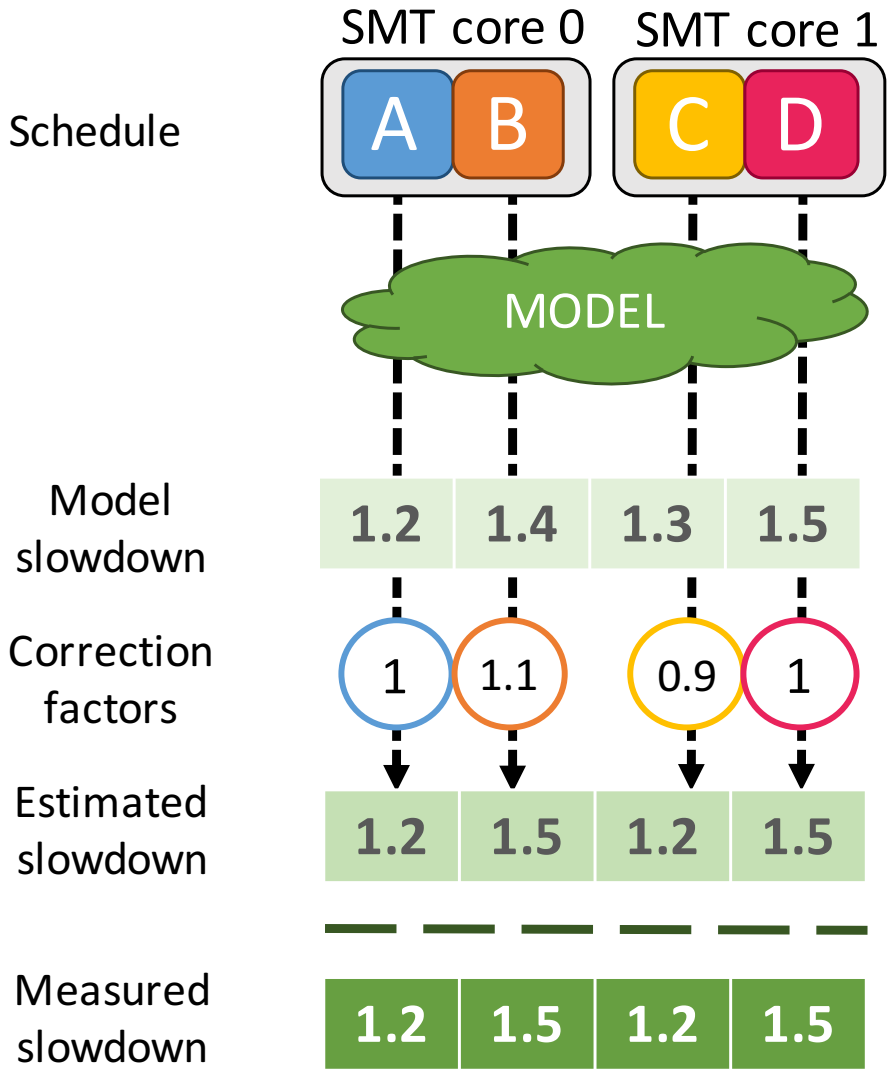

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  - Updated using an exponential moving average, to smooth out sudden changes
- Requires knowledge of the isolated performance
  - Very sparsely run the applications in ST mode, incurring 0.2% overhead

Selection of the optimal schedule

- Too large number of different schedules
  - $\frac{n!}{c!\left(\frac{n}{c}!\right)^c}$ n applications onto c cores
  - More than 2M schedules for 16 applications in 8 cores!

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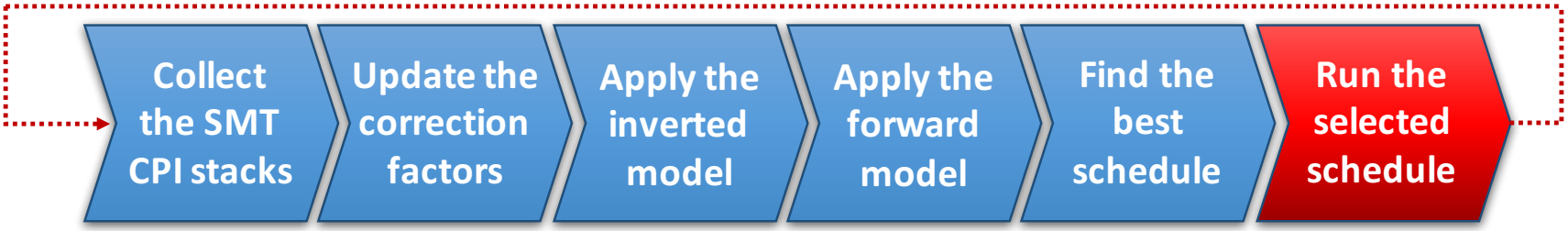
  - $\frac{n!}{c!\left(\frac{n}{c}!\right)^c}$ n applications onto c cores
    - More than 2M schedules for 16 applications in 8 cores!
- **Modeled as a minimum-weight perfect matching problem**, that can be solved in polynomial time using the blossom algorithm

Scheduling steps



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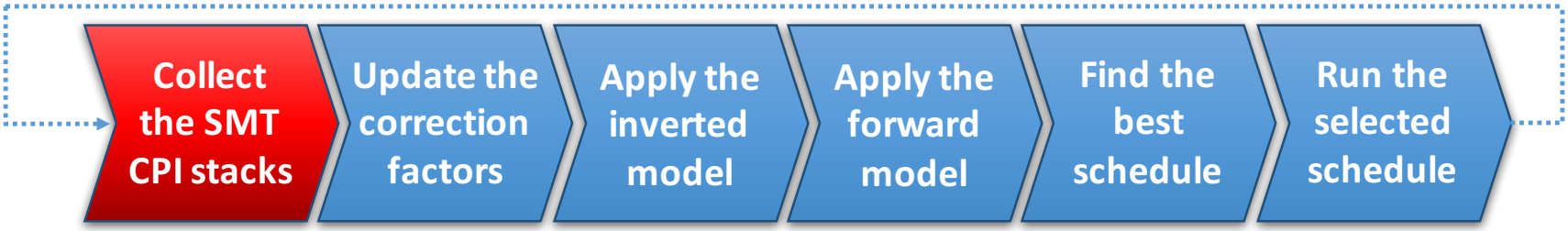
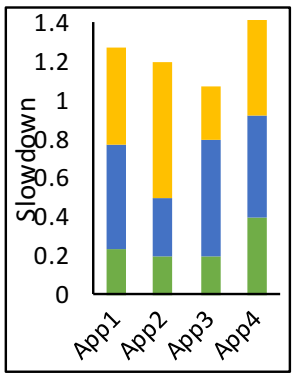


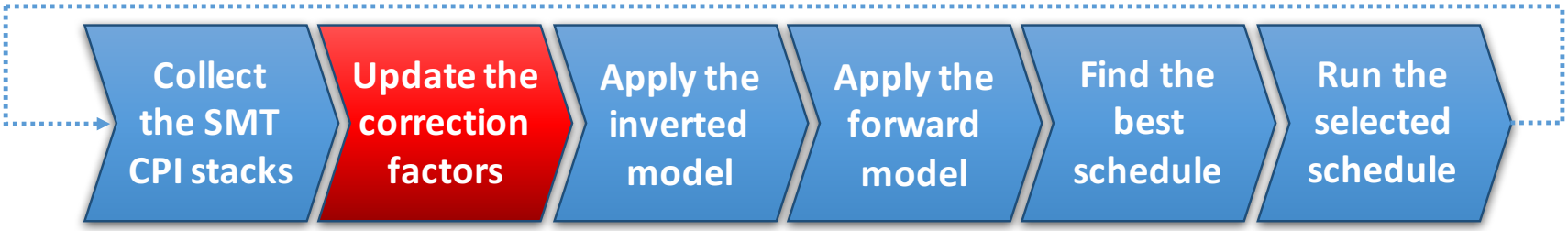
Measured SMT CPI stacks



Normalized SMT CPI

1.3 1.2 1.1 1.4

Scheduling steps



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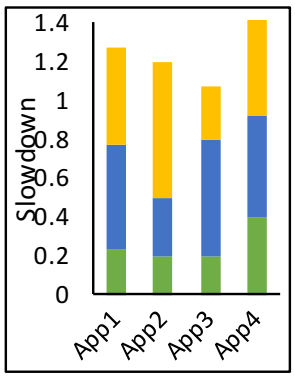
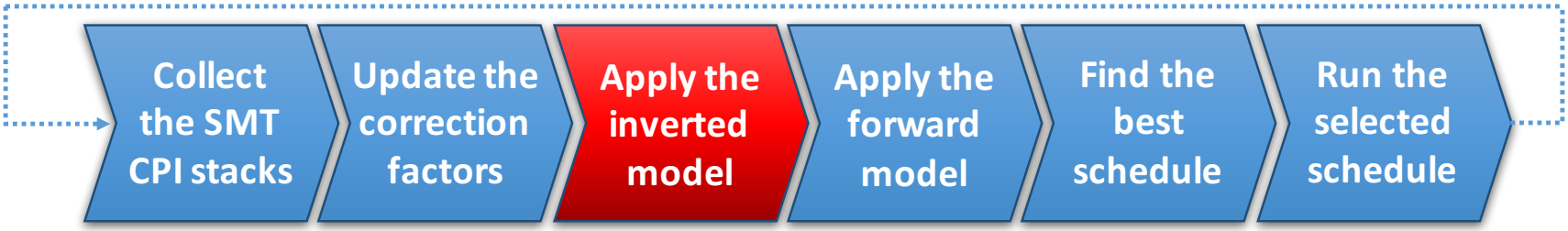


Update correction factors

Normalized SMT CPI

	A	B	C	D
A	-	1.0	1.0	1.0
B	0.9	-	1.0	1.0
C	1.0	1.0	-	0.8
D	1.0	1.0	1.0	-

Scheduling steps



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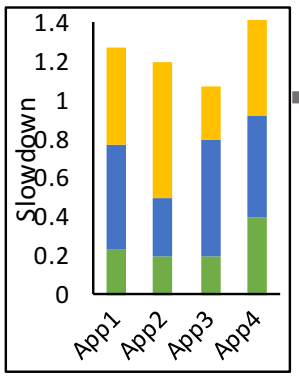
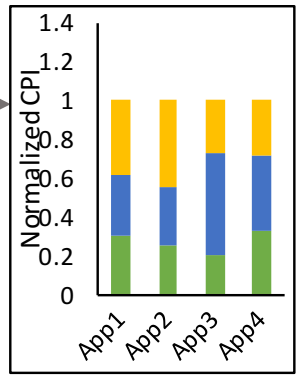


Inverted model

Estimated ST CPI stacks



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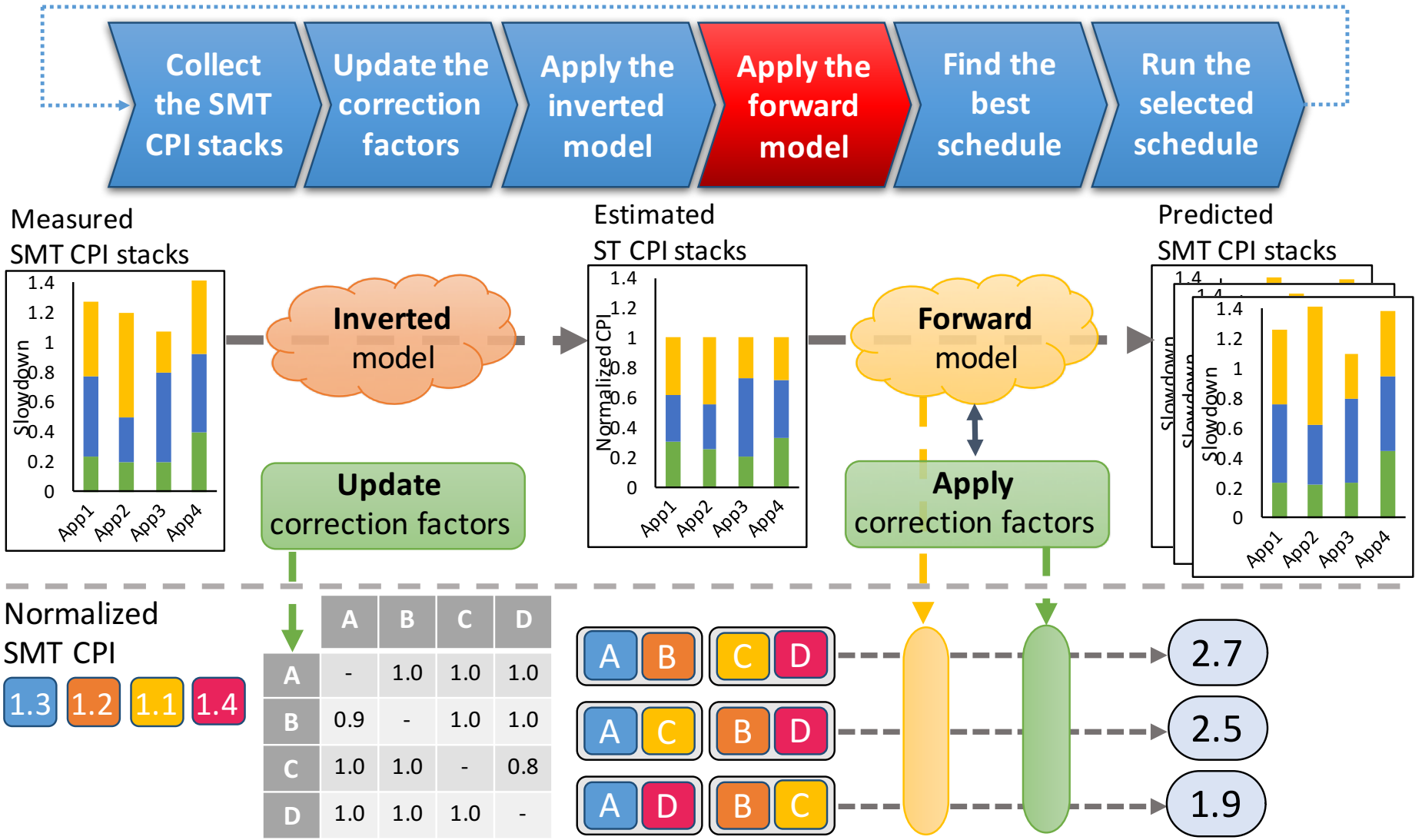
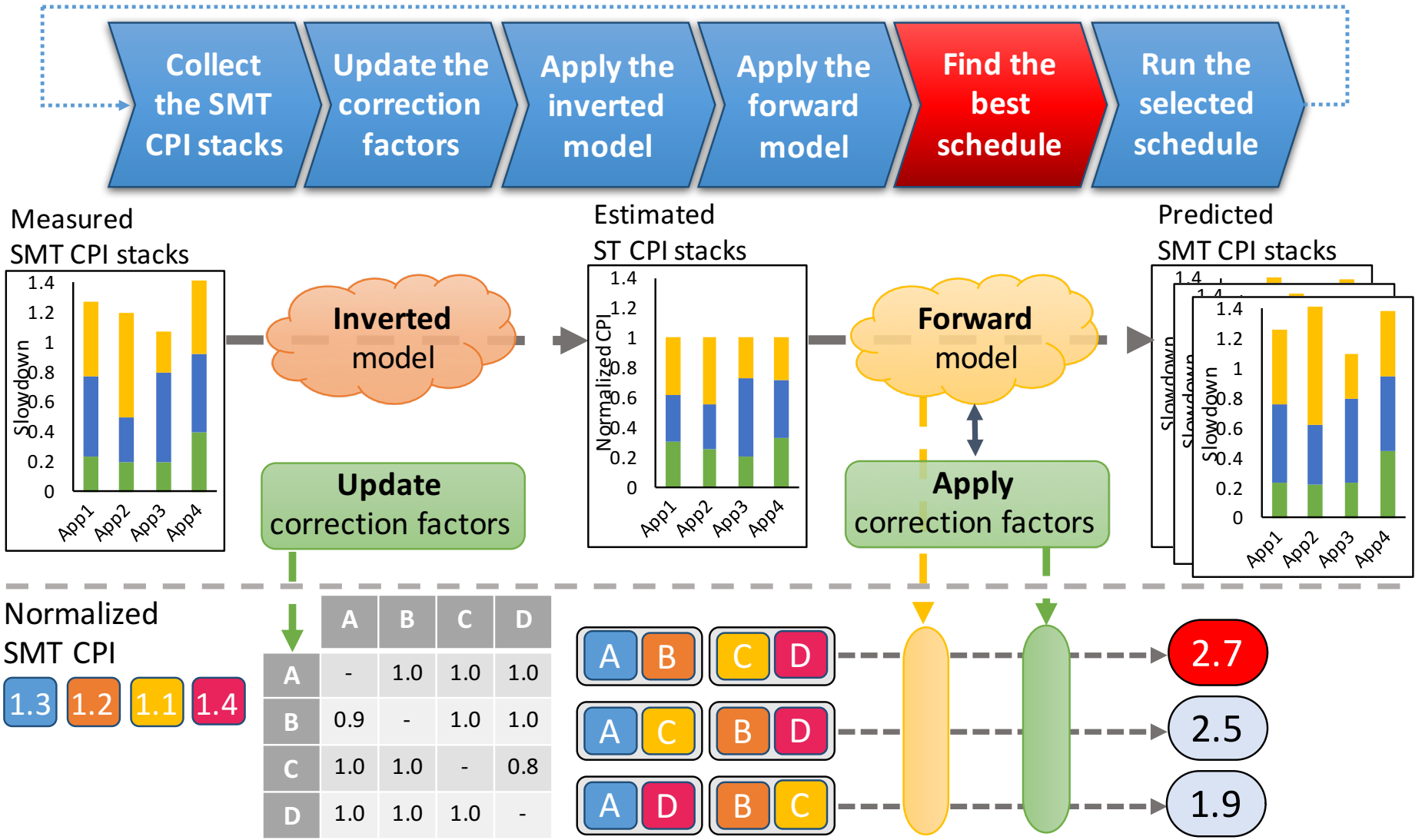
	A	B	C	D
A	-	1.0	1.0	1.0
B	0.9	-	1.0	1.0
C	1.0	1.0	-	0.8
D	1.0	1.0	1.0	-

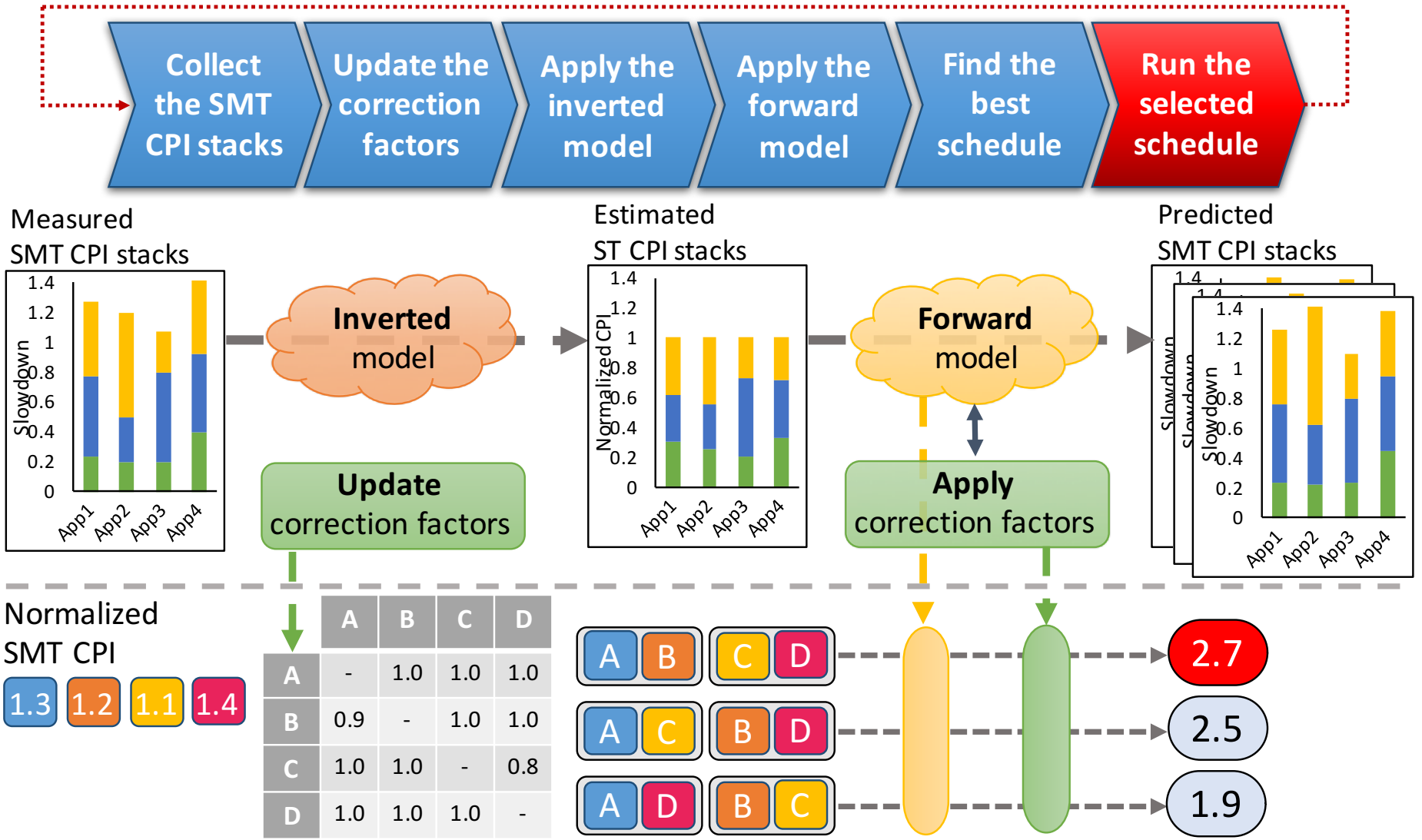
Scheduling steps



Scheduling steps



Scheduling steps



Outline

Experimental setup

- 10-core IBM POWER8
- SPEC CPU2006 benchmarks (reference input set)
- 105 multiprogram workloads
  - From 8-application combinations on 4 cores to 20-application combinations on 10 cores
- Metrics:
  - System throughput (STP), by means of the weighted speedup metric
  - System fairness, $Unfairness = \frac{Max\ Slowdown_i}{Min\ Slowdown_j}\ \forall\{i,j\} \in \{1,N\}$

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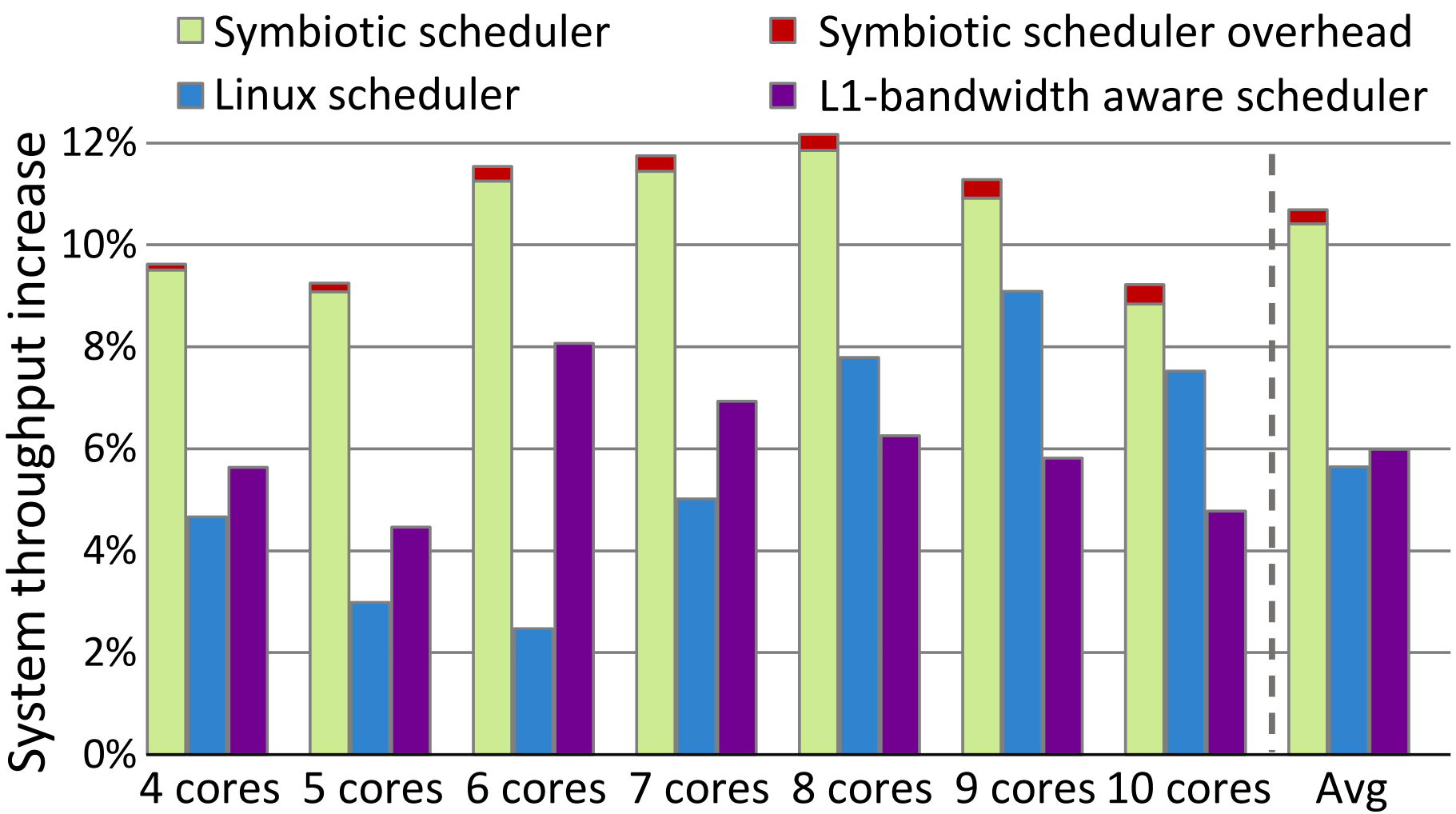
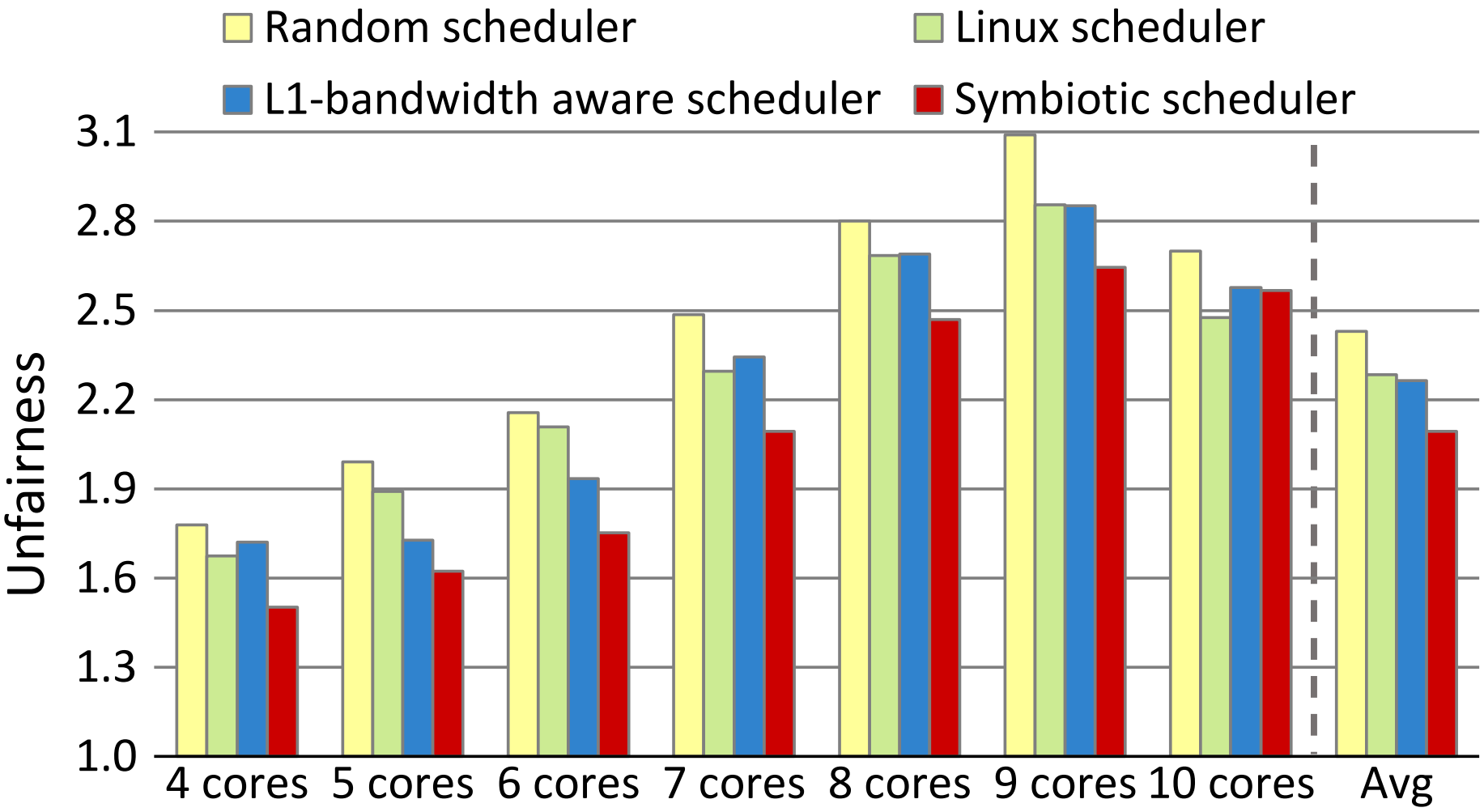
- **Four schedulers are compared:**
  - Random
  - Linux, default Completely Fair Scheduler (CFS)
  - L1-bandwidth aware scheduler, which balances the L1 bandwidth utilization among cores. *Feliu et al., PACT'13*
  - Symbiotic scheduler

System throughput increase

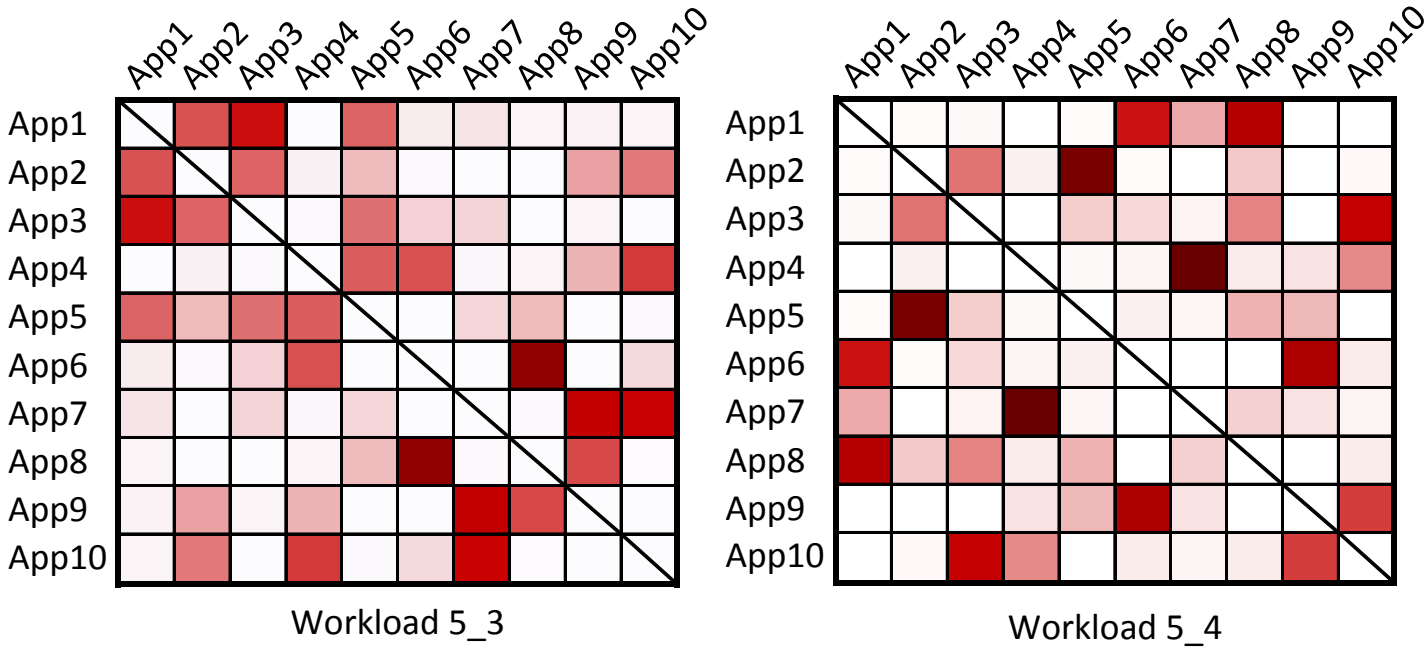


System unfairness



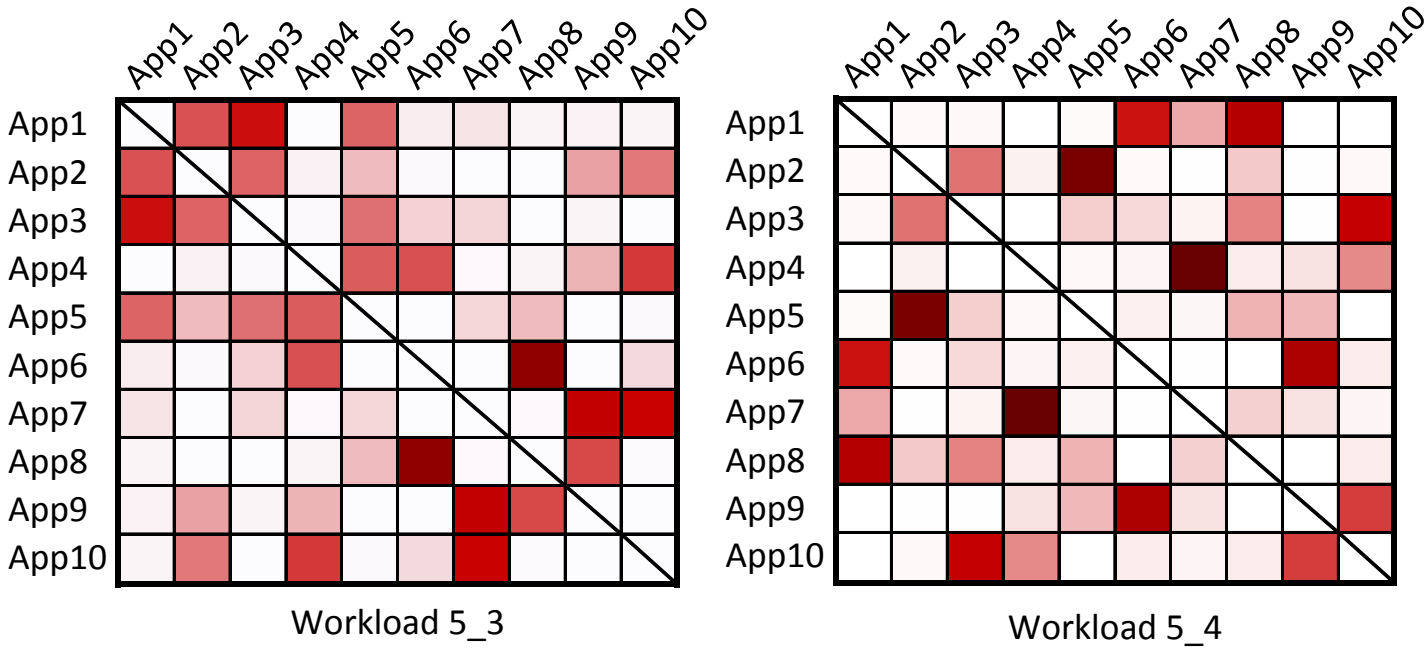
Unfairness is a lower is better metric

Symbiosis patterns



- Frequency matrices of the job co-schedules
  - The darker the color the more frequently the couple is scheduled together on a SMT core

Symbiosis patterns



- Frequency matrices of the job co-schedules
  - The darker the color the more frequently the couple is scheduled together on a SMT core
  - In workload 5_4 two couples are scheduled very frequently ($> 65\%$) $\Rightarrow$ High symbiosis
  - In workload 5_3 there is not that predominant couple $\Rightarrow$ High phase behavior

Outline

Conclusions

- Scheduling has considerable impact on the performance of SMT multicores
- **Novel symbiotic job scheduler for SMT multicores**
  - Quick estimation of the performance of schedules to select the optimal one
  - Using CPI stacks can quickly adapt to phase behavior
  - No need of additional hardware nor sampling schedules
- Improve the system throughput of the random and Linux schedulers, on average, by 10.3% and 4.7%

Symbiotic Job Scheduling on the IBM POWER8

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March 16th, 2016

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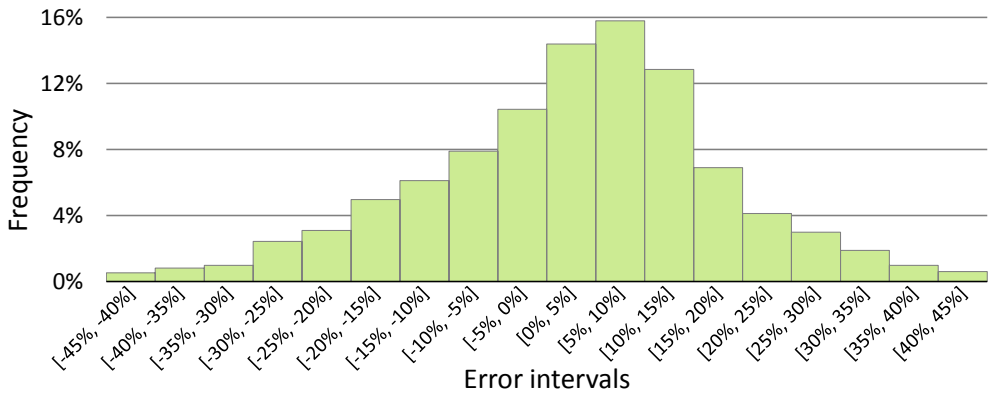
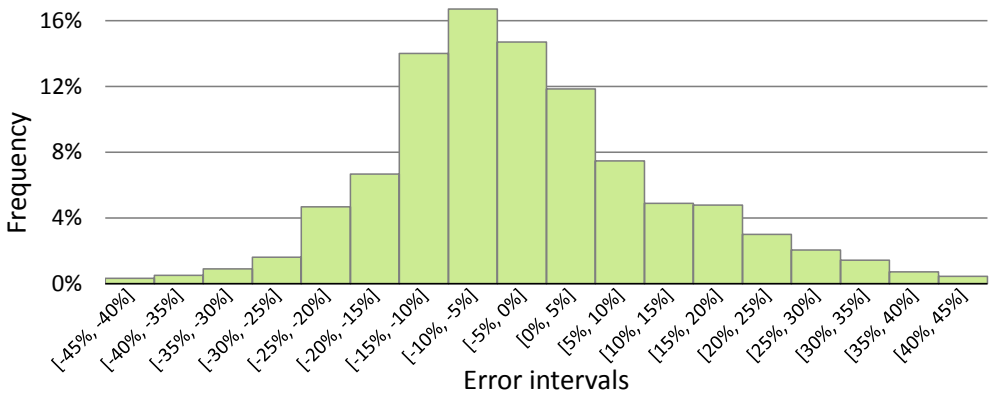
Model accuracy



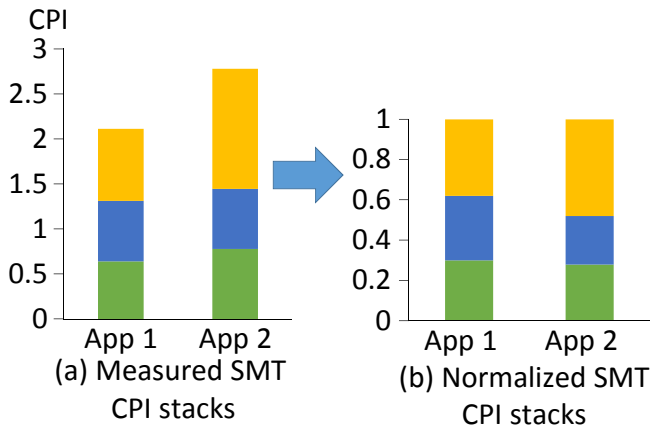
- Distribution of error from ST CPI stacks alone to SMT CPI stacks together
- Average absolute error: 12.3%

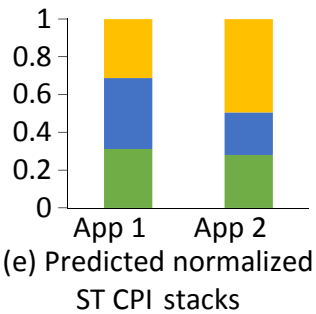


- Distribution of error from SMT CPI stacks together to ST CPI stacks alone
- Average absolute error: 13.4%

Obtaining ST CPI stacks in SMT mode

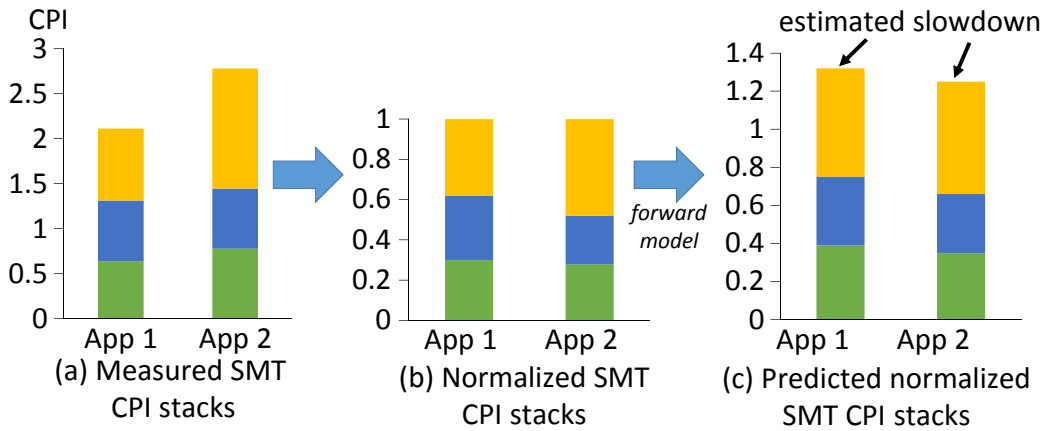
- Approximate approach
  - SMT components normalized to SMT CPI $\approx$ ST components normalized to ST CPI
    - Both add to one
    - If the relative increase of the components is the same, then both stacks are equal
  - However, it is not accurate enough





Obtaining ST CPI stacks in SMT mode

- Approximate approach
  - SMT components normalized to SMT CPI $\approx$ ST components normalized to ST CPI
  - Estimate the slowdown applying the model to the estimated normalized ST CPI



Obtaining ST CPI stacks in SMT mode

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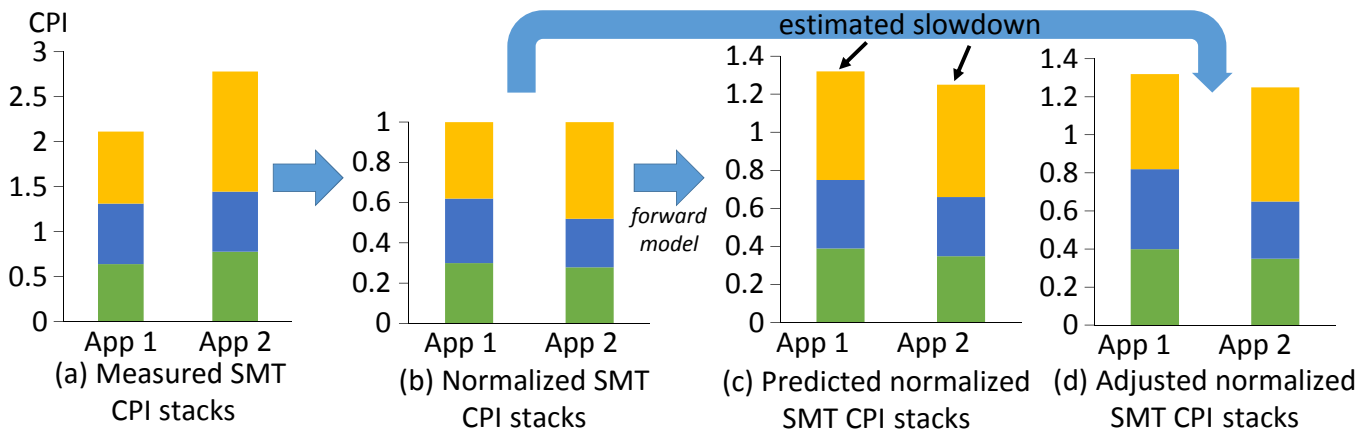
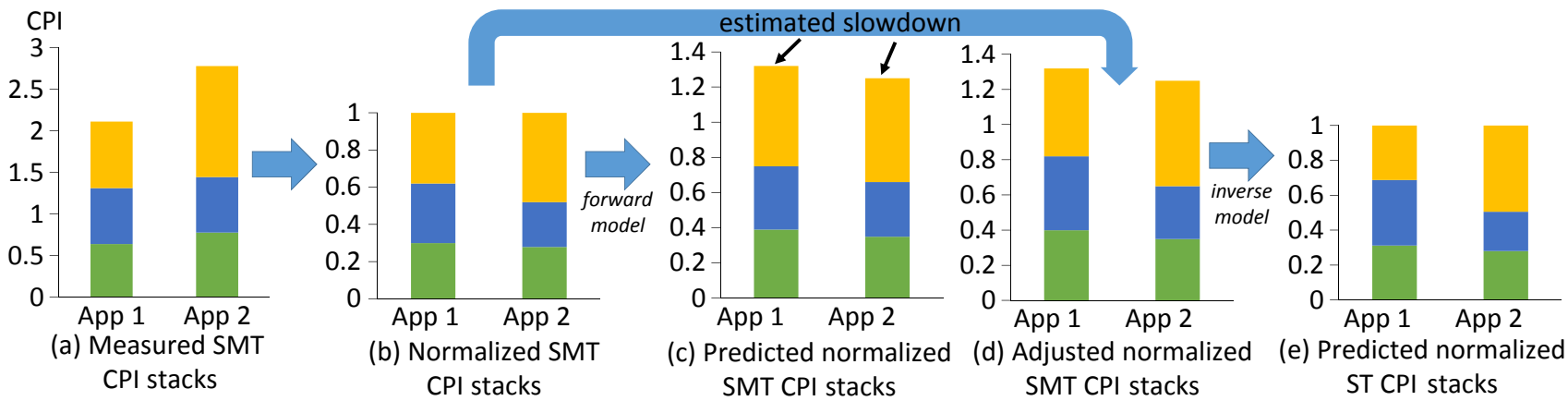
  - Renormalize the measured SMT CPI stacks using the estimated slowdown

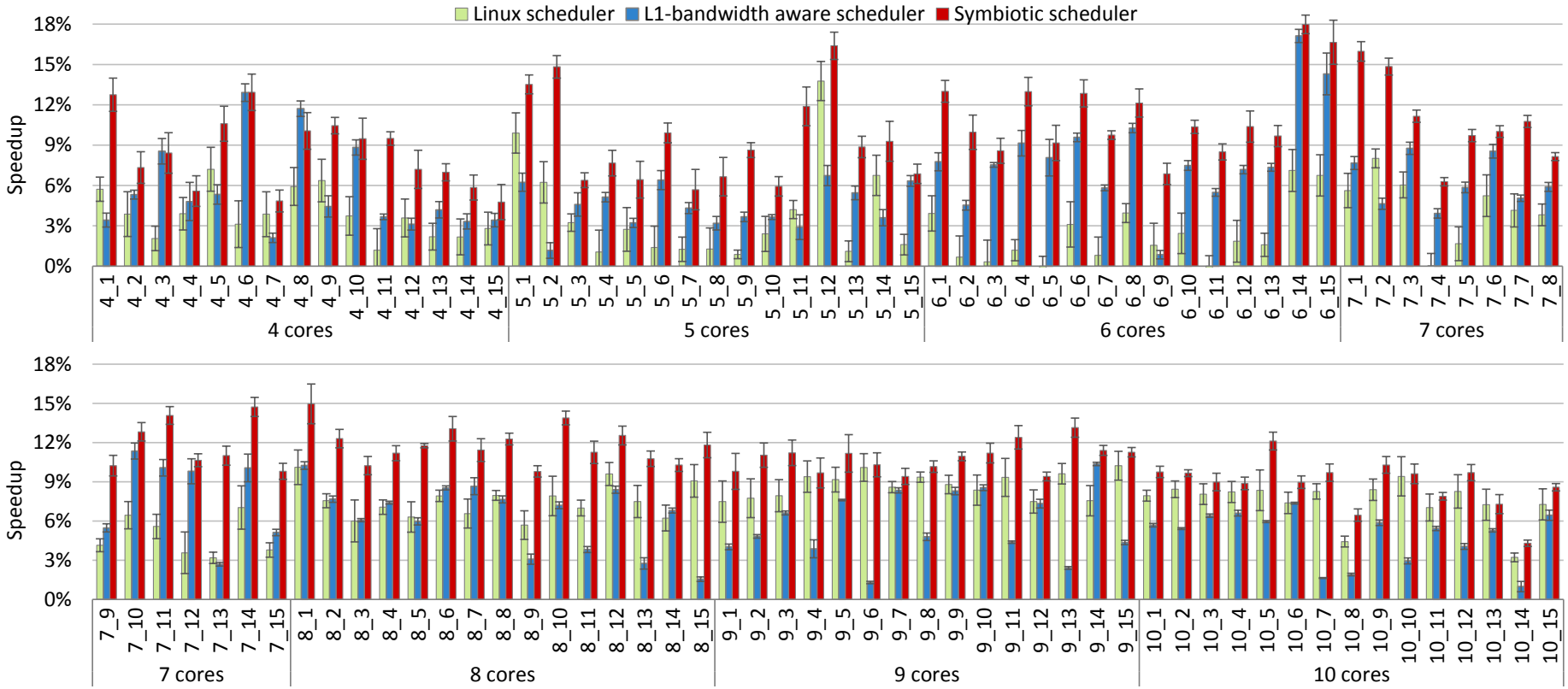


Obtaining ST CPI stacks in SMT mode

- Approximate approach
  - SMT components normalized to SMT CPI $\approx$ ST components normalized to ST CPI
  - Estimate the slowdown applying the model to the estimated normalized ST CPI
  - Renormalize the measured SMT CPI stacks using the estimated slowdown
  - Apply the inverse model to obtain new estimates for the ST CPI stacks



System throughput performance



Core asymmetry