# A Comprehensive Scheduler for Asymmetric Multicore Systems

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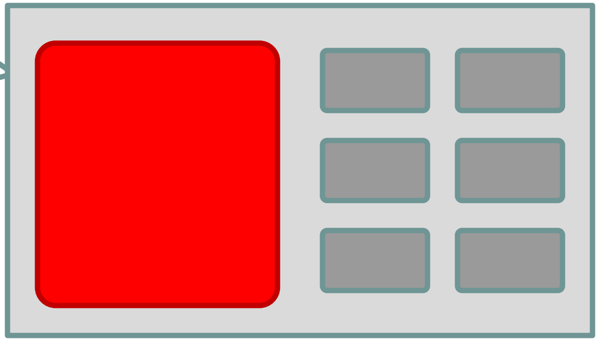
# Contents

# Asymmetric Multicore Processors

- Asymmetric Performance
- Common ISA

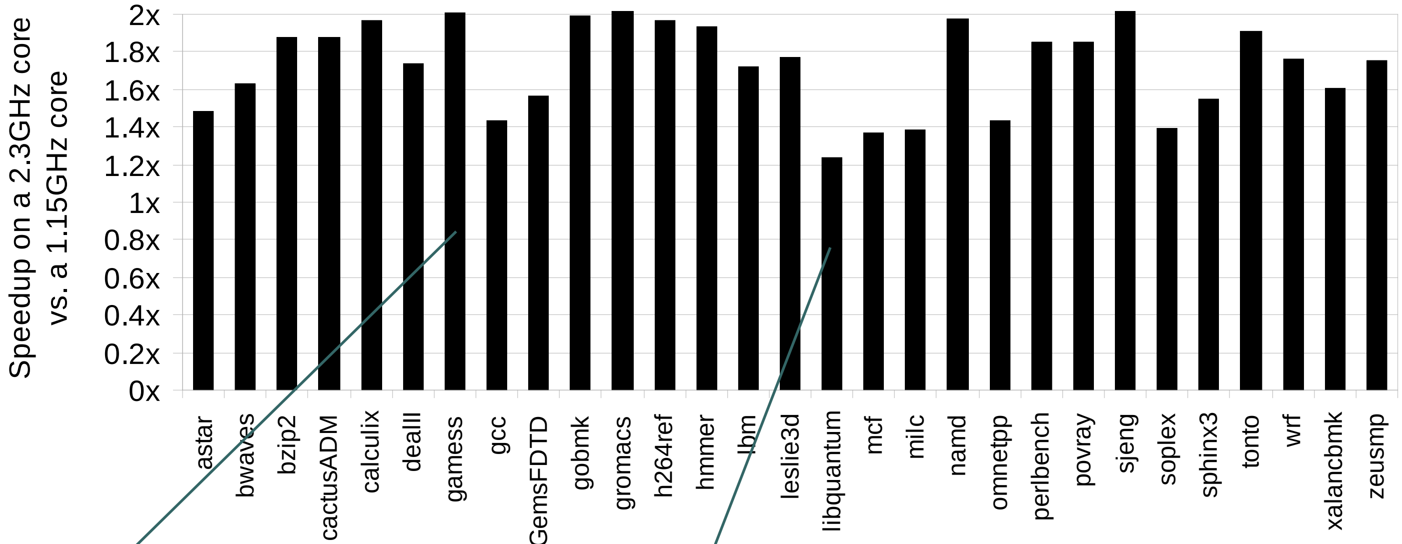
<u>Fast Core:</u>
- High Frequency
- Superscalar
- OOO execution
- Large area requirements
- High power



<u>Slow Cores:</u>
- Lower frequency
- Single-Issue
- In order pipelines
- Reduced area
- Low power

# Efficiency Specialization: Exploiting ILP diversity

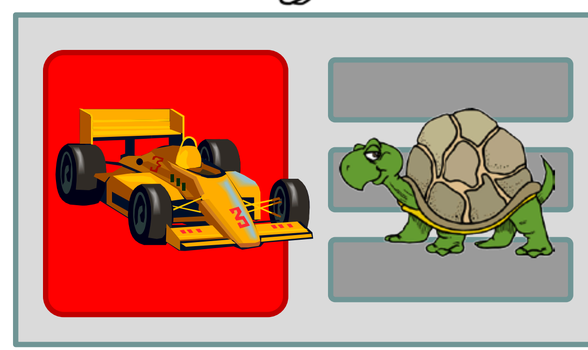
**Speedup Factor**




**SPEC CPU 2006**

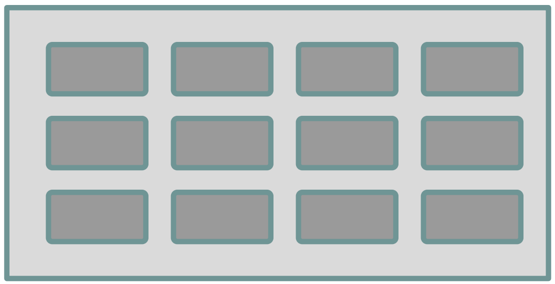
Sensitive to CPU performance:
- Use complex pipelines efficiently
- Few pipeline stalls

Insensitive to CPU performance:
- High LLC miss-rate
- A lot of mispredicted branches
- Frequent pipeline stalls



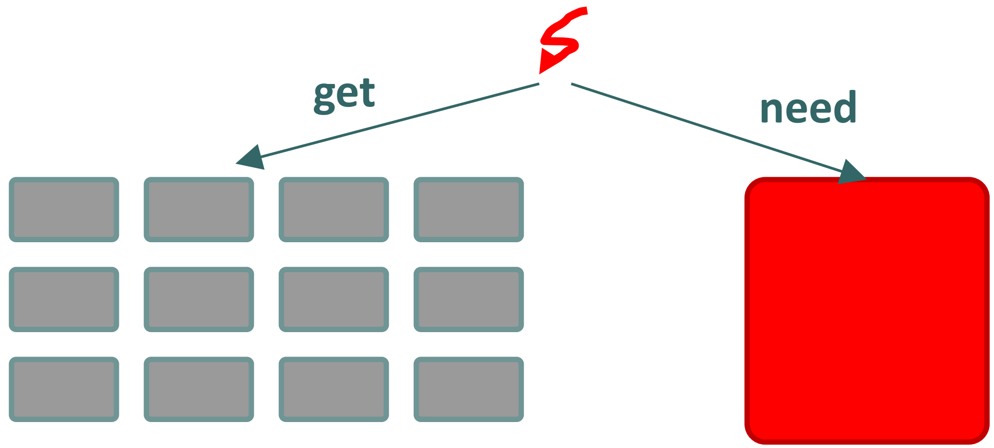
# TLP Specialization: Exploiting TLP Diversity

CMPs → cores per chip ⇧⇧



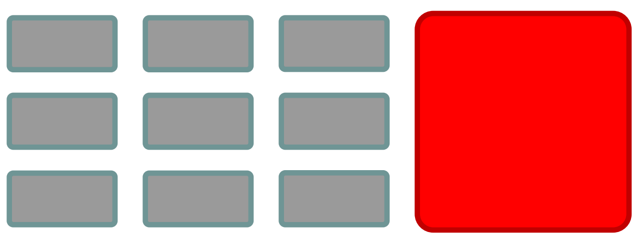
Good performance for scalable parallel applications

Not so "good" for sequential and non-scalable parallel applications




**AMPs: offer the best of both worlds for multi-application workloads**

Abundant "low-power" cores for **running parallel code**



Cores with high single-thread performance for:
- ST apps.
- Accelerate seq. sections of parallel applications

**Detection by OS**: *Runnable thread count*

# Unleashing the Potential of AMP systems

- Efficiency Specialization: ST apps.
- TLP Specialization: ST and MT apps
- *Previous asymmetry-aware schedulers employed one type of specialization only*

➔ Our goal is to design the *comprehensive scheduling* support to cater to TLP and ILP diversity

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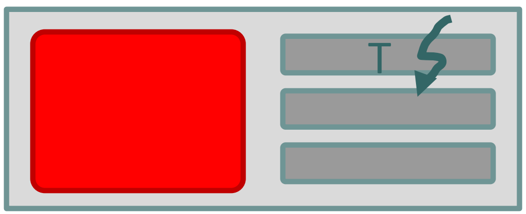
# Direct SF measurement

**The IPC-Driven algorithm**

Monitor Instructions per second ($IPS_{slow}$) of the current core type → *phase change* → Migrate to FC to obtain $IPS_{fast}$ → *Refresh SF* → Update SF → Assign to cores

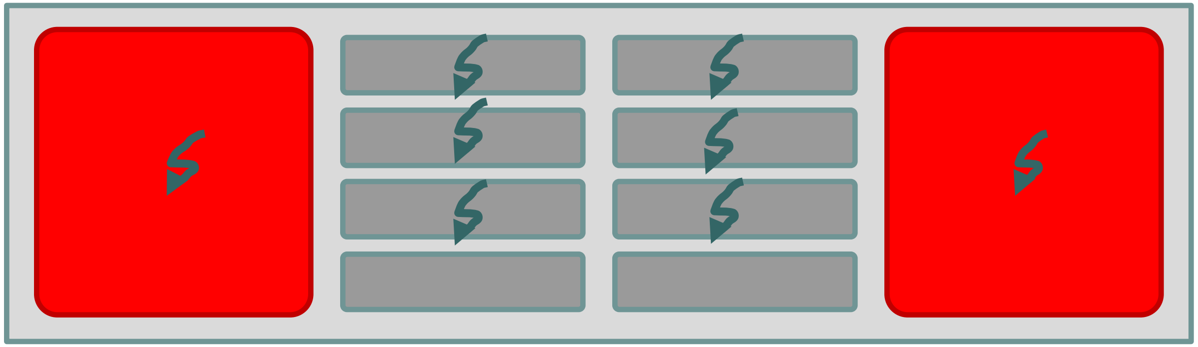



- First evaluation of **IPC-Driven** done on a simulator
- We implemented it in a real OS and evaluated on real HW
- **Two problems**:
  - **Inaccurate IPC ratios**
    - Phase change may happen <u>during</u> measurement
  - Refreshing threads create **load imbalance**
    - Contention on scarce FCs

# Estimating Speedup Factors

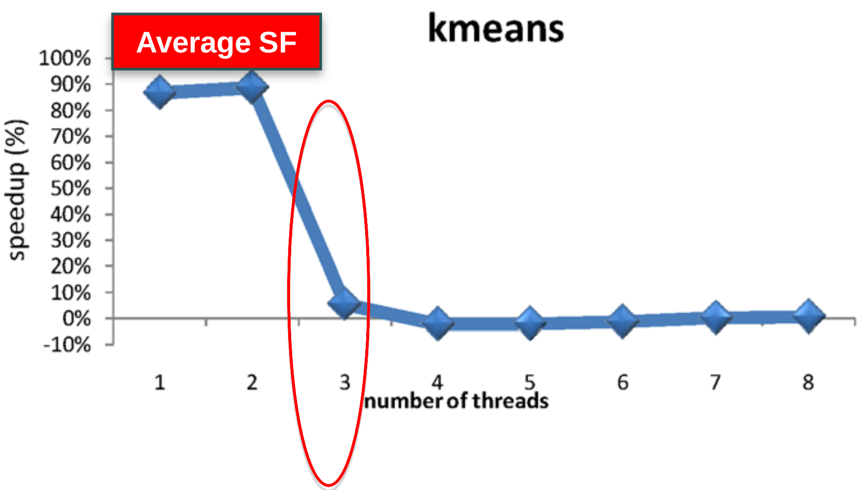
- Our **scheduling policy** relies on **estimating SF** on the current core type
  - \+ Cross-core migrations not required
  - \- **SF Model** designed **specifically for the asymmetric system** in question ➔ more complex
- We provide SF estimation **model for cores differing in frequencies**
  - Estimate completion time for *K* instructions
  - **`CT= Computation_Time + Stall Time`**
- Stall time estimated from Last-Level-Cache miss rates (off-core requests)

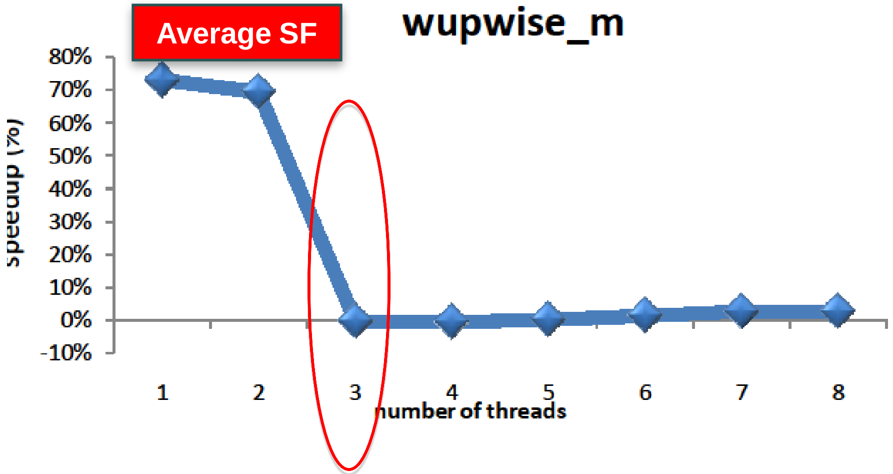
# Do *Well-Balanced* Parallel Applications benefit from using FCs?



Both fast and slow cores → Keeping FCs Busy

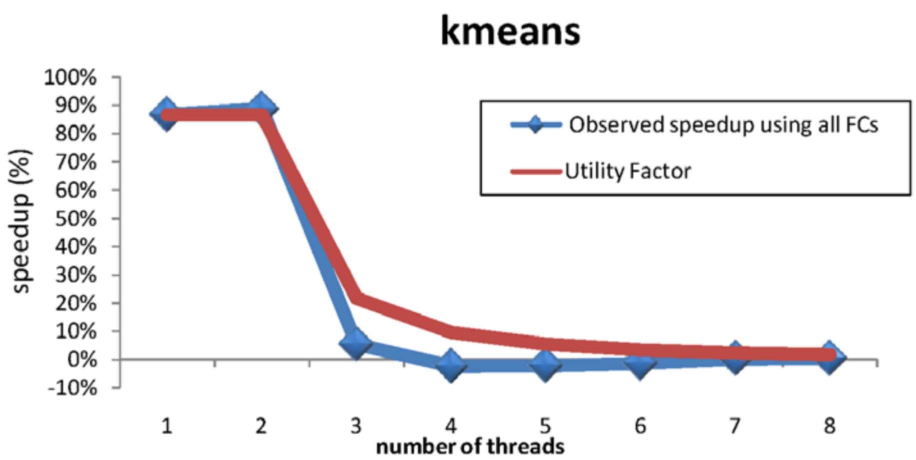
Slow cores only

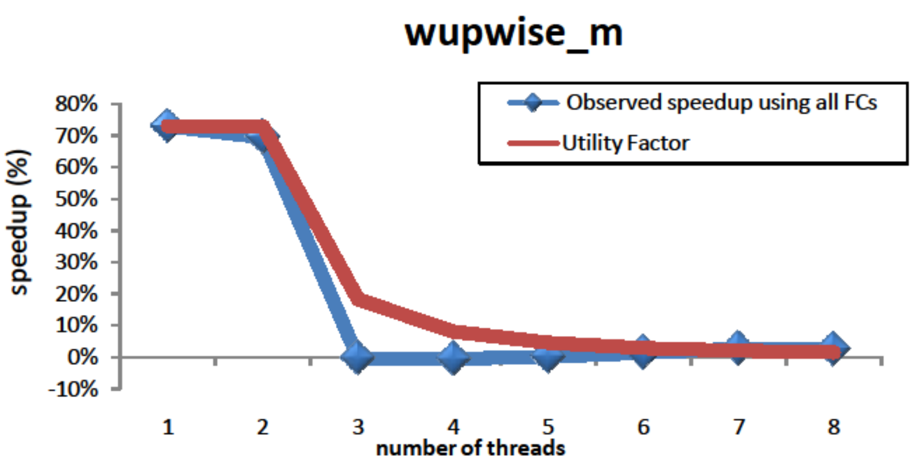



$$Speedup_{app} = f(SF_{app}, N_{threads}, NFC)$$

# Utility Factor (TLP+ILP)




$$Ufactor_{app} = \frac{SF_{app}}{MIN\left(SF_{app}\, ,\ \sum_{i=1}^{\left\lceil \frac{N_{threads}}{NFC} \right\rceil} \frac{1}{SF_{app}^{i}}\right)}$$

$$Ufactor_{app} = \frac{SF_{app}}{\left(MAX\left(1, N_{threads}\text{-}(NFC\text{-}1)\right)\right)^2}$$

$$\boxed{Ufactor_{Ti} = \frac{SF_{Ti}}{\left(MAX\left(1, N_{threads}\text{-}(NFC\text{-}1)\right)\right)^2}}$$

- Compact metric (ILP+TLP)
- For ST apps ➔ UF=SF
- Foundation for CAMP

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# Goals of CAMP

- **CAMP**: *A Comprehensive scheduler for Asymmetric Multicore Processors*
- Design **goals**:
  - **Efficiency Specialization + TLP Specialization**
  - **Accelerate sequential parts of parallel applications**
    - Boost `SEQUENTIAL_PART` threads without monopolizing FCs
  - **Fair-Share scarce FC** among threads that benefit the most in the workload (`HIGH_UTILITY` threads)
  - **Low runtime overhead**
    - Light-weight mechanism to filter out short program phases and reduce migrations
  - **Topology-aware design**
    - Avoid cross-LLC migrations when thread-to-core mapping need readjusting

# Utility Factor and Classes

- **Threads' UFs guide scheduling decisions**, so the OS needs to monitor:
  - The *runnable thread count* of the application (*process*)
  - LLC miss rate to estimate SF

$$Ufactor_{Ti} = \frac{SF_{Ti}}{\left(MAX\left(1, N_{threads} - (NFC - 1)\right)\right)^2}$$

- UF of a thread determines its **Utility Class**
  - `LOW_UTILITY`
  - `MEDIUM_UTILITY`
  - `HIGH_UTILITY`
  - *`SEQUENTIAL_PART`*

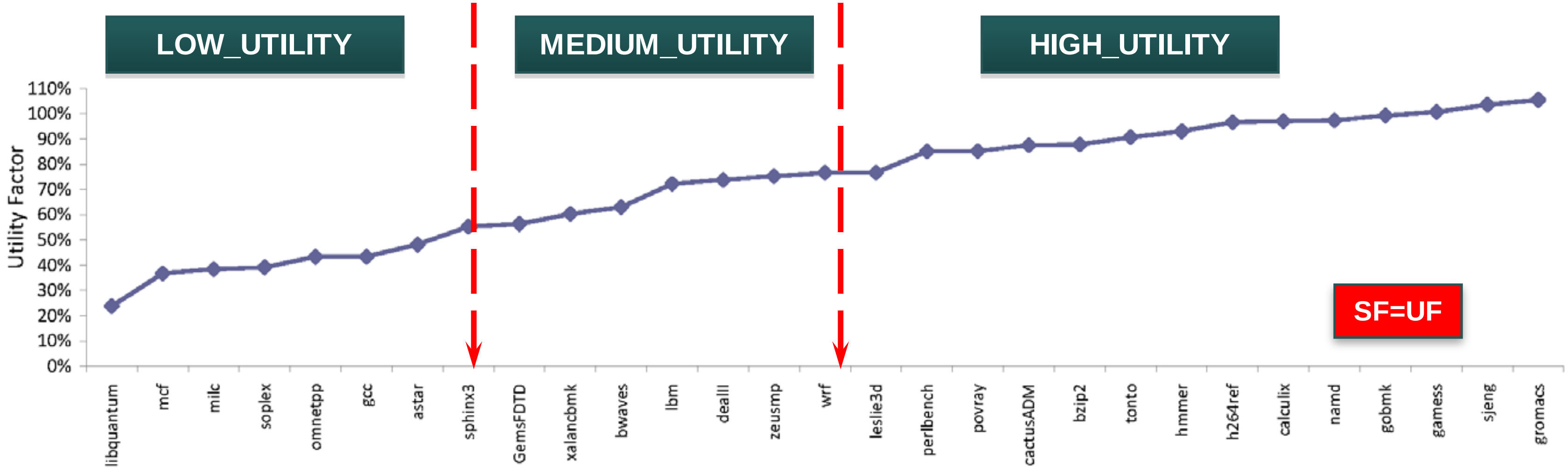
Lower

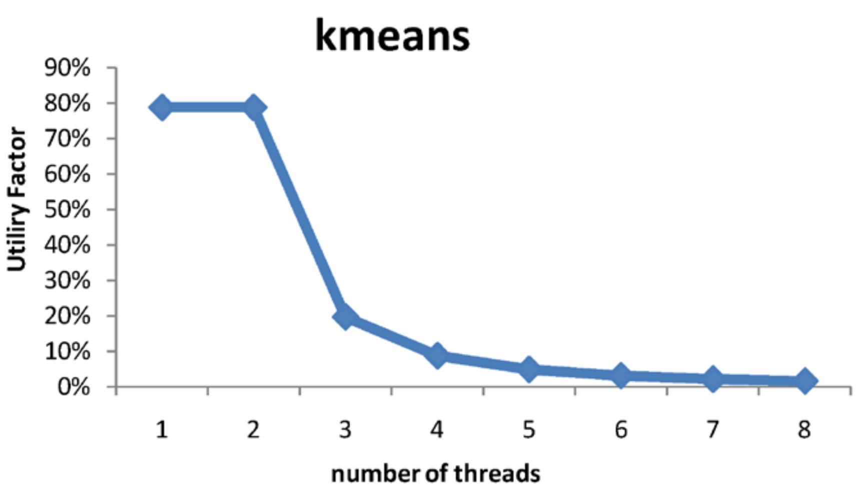
Upper

**UF**

**Priority to Run on FCs**

# Utility Factor and Classes




➔A pair of thresholds (upper and lower) determines the boundaries between utility classes

➔ For ST apps UF ranges from 23% to 100%

➔ When MT apps are present, UFs as low as 0%

***CAMP adjusts thresholds dynamically based on the workload***

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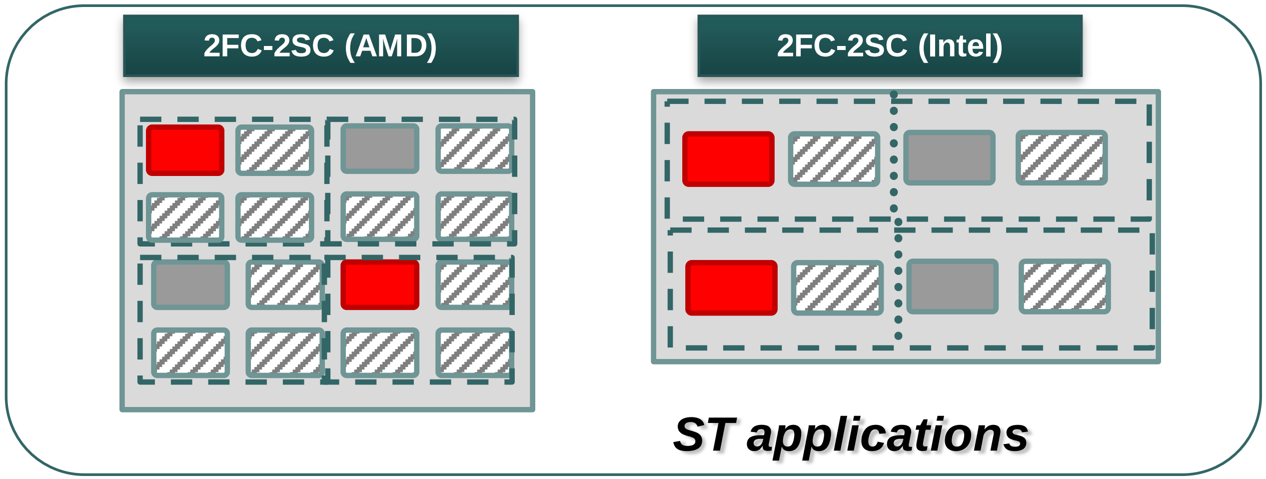
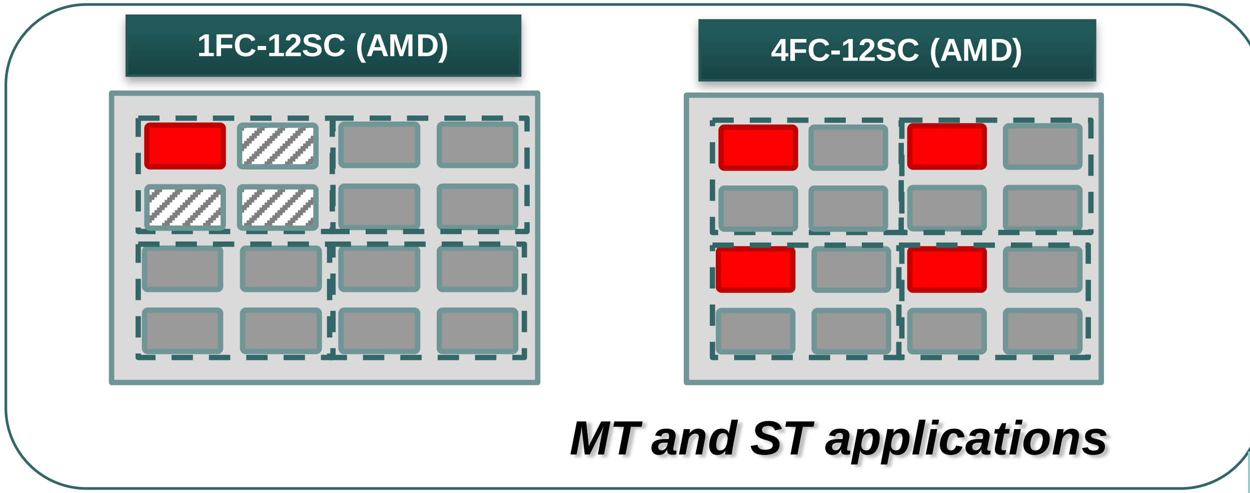
# Schedulers and Workload types

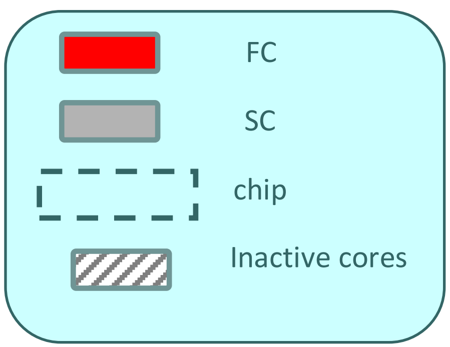
- **CAMP vs. other schedulers**:
  - **Speedup Factor Driven (SFD) ➔** Efficiency Specialization only
  - **Parallelism-Aware Scheduler (PA) ➔** TLP Specialization only
  - **Asymmetry-aware Round Robin Scheduler (RR) ➔** Fair-shares FCs
- All schedulers **implemented in OpenSolaris**
- We report **gmean speedup over RR** (per application and workload)
- **Workloads** (SPEC CPU 2006, OMP 2001, Minebench, ...)
  - **ST applications ➔** Efficiency Specialization
    - Wide variety of SFs
    - Assess Accuracy SF model (comparison with “Best Static”)
  - **2 workload sets (ST and MT) ➔** TLP specialization
    - Wide range of apps: sequential portion and SF
    - 10 Application pairs
    - More than two apps.

# Experimental setup

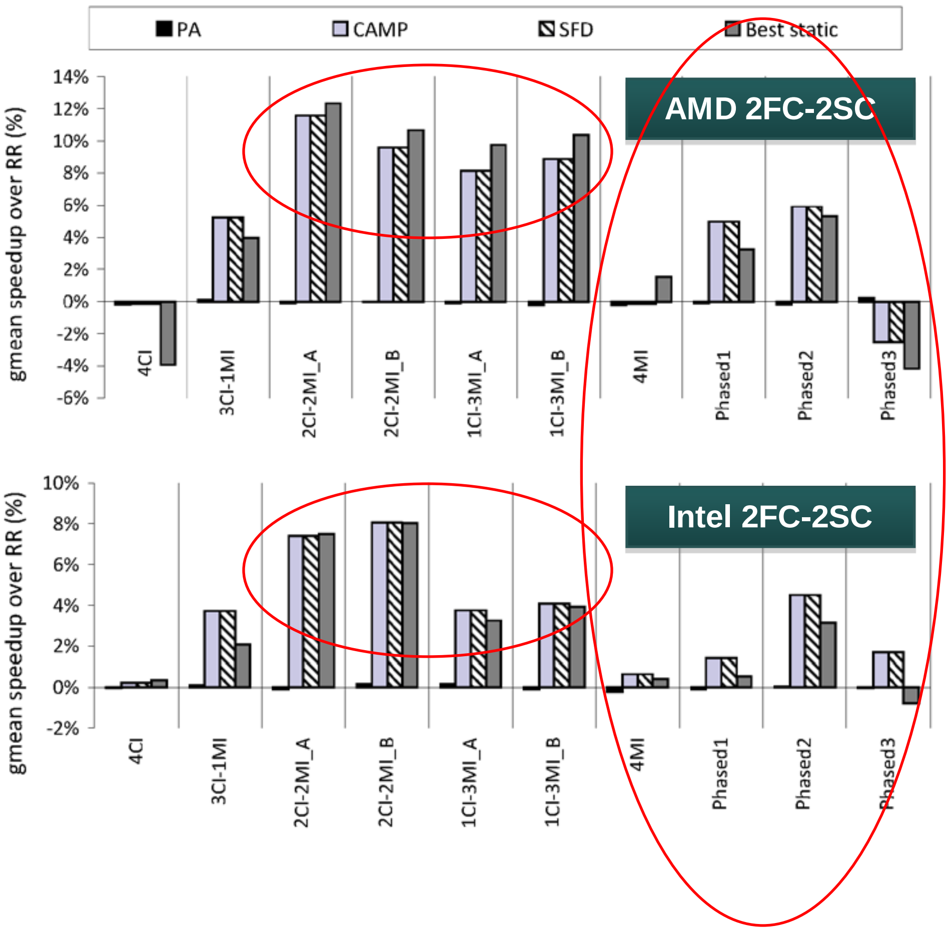
| Property | Description |
|---|---|
| ***Hardware Platforms*** | •AMD Opteron system (NUMA) with 4 quad-core "Barcelona" chips (16 cores)<br>• Intel Xeon system (UMA) with 2 "quad-core" chips (8 cores) |
| ***DVFS Settings*** | AMD➔ FCs @ 2.3 GHz<br>SCs @ 1.15 GHz<br><br>Intel ➔ FCs @ 3.0 GHz<br>SCs @ 2.0 GHz |



# Singlethreaded applications: *Efficiency Specialization*



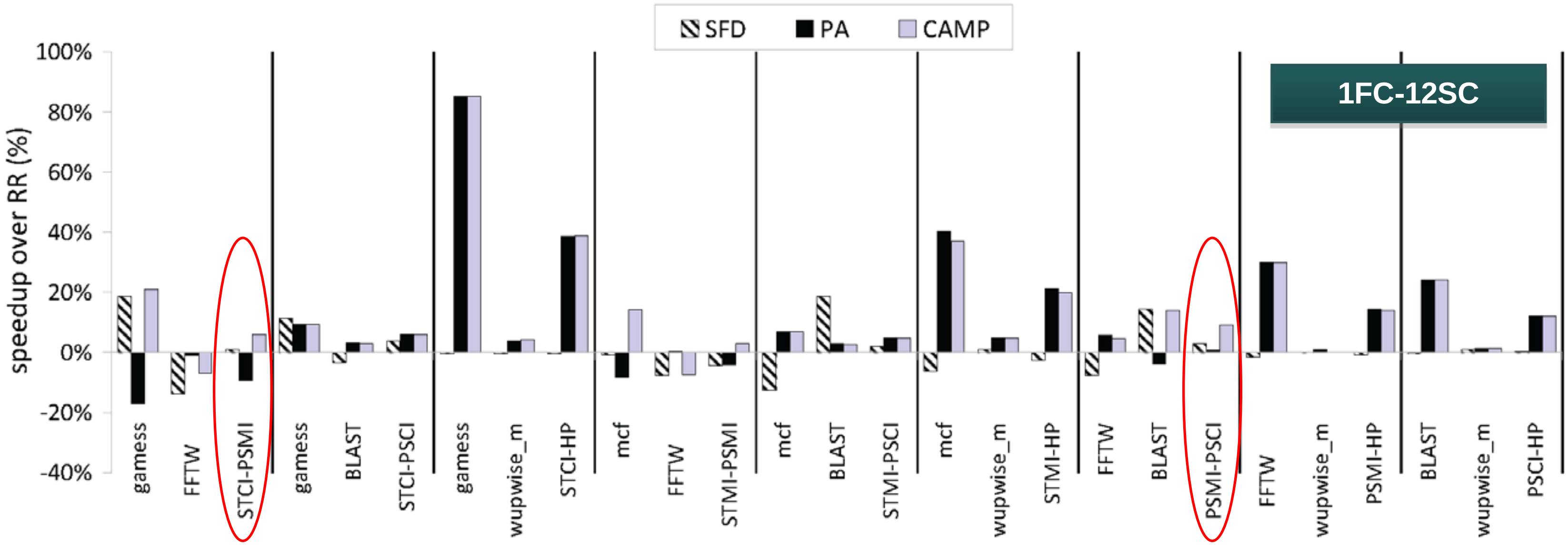

➔CAMP and SFD perform similarly since UF=SF for ST apps.

➔ CAMP performs within 1% range of Best Static in the absence of phase changes but outperforms it when they are present

➔On the Intel platform, SFD and CAMP behave better due to the higher accuracy of the SF model

➔ PA behaves like RR since it is unaware of the efficiency of individual threads

# ST and MT applications (set #1): *TLP Specialization*

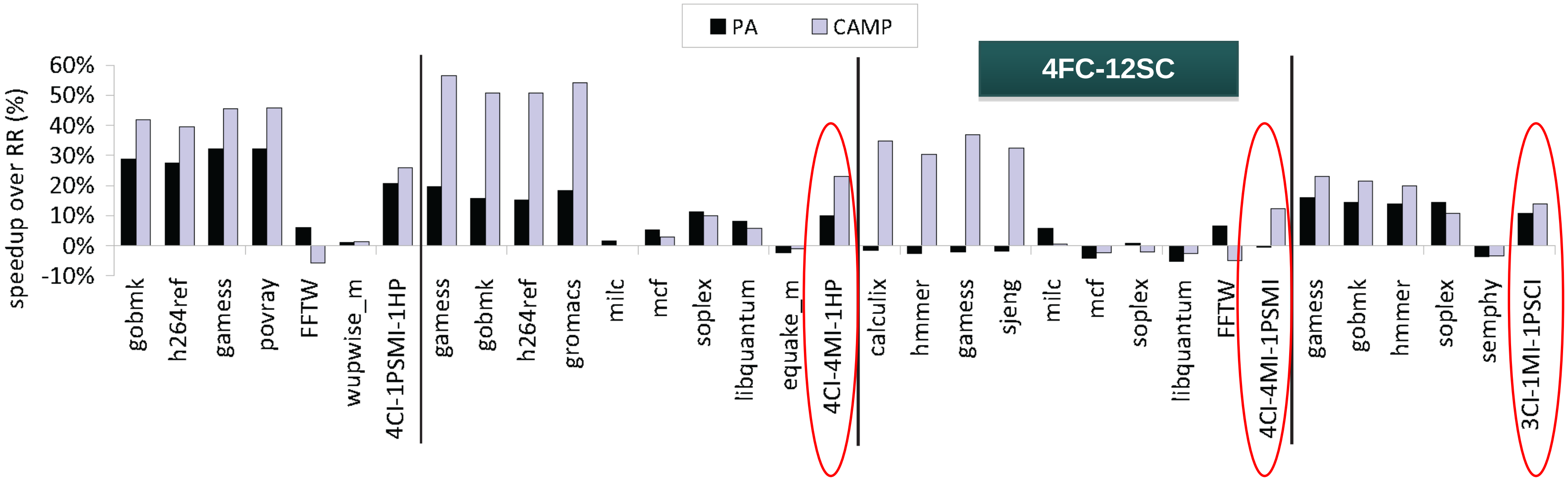



➔ **CAMP and PA performed comparably in most cases, because they both considered TLP while SFD fails to deliver significant performance gains**

➔ **CAMP "properly" schedules memory-intensive sequential parts on SCs**

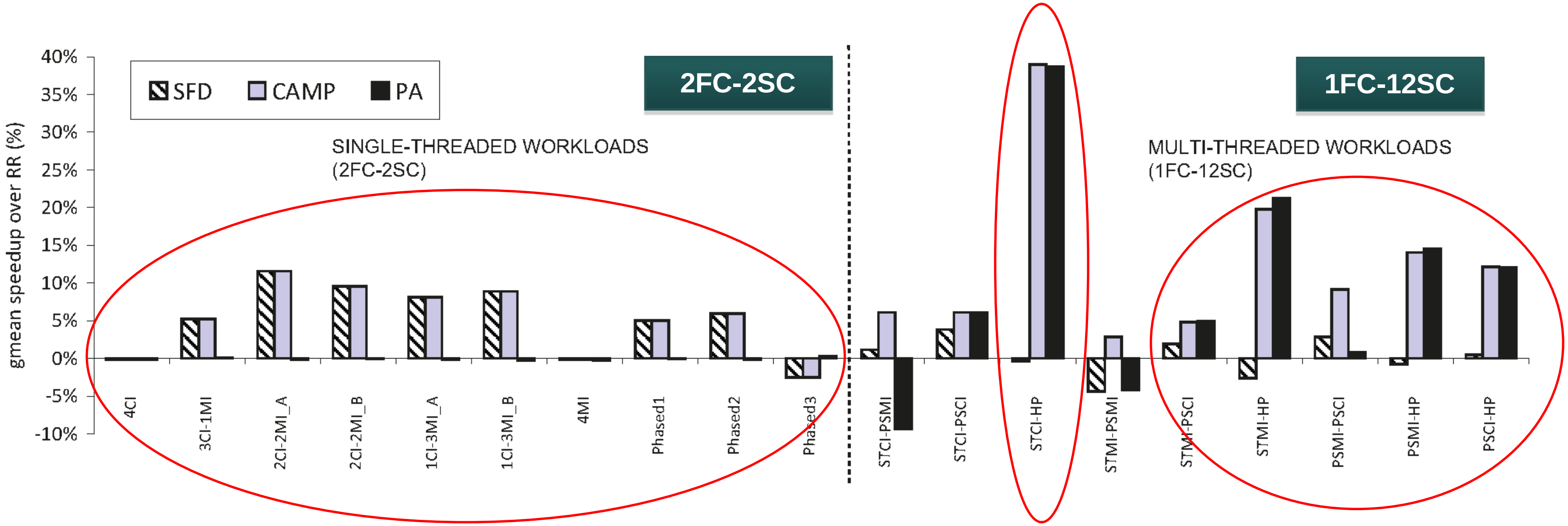
***Does Information on TLP+ILP bring further improvements?***

# ST and MT applications (set #2): *TLP Specialization*




➔ CAMP delivers greater performance gains over PA (up to 13%) for workloads that exhibit a wider diversity in memory-intensity

# Overall results




- ➔ PA fails to deliver *efficiency specialization* (no speedup)
- ➔ SFD is unable to deliver performance comparable to CAMP for workloads that include multi-threaded applications

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# Conclusions

- CAMP accomplishes an **efficient use** of an AMP system for a **wide variety** of workloads
  - SFD does not cater to TLP diversity
  - PA does not take advantage of the ILP diversity of workloads
- **Key elements** for the success of CAMP
  - The **Utility Factor (UF) is a compact metric** to account for TLP+ILP of applications
  - **Light-weight technique** for discovering which threads utilize fast cores most efficiently
    - Obtaining SF for a thread **does not require running** it **on each core type**
  - **Short program phases are filtered out** to avoid premature migrations
- **Considering the *speedup factor* in addition to TLP** brings higher performance improvements (up to 13%)
  - Evident for multi-application workloads exhibiting **a wider variety of memory intensity**

# Future Work

- Designing a methodology to **find performance metrics to define SF esimation models** for highly-asymmetric systems:
  - *Profound microarchitectural differences*
  - Different cache hierarchy/size
  - ➔ *Not requiring cross-core migrations for obtaining SF*
- **Cache-aware** version of CAMP
  - Light-weight policy that complements to *asymmetry-aware scheduling*
  - Assess the impact of cross-core migrations aimed to keep fast cores busy

# Questions?