Energy-Performance Trade-offs on Energy-Constrained Devices with Multi-Component DVFS

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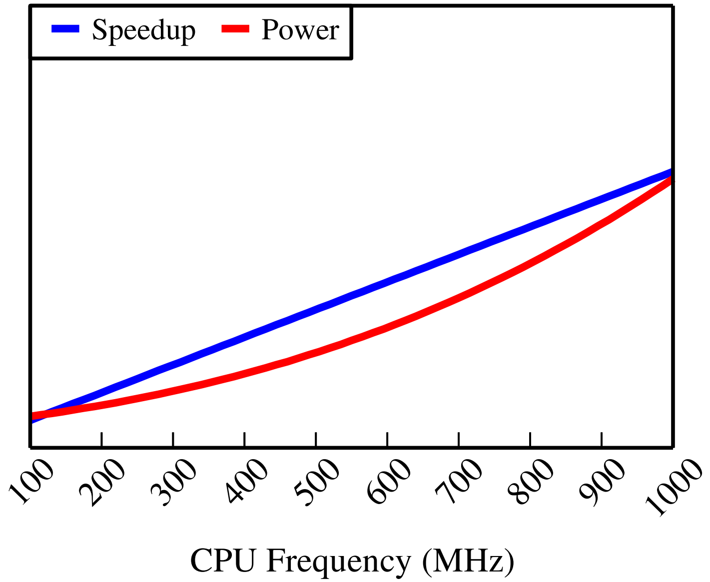
Dynamic Voltage and Frequency Scaling



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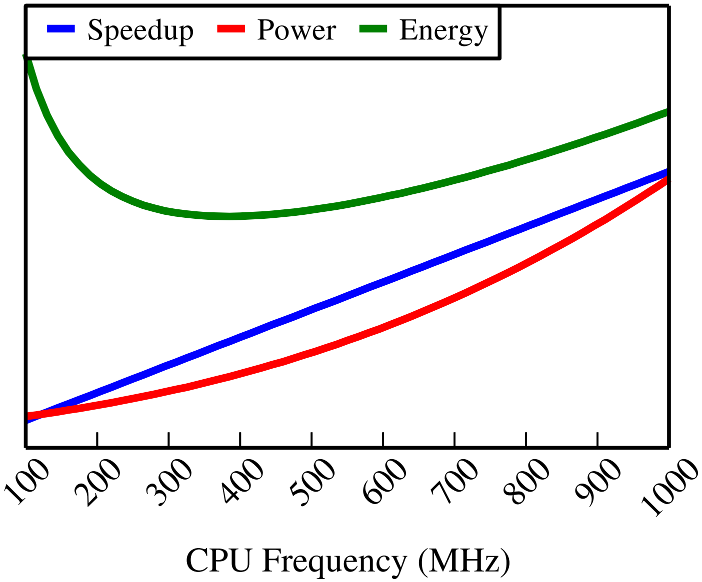

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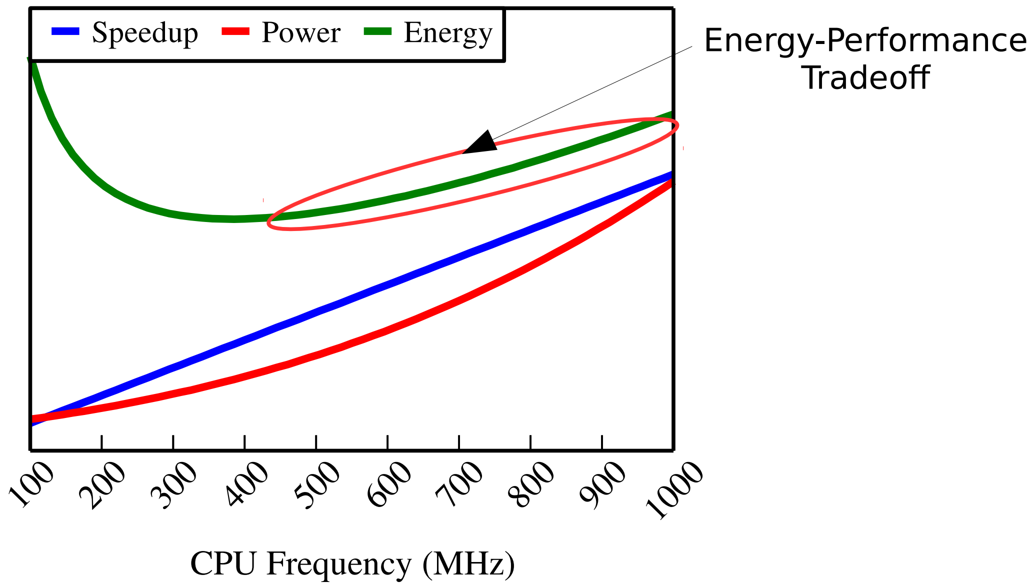

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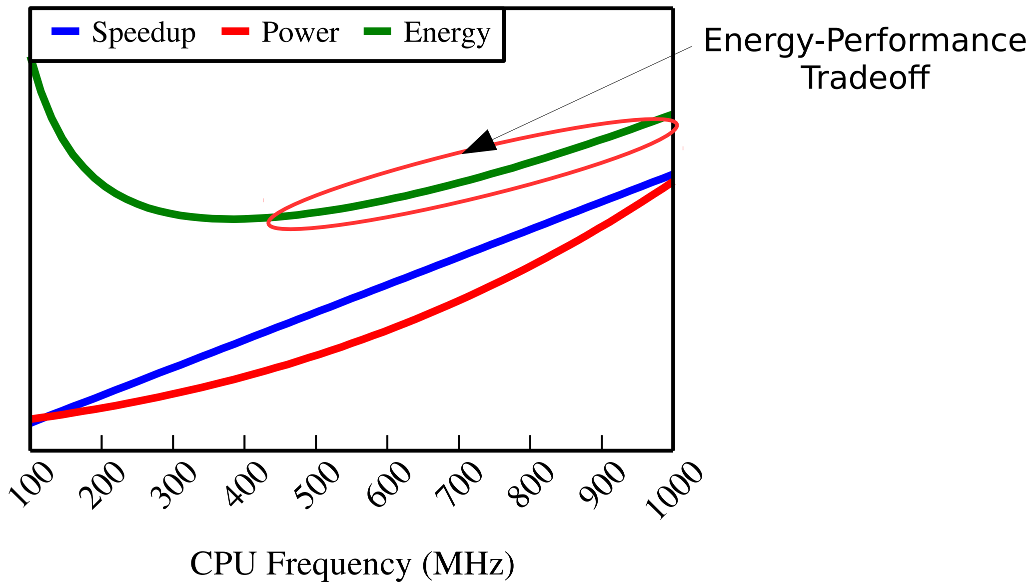
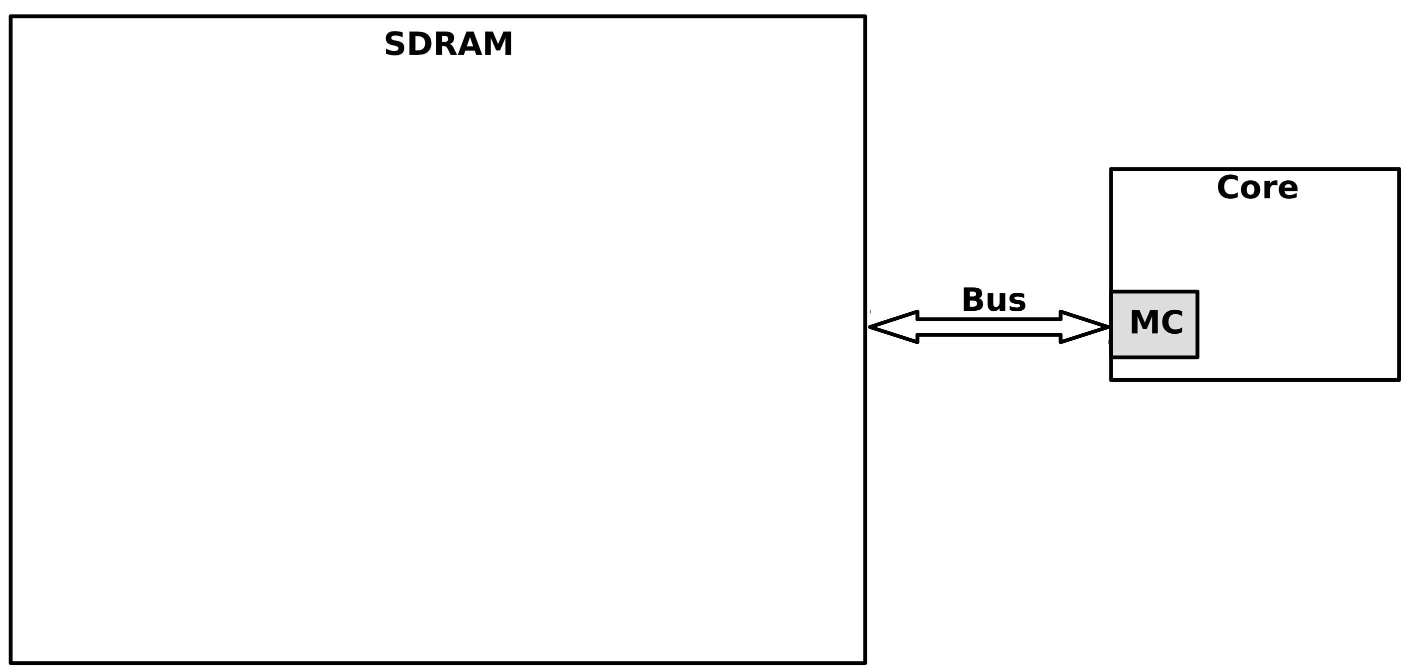


SDRAM Frequency Scaling



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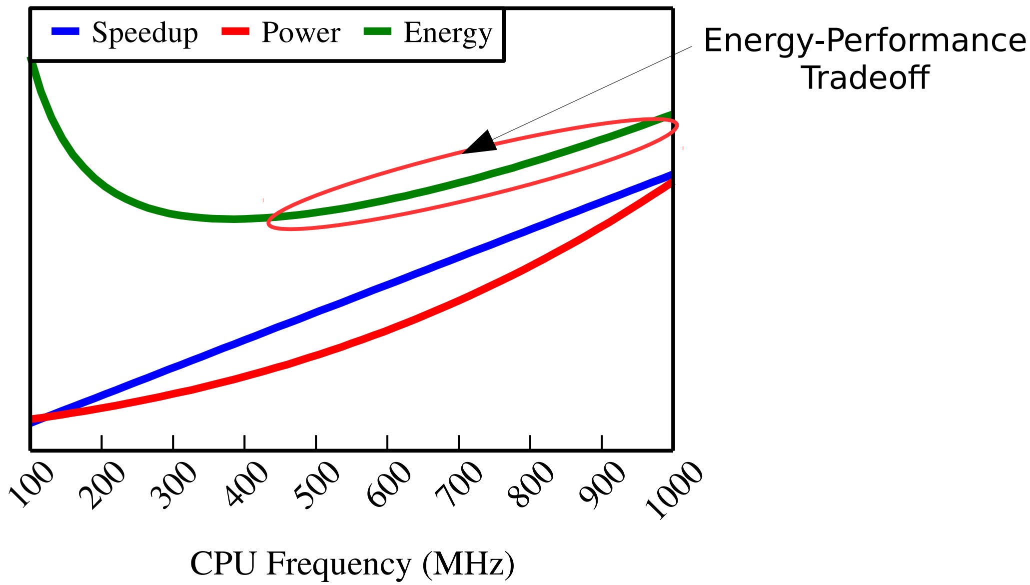

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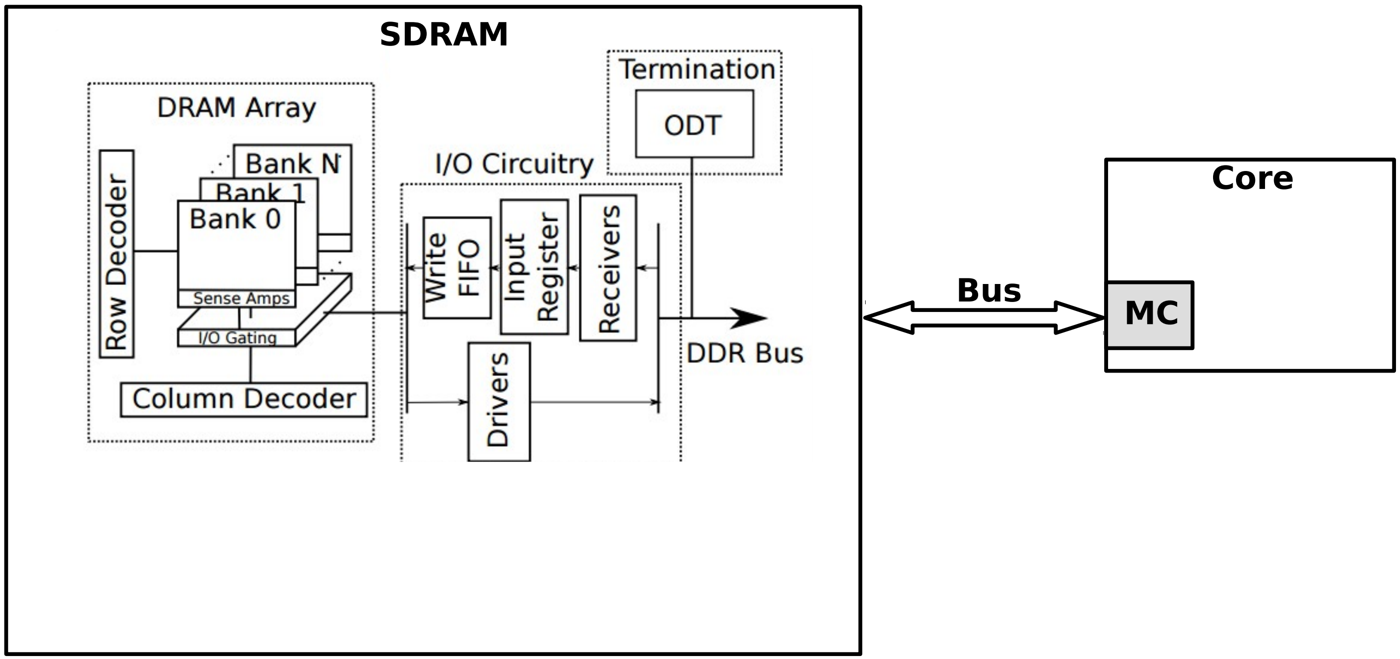

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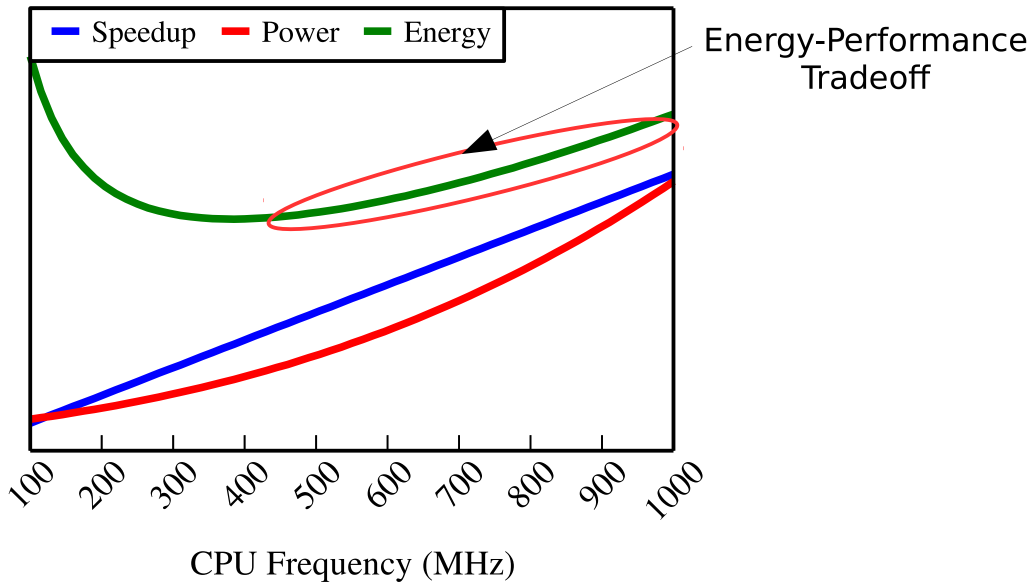

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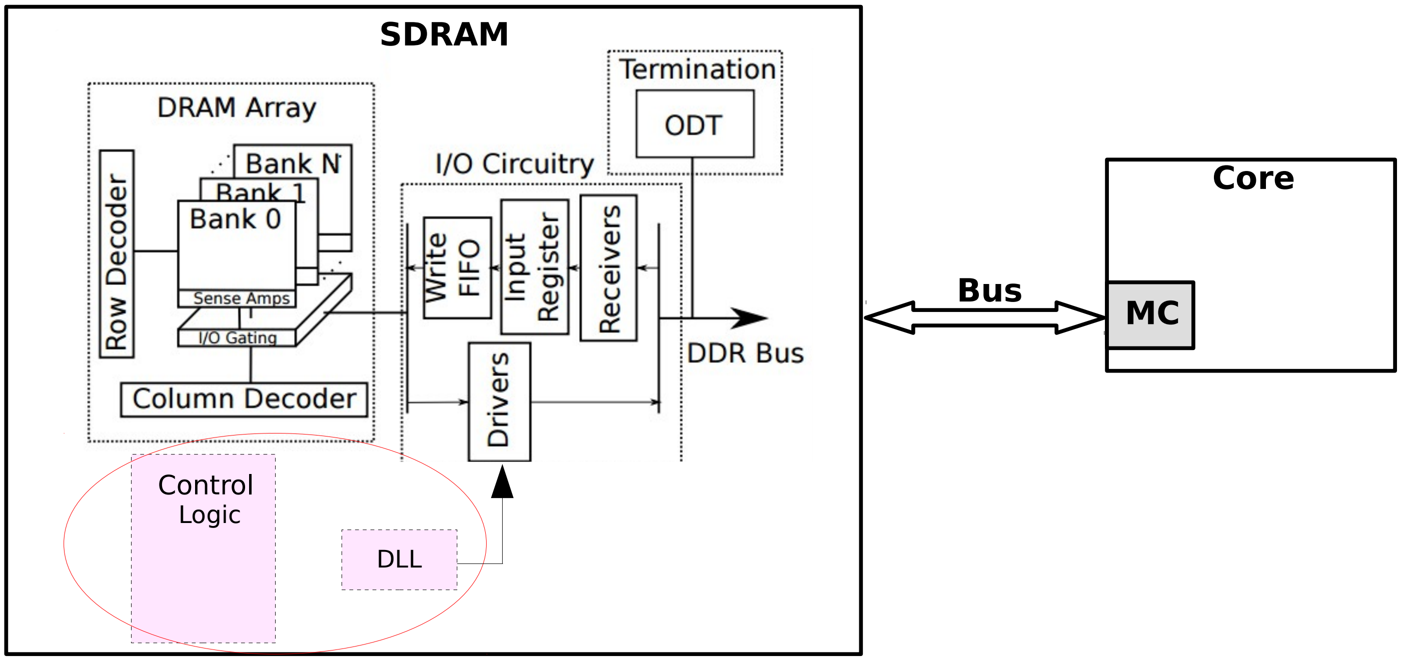

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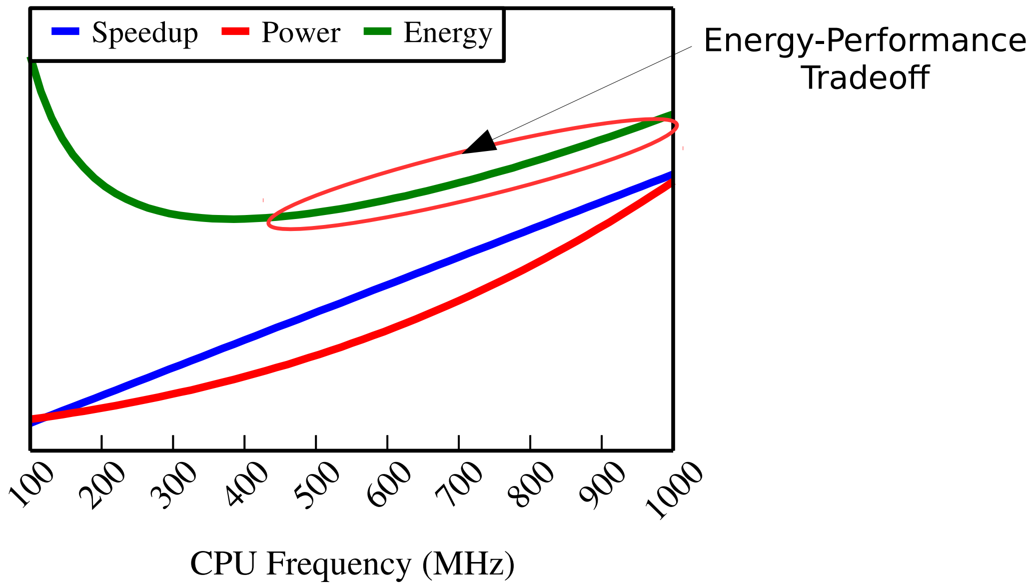

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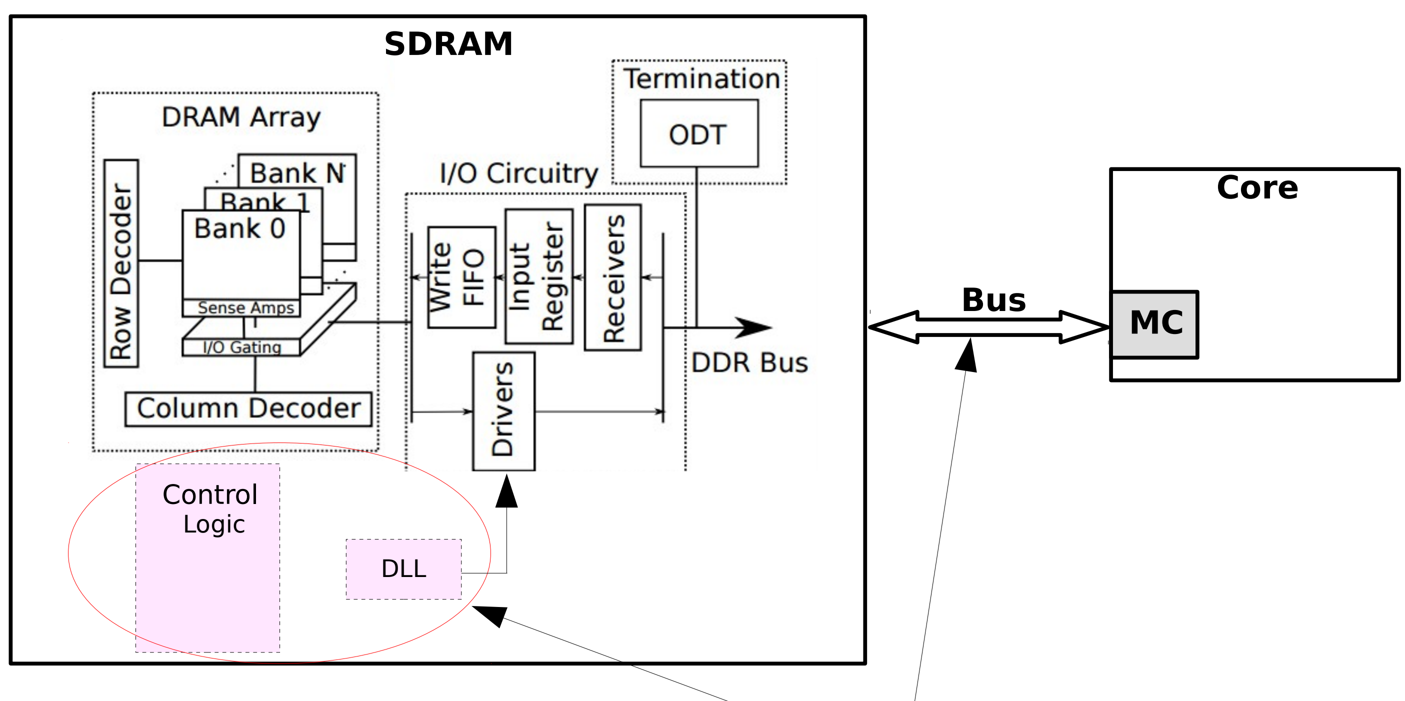

DRAM DFS

- Only Frequency Scaling
- Performance and power are proportional to DRAM frequency
- Increase in energy with DRAM frequency is due to scalable and non-scalable parts of DRAM

David, Howard, et al. international conference on Autonomic computing. ACM, 2011.

CPU DVFS and Memory DFS

- Managing Systems - a challenging task

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CPU DVFS and Memory DFS

- Managing Systems - a challenging task

- CPU intensive applications – higher CPU frequency
- Interplay of performance and energy of CPU and memory frequency scaling is complex

Performance vs. Energy Constraints

- Previous efforts explored DVFS under performance constraints

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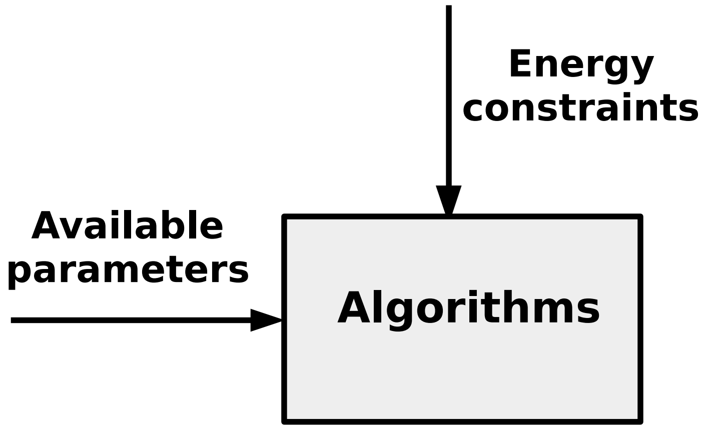
- Servers --- working under performance constraints is imperative
- Mobile systems –-- operating under energy constraints is fitting
- Absolute energy or rate of energy consumption as energy constraints --- application and device dependent
- Need for a new metric –-- ***Inefficiency***

Outline

- Inefficiency
- Inefficiency vs. Speedup
- Characteristics of Optimal Frequency Settings
- Performance Clusters and Stable Regions
- Conclusions and Future Work

Energy Management Algorithms



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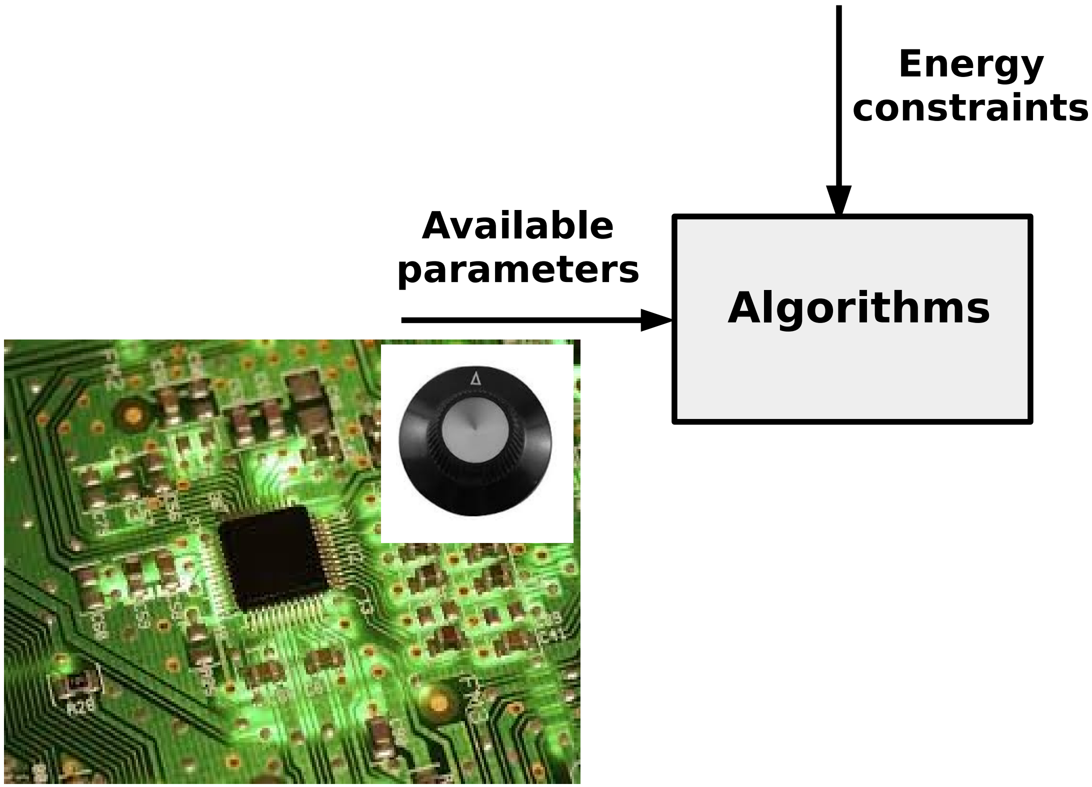

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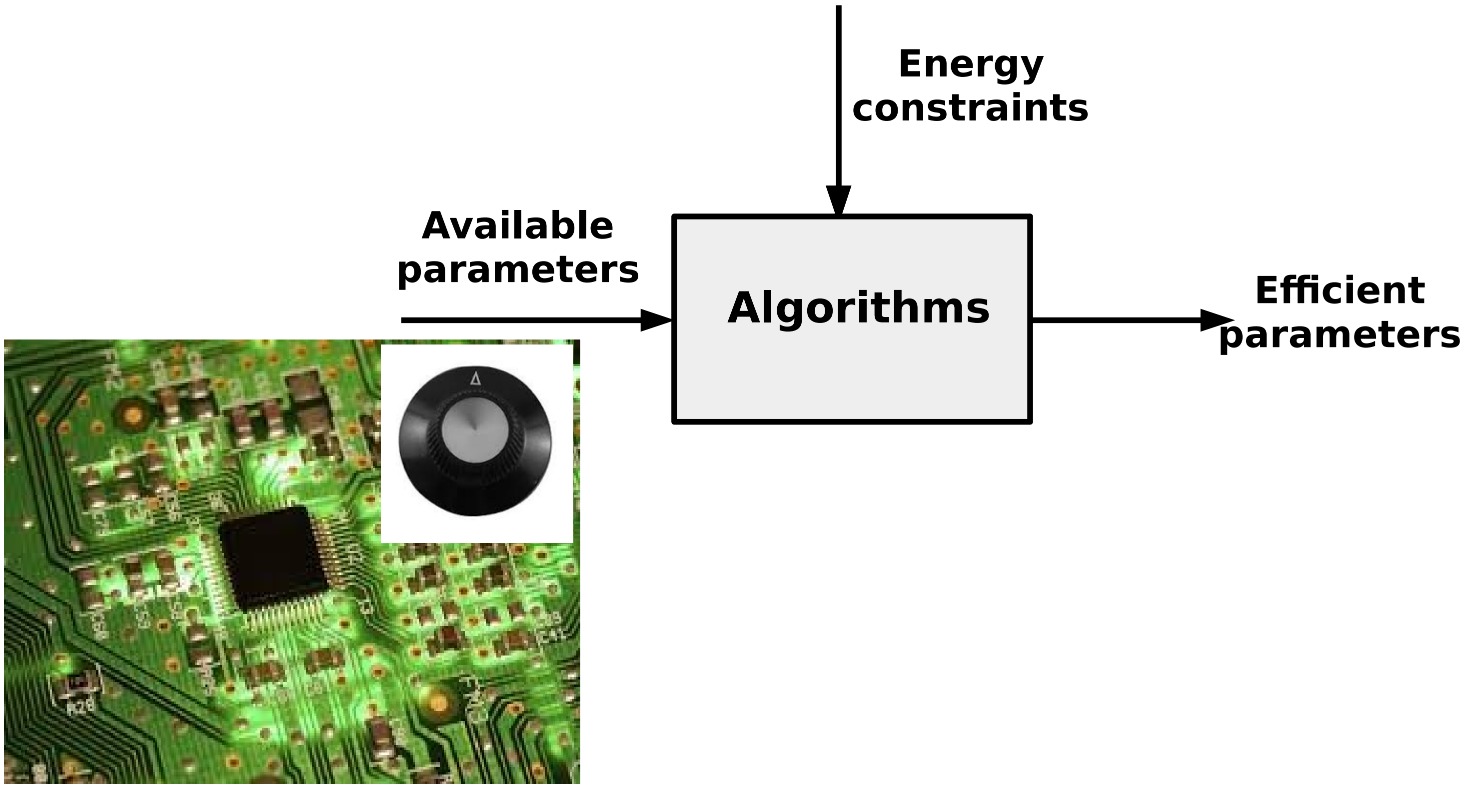


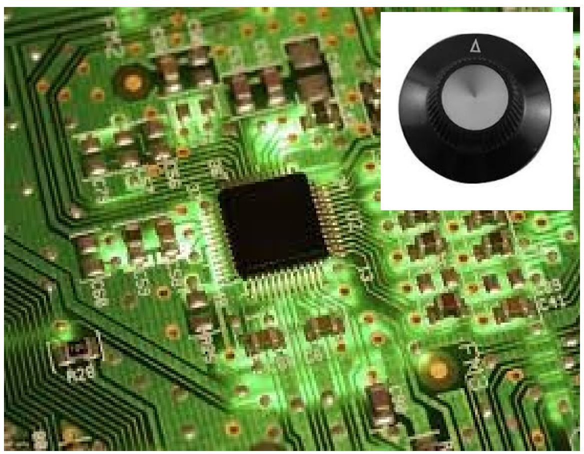
Energy Management Algorithms

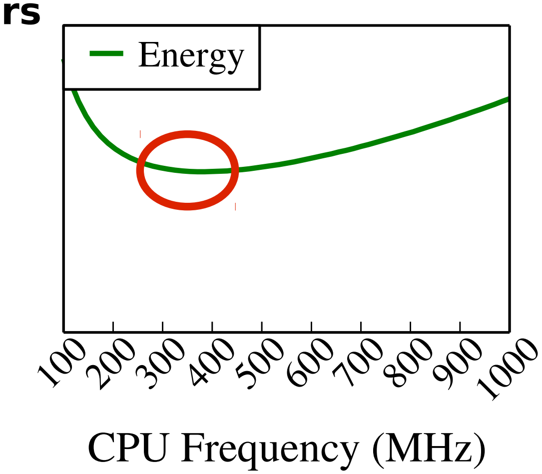
Energy constraints

Available parameters

Algorithms

Efficient parameters



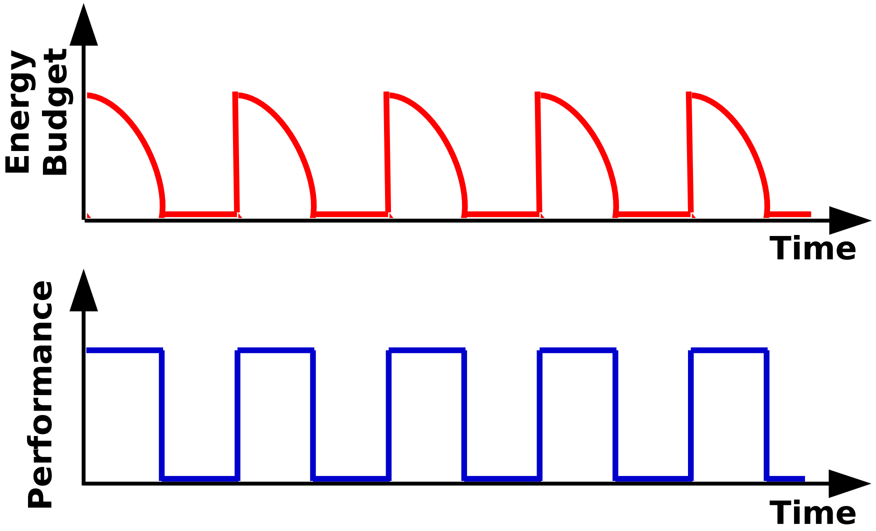


Energy Management Algorithms

- Rate limiting

Energy Efficient Algorithms

- Rate limiting
  - Impacts both performance and energy



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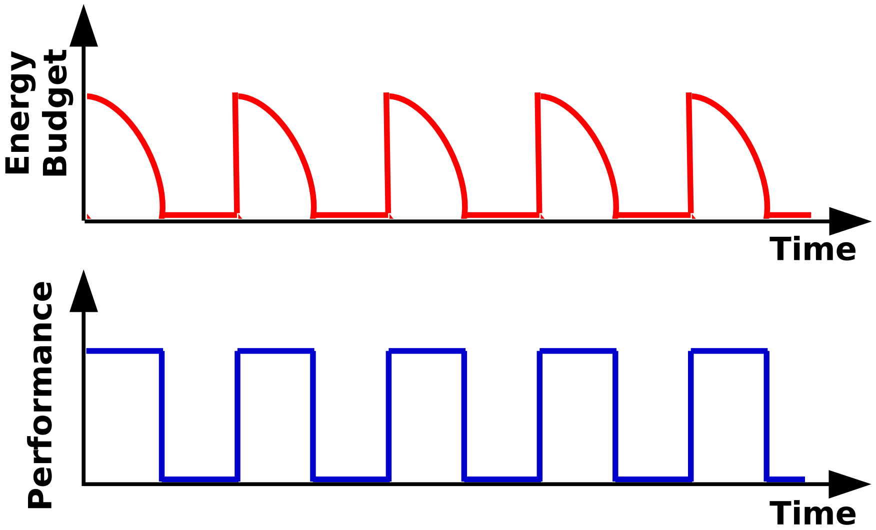

- Energy–Delay products – EDP, ED^{2}P etc.

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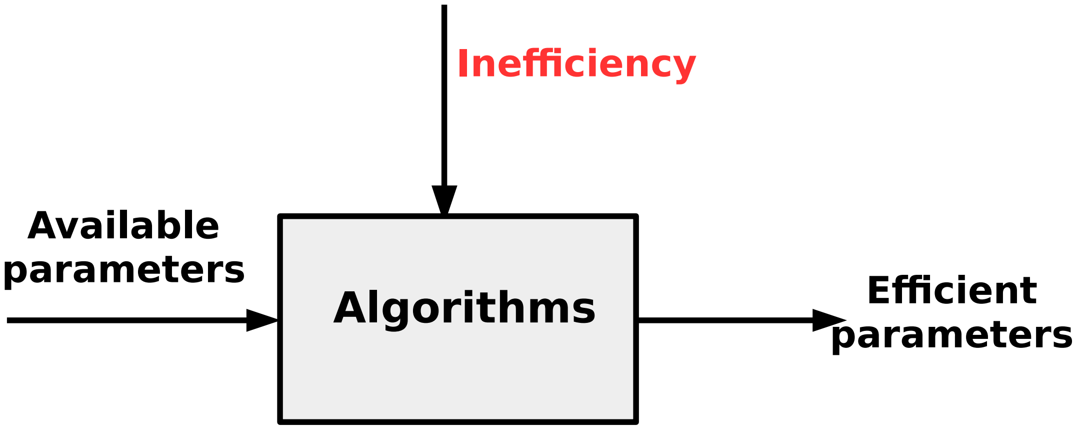

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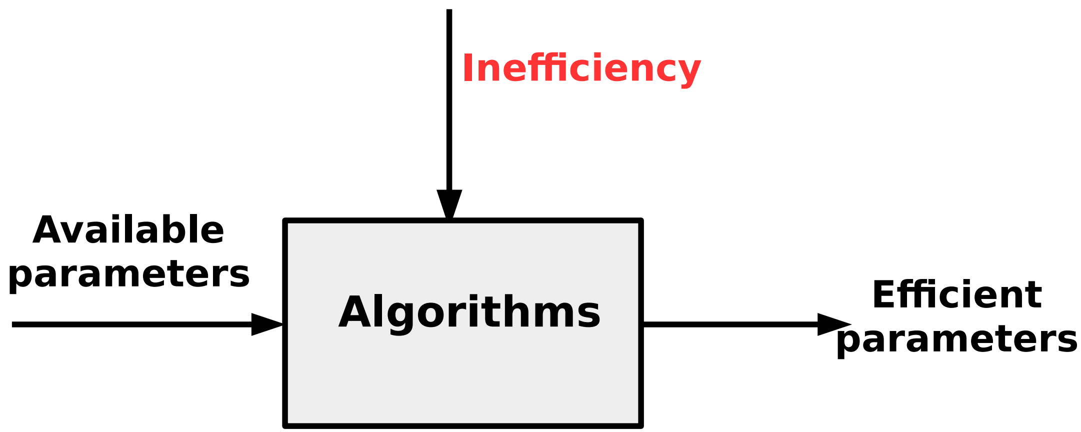

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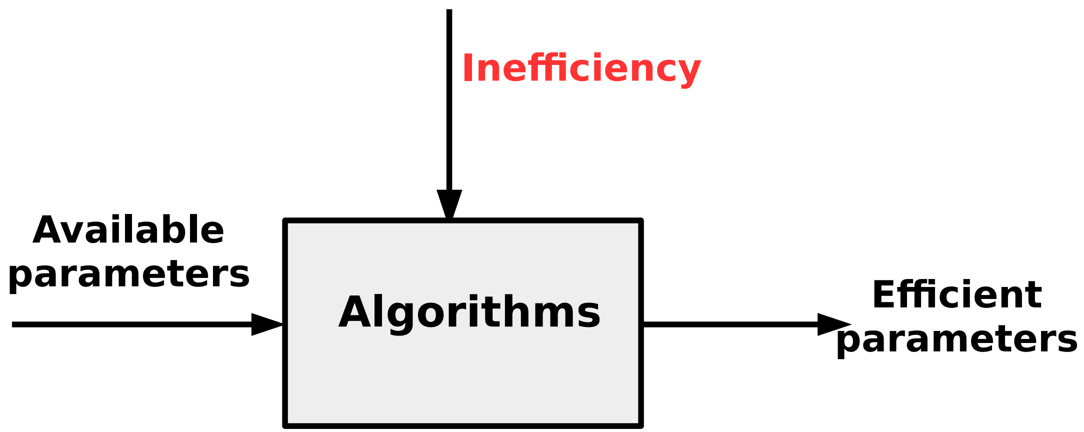

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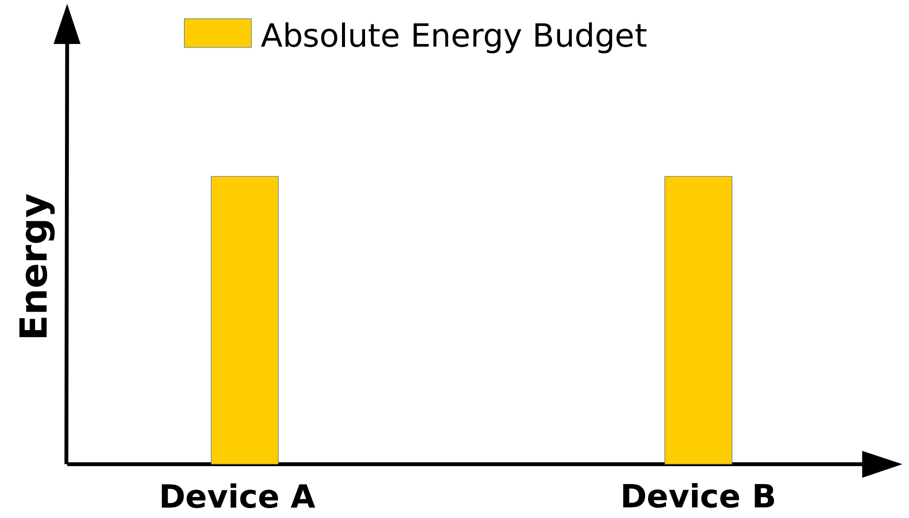
E_{min} – Minimum energy application could have consumed on the same device

E_{total} – Additional energy application can use to improve performance

Inefficiency as a System Resource

- Agnostic to Devices



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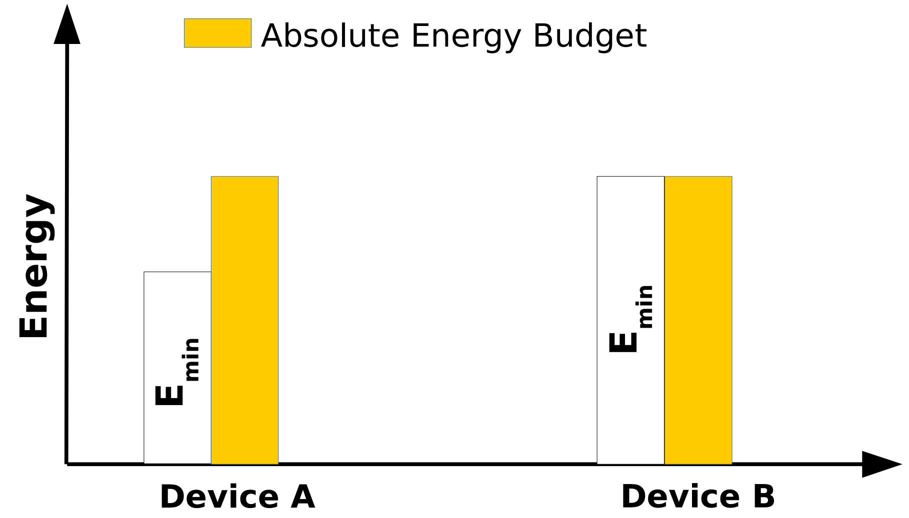

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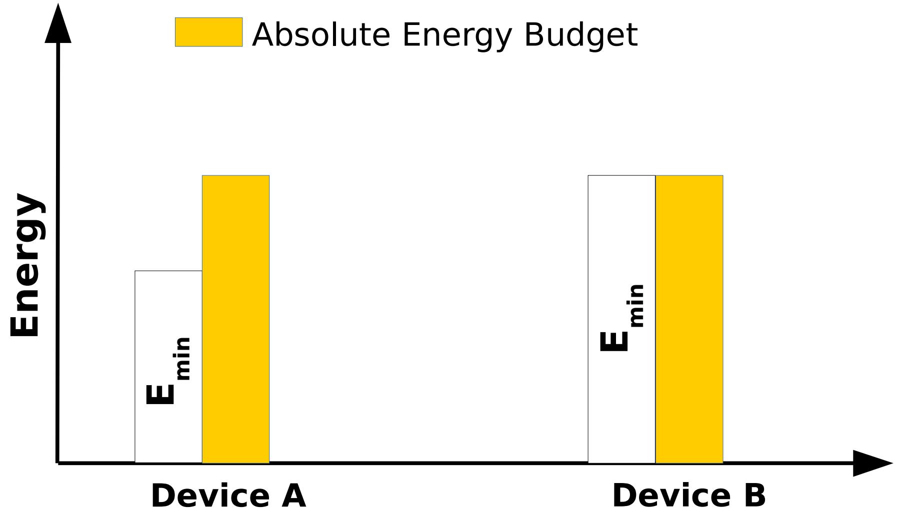

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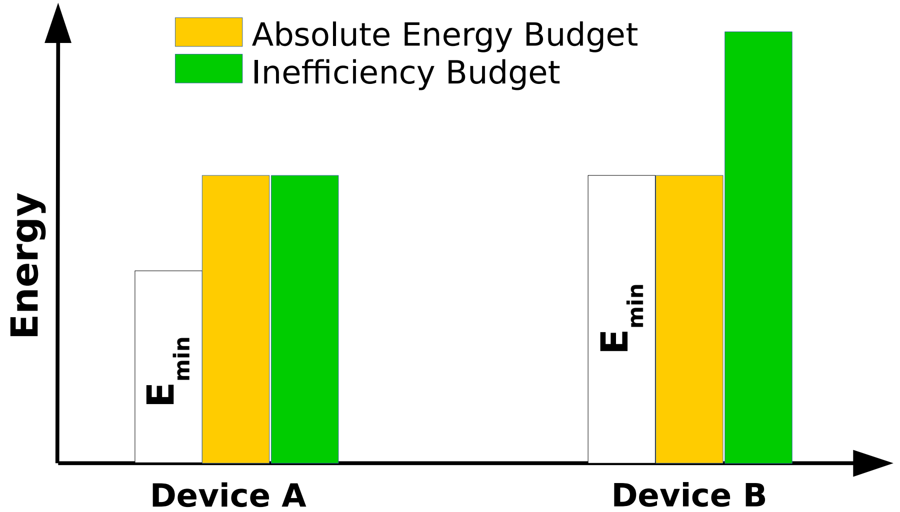

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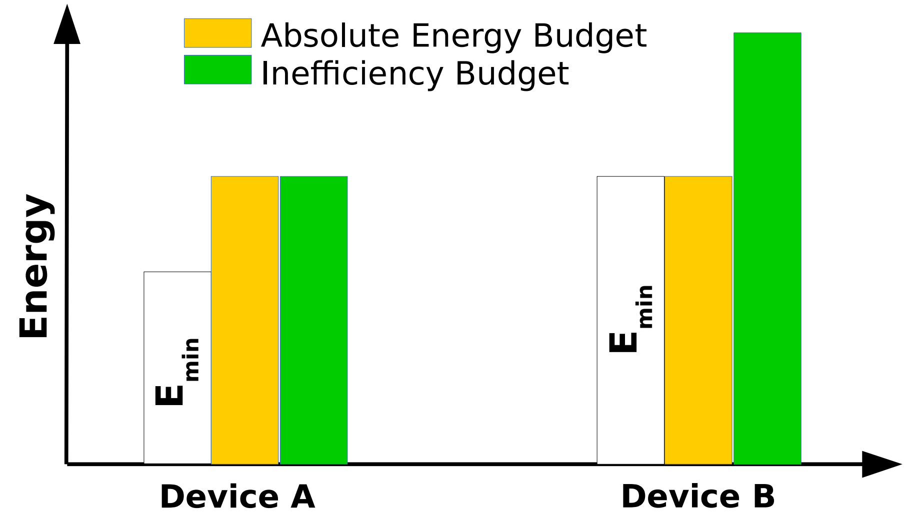

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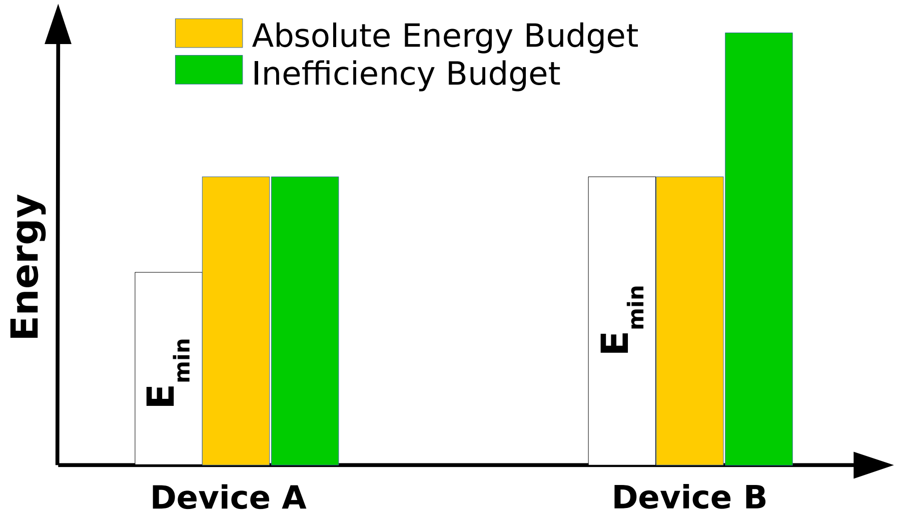

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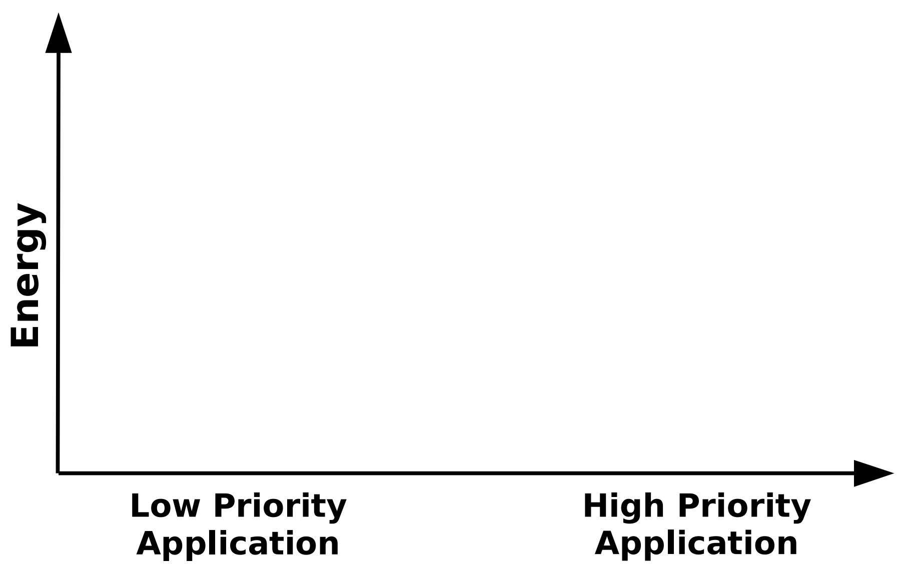

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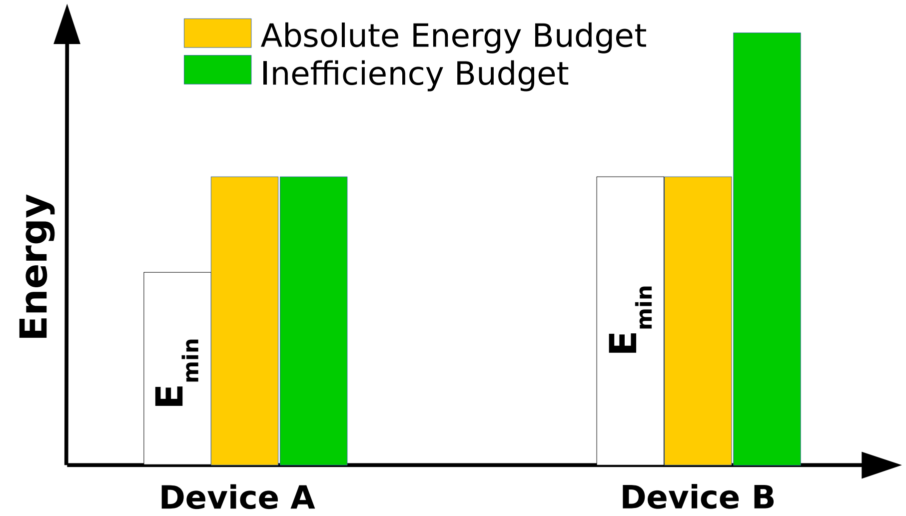

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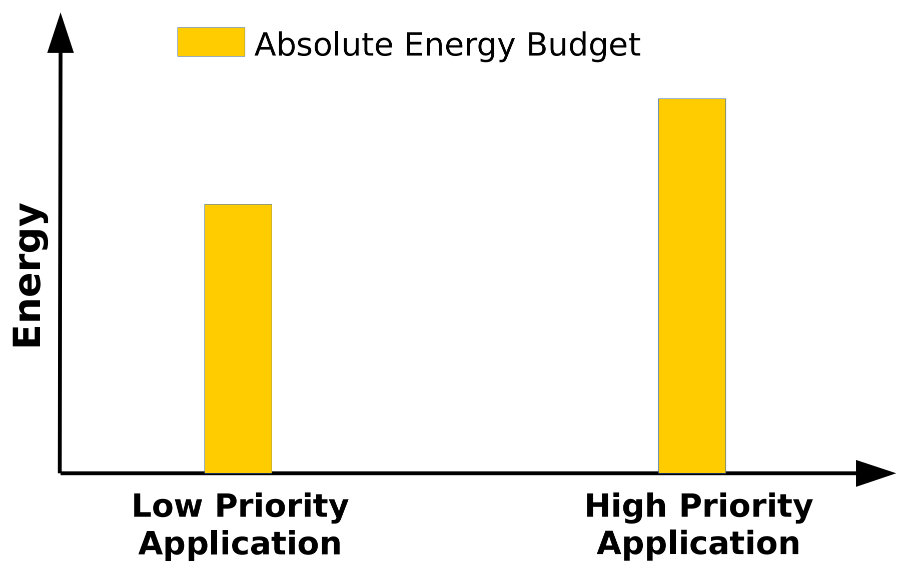

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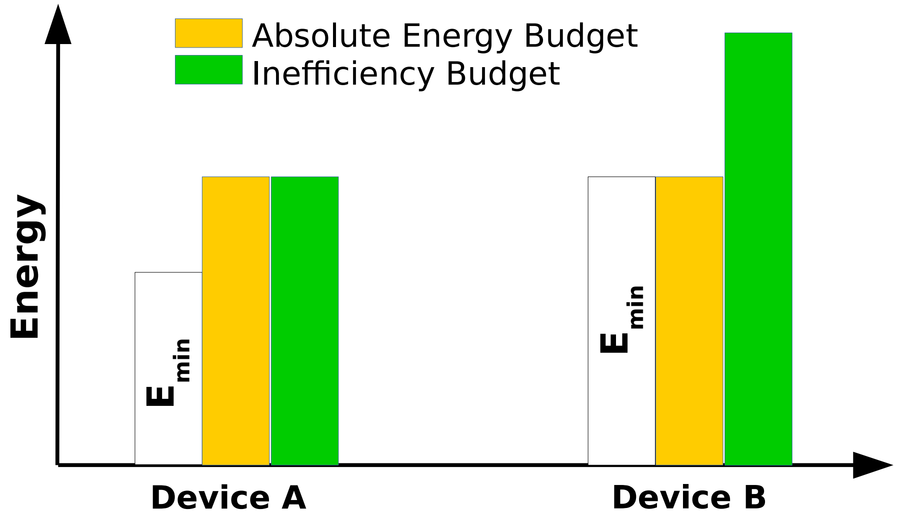

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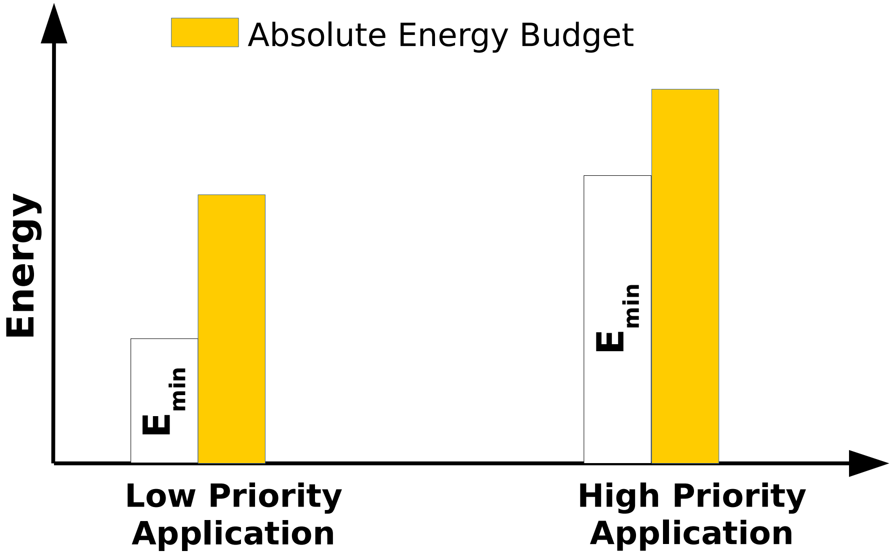

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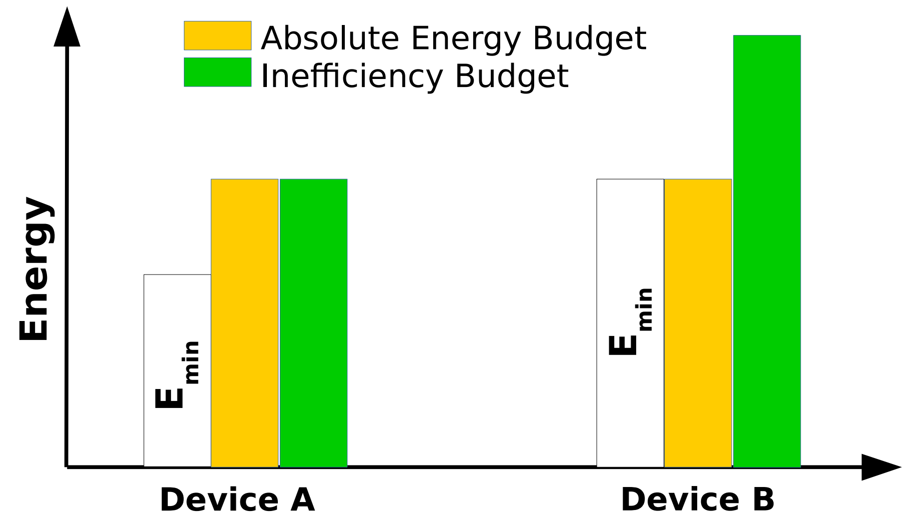

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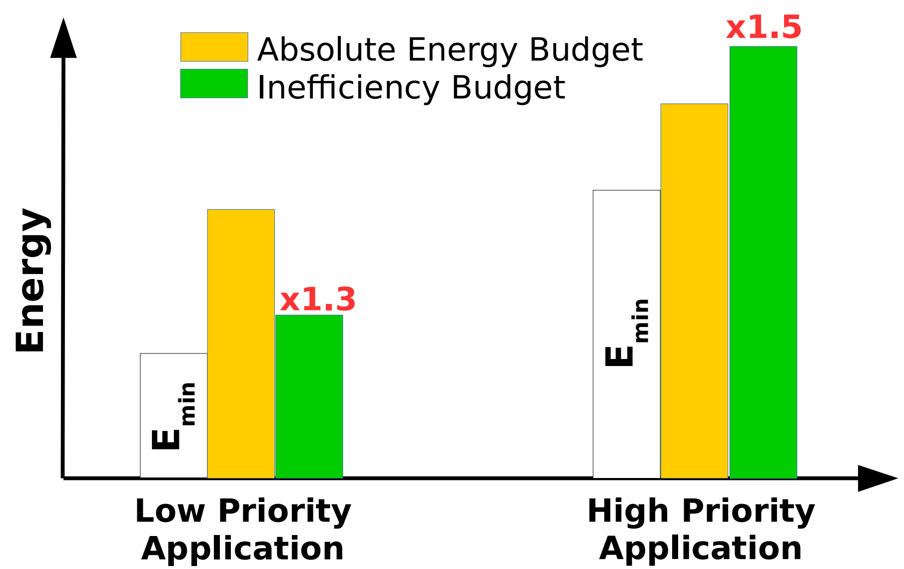

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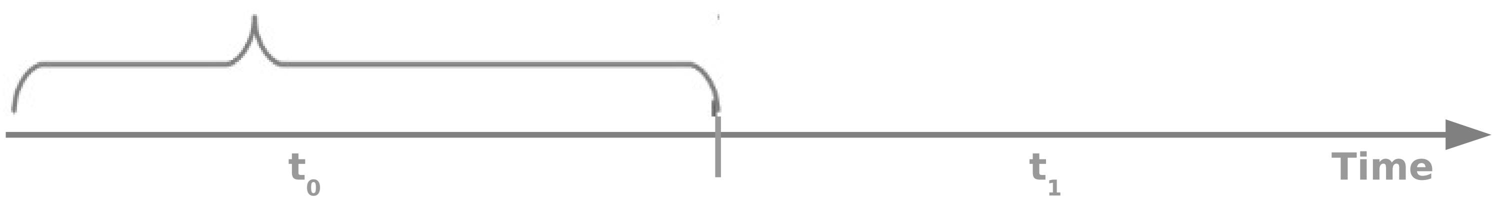

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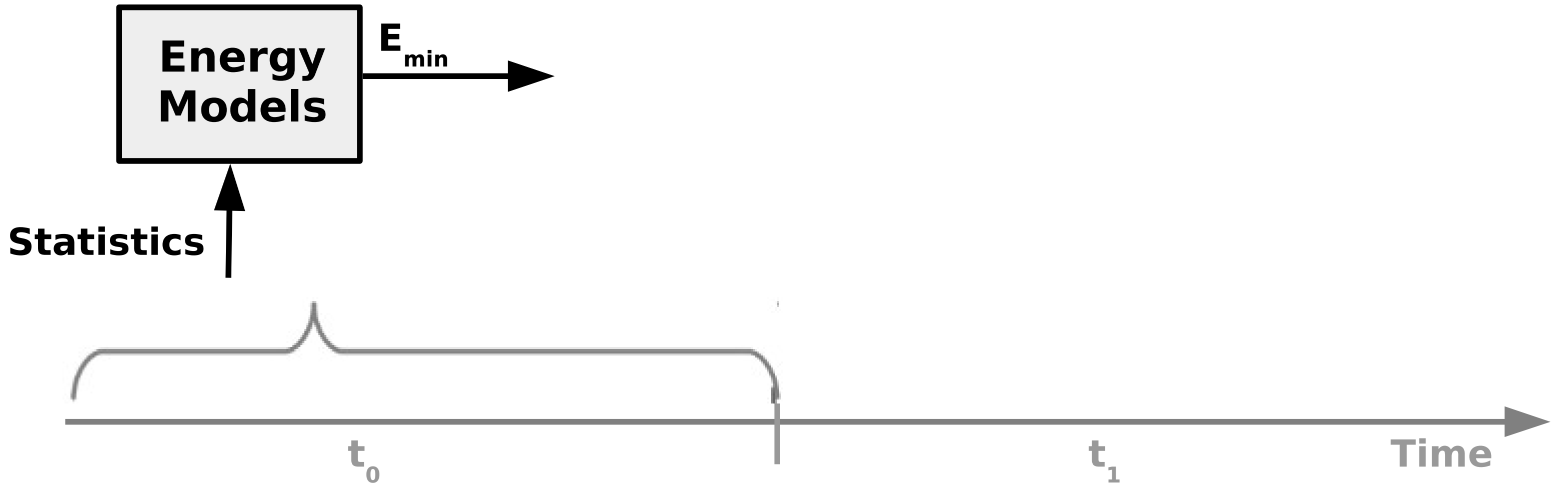

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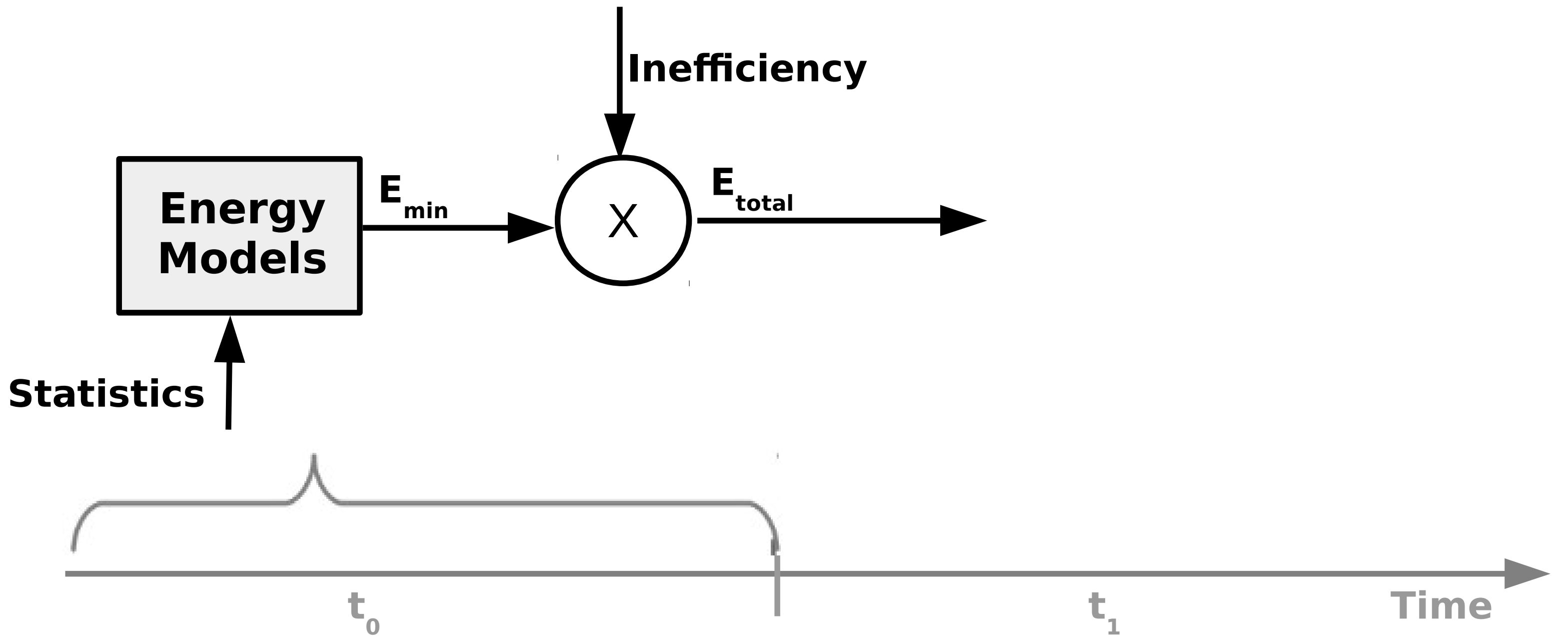

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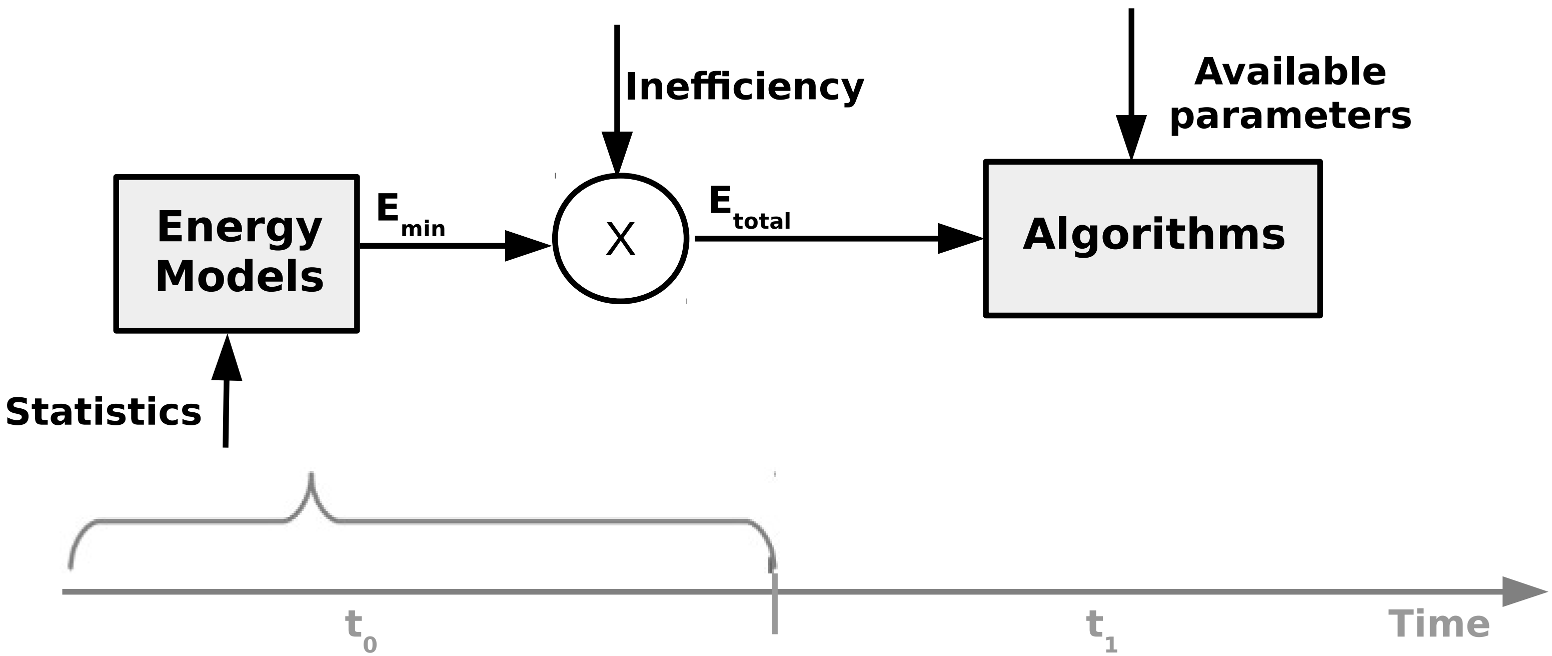

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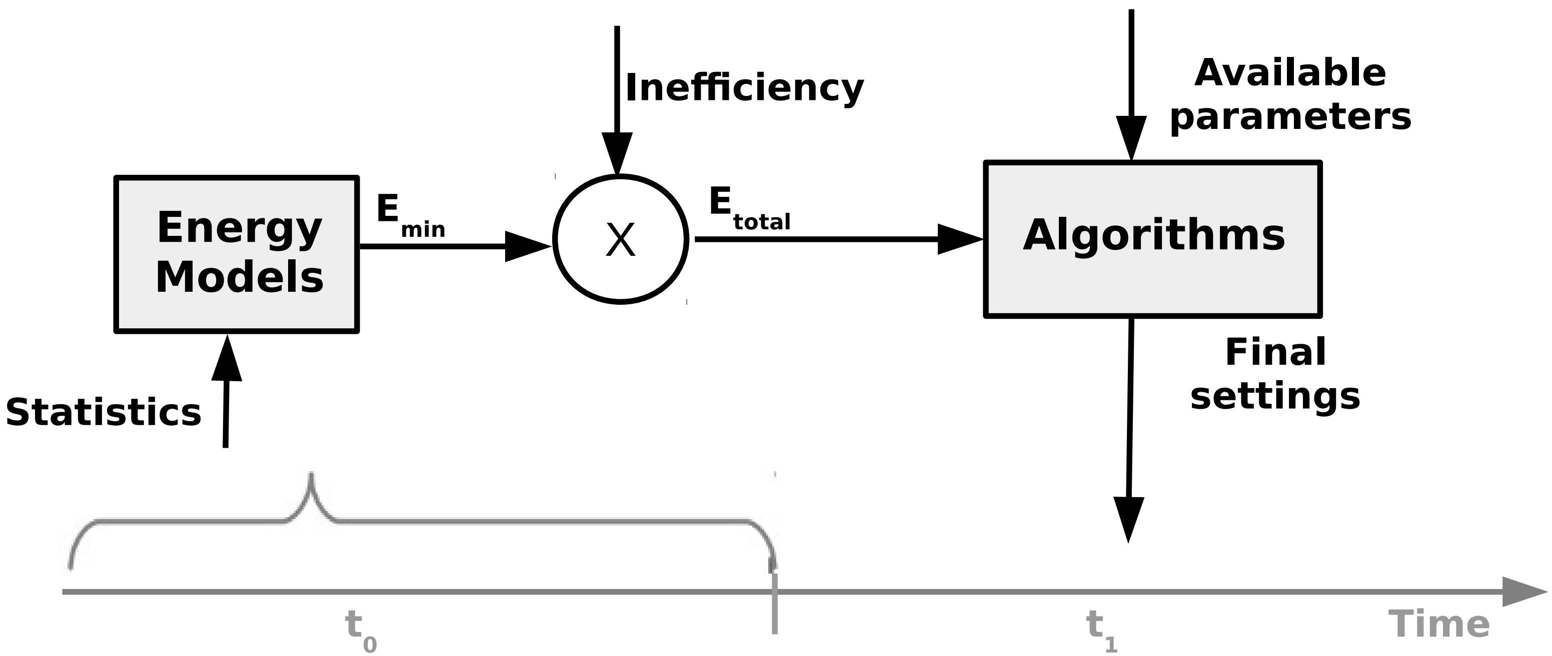

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- **Inefficiency vs. Speedup**
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Inefficiency vs. Speedup

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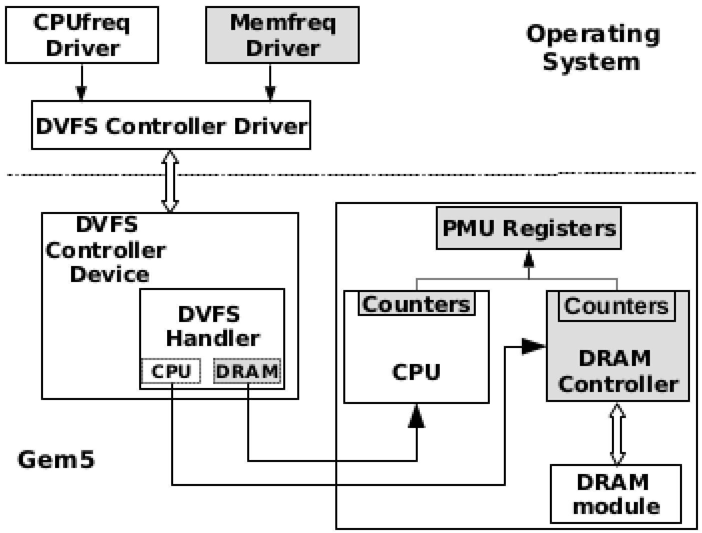
- Methodology
  - Gem5
  - DVFS controller driver



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  - CPU : 100 – 1000 MHz,

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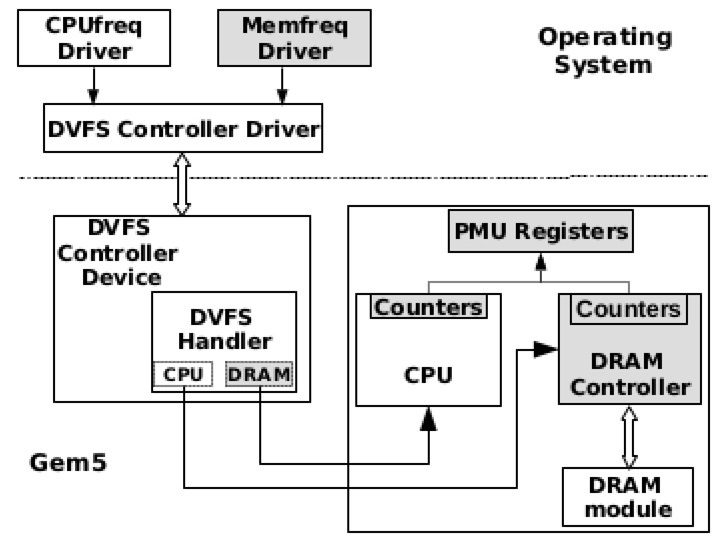

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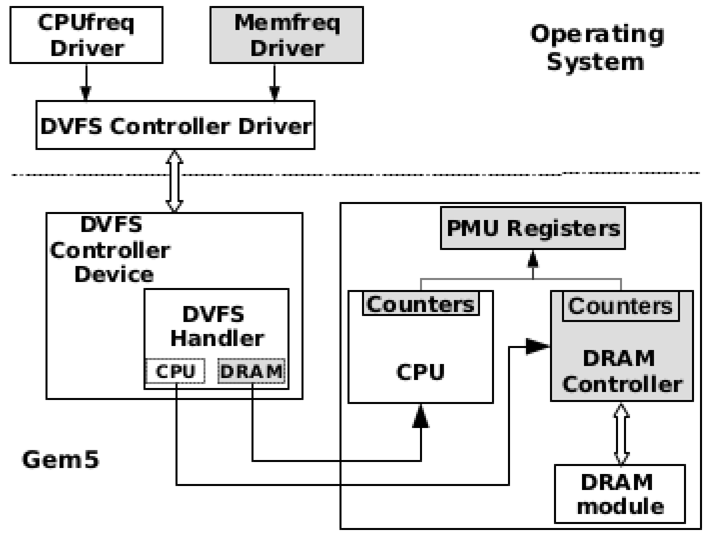
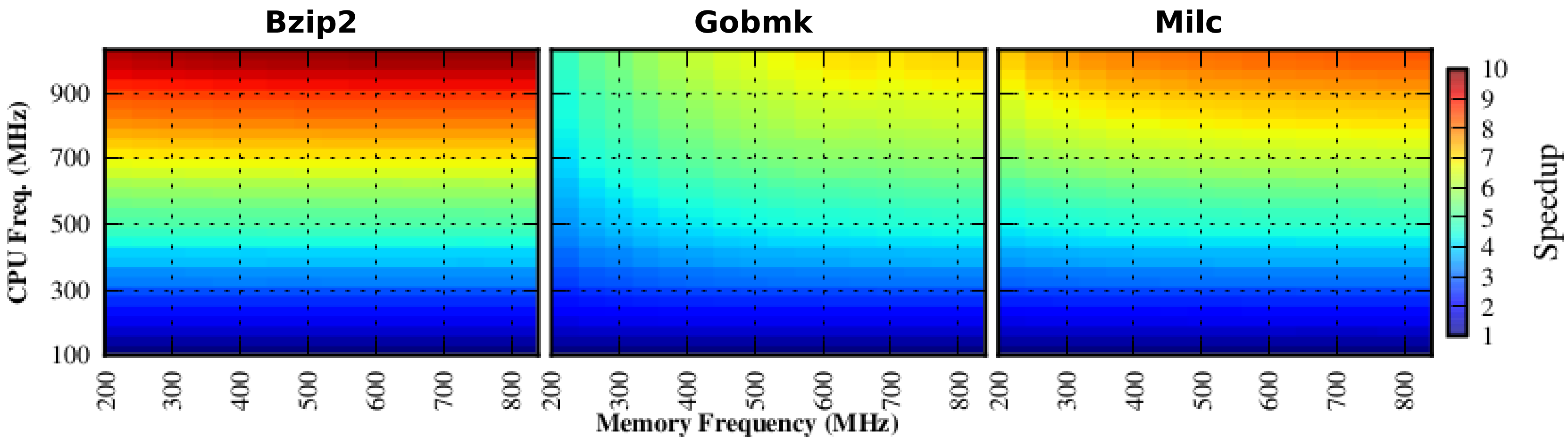


- Energy Models
  - Cortex – A9, Pandaboard
  - Micron power model --- extended to incorporate frequency scaling

Inefficiency vs. Speedup



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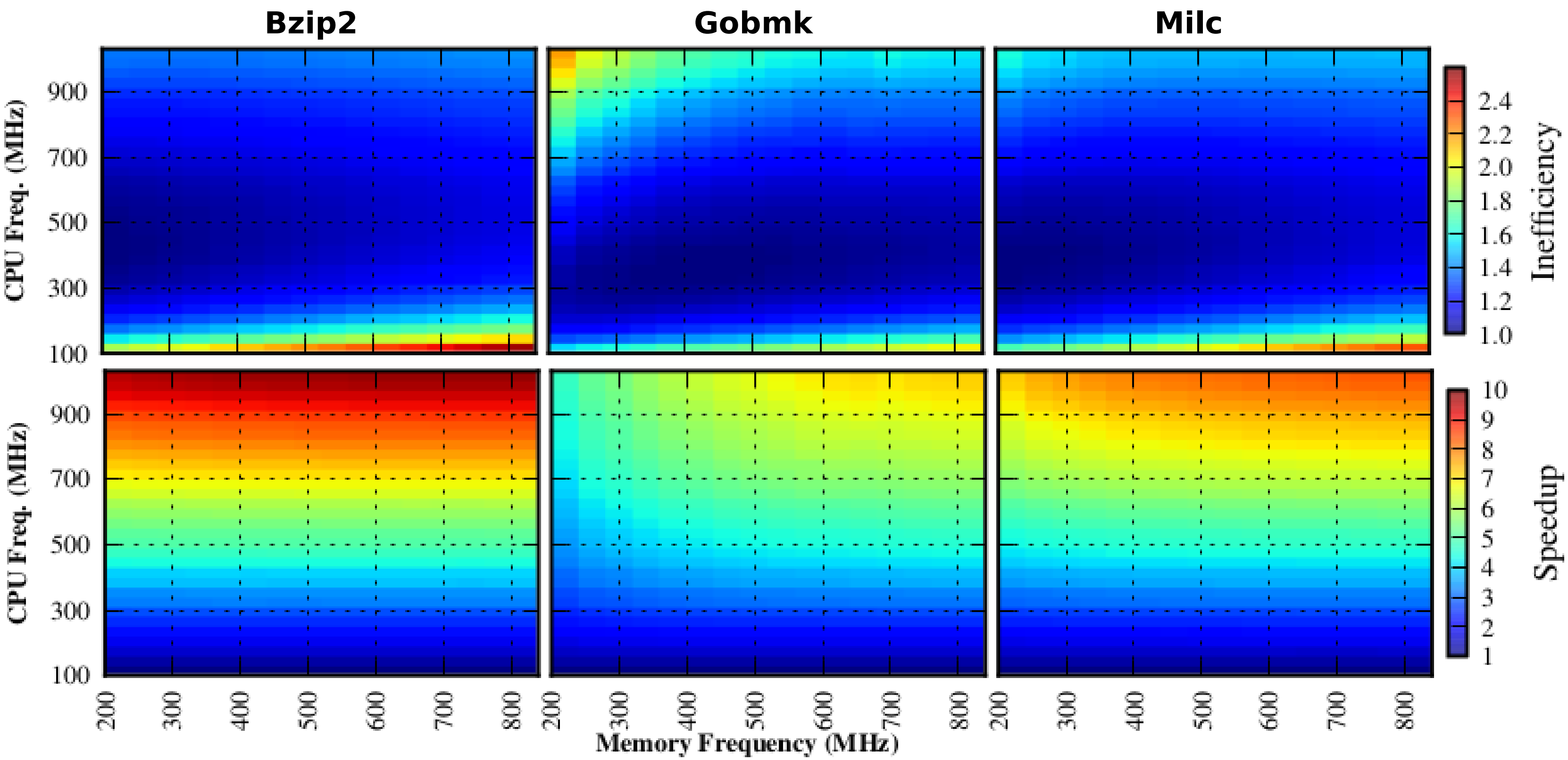

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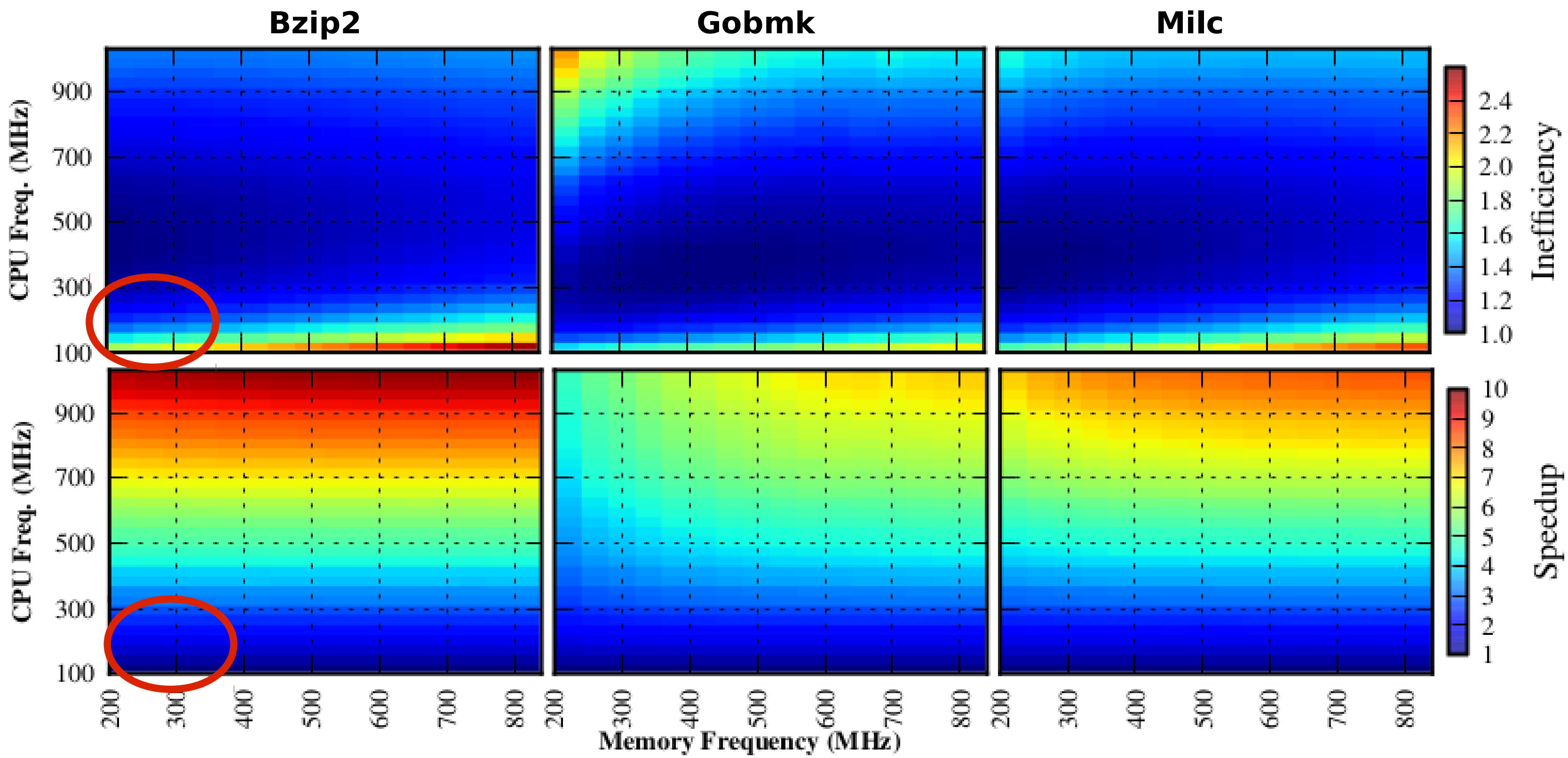

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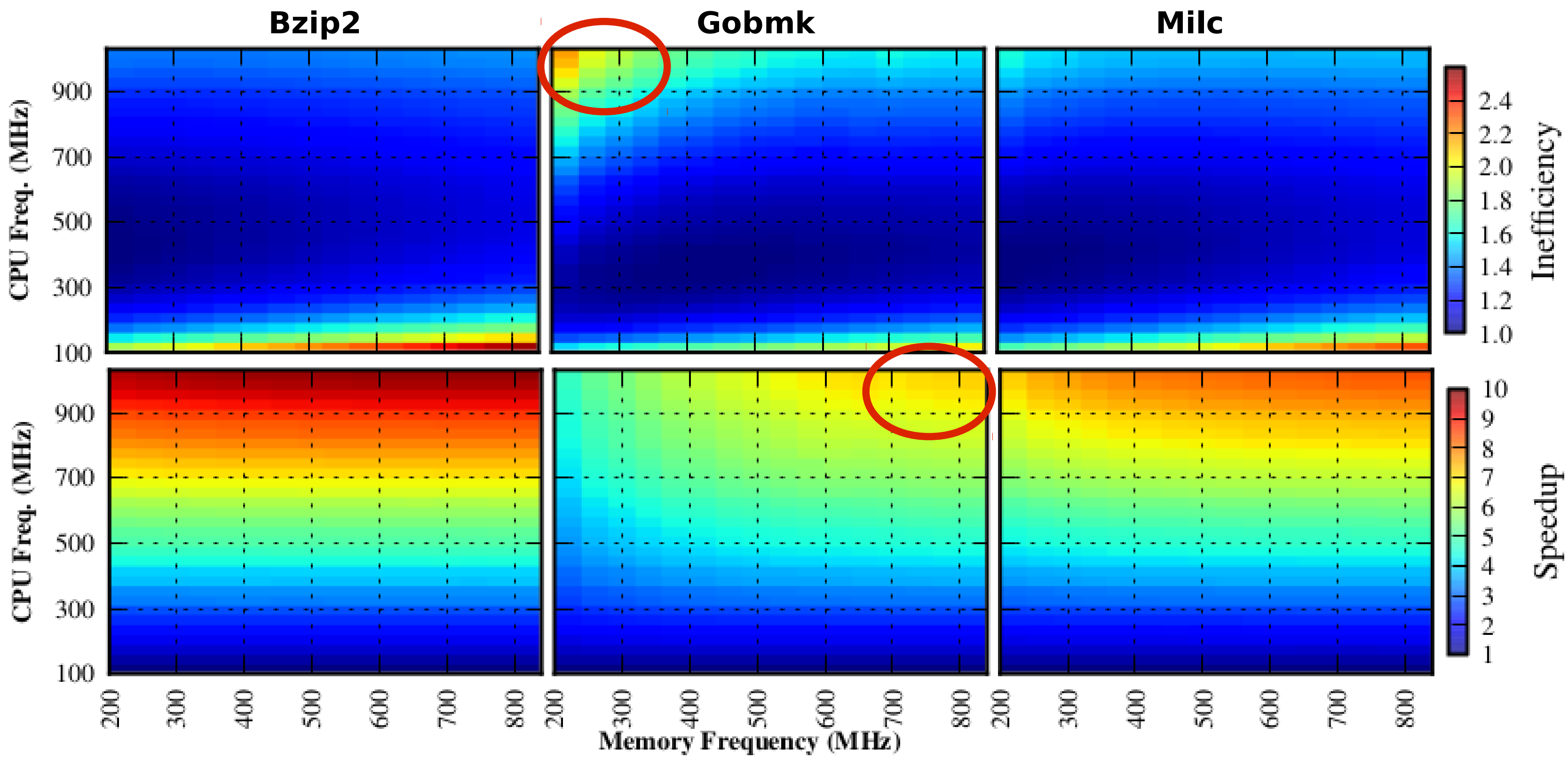

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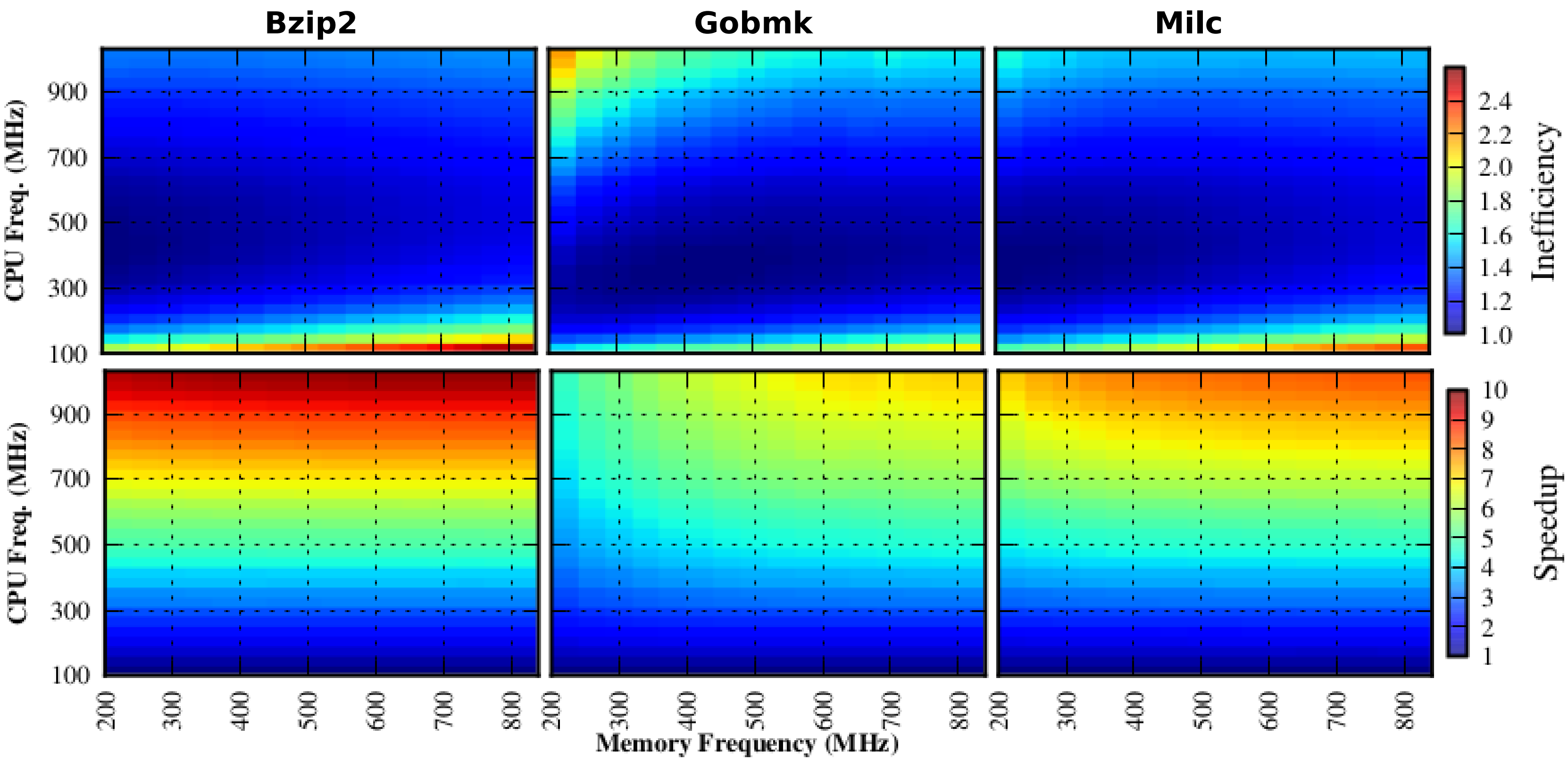

- Running slower doesn't mean system is running efficiently
- Higher inefficiency doesn't always result in higher performance
- Smart algorithms should search for optimal frequency settings ***under*** the inefficiency constraint and ***not*** just ***at*** the inefficiency constraint

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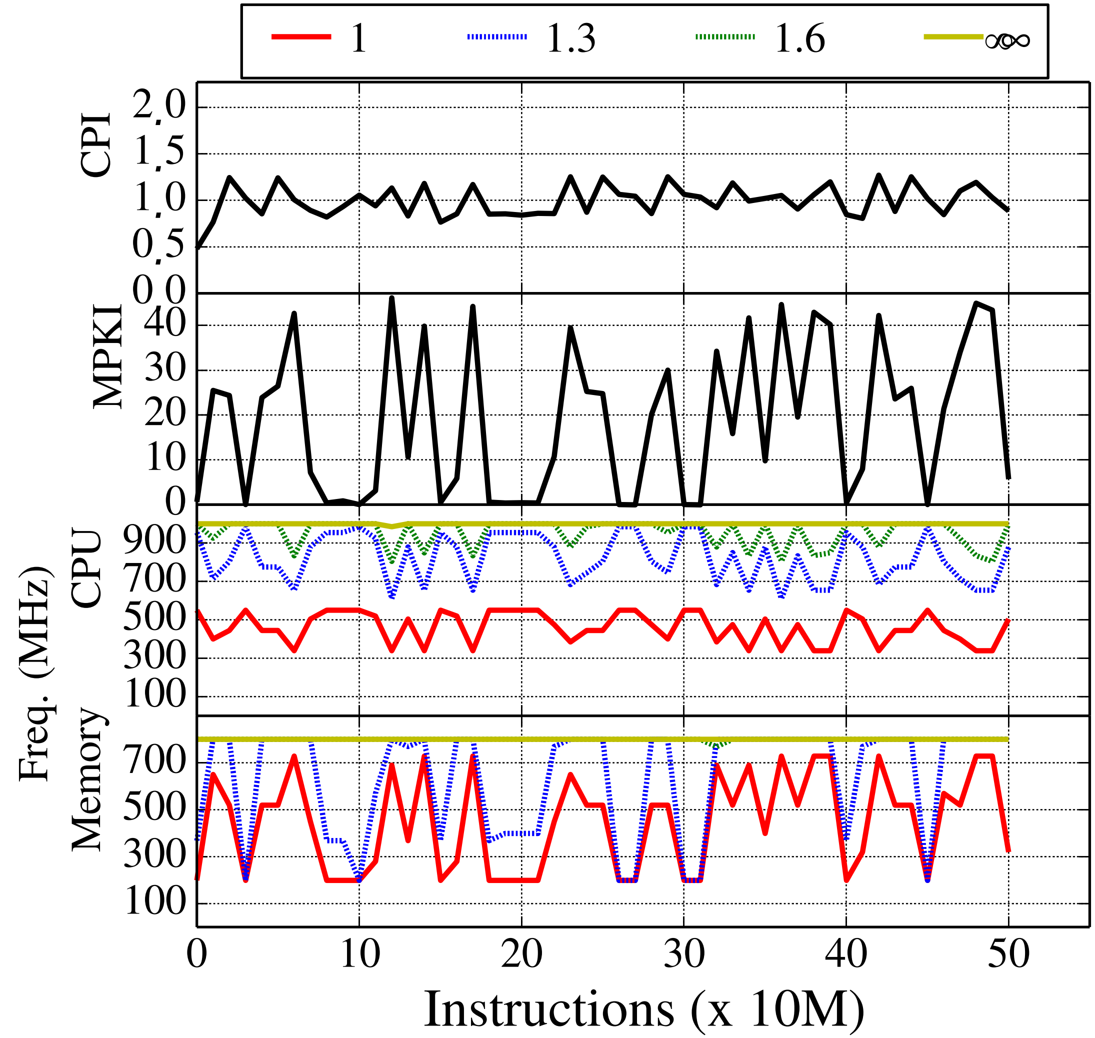

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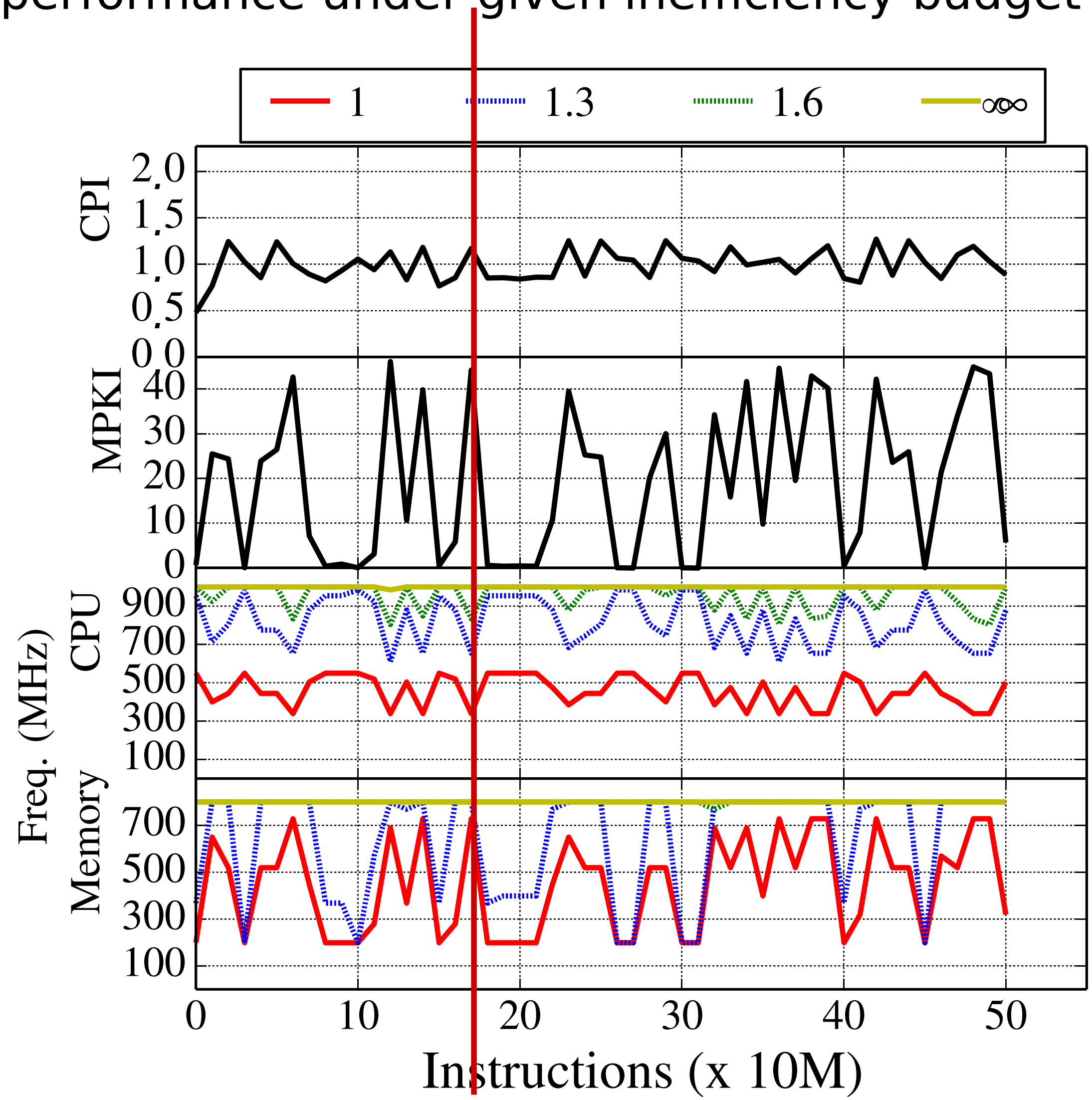

- Higher CPI results in higher memory frequency and lower CPU frequency

Optimal Frequency Settings

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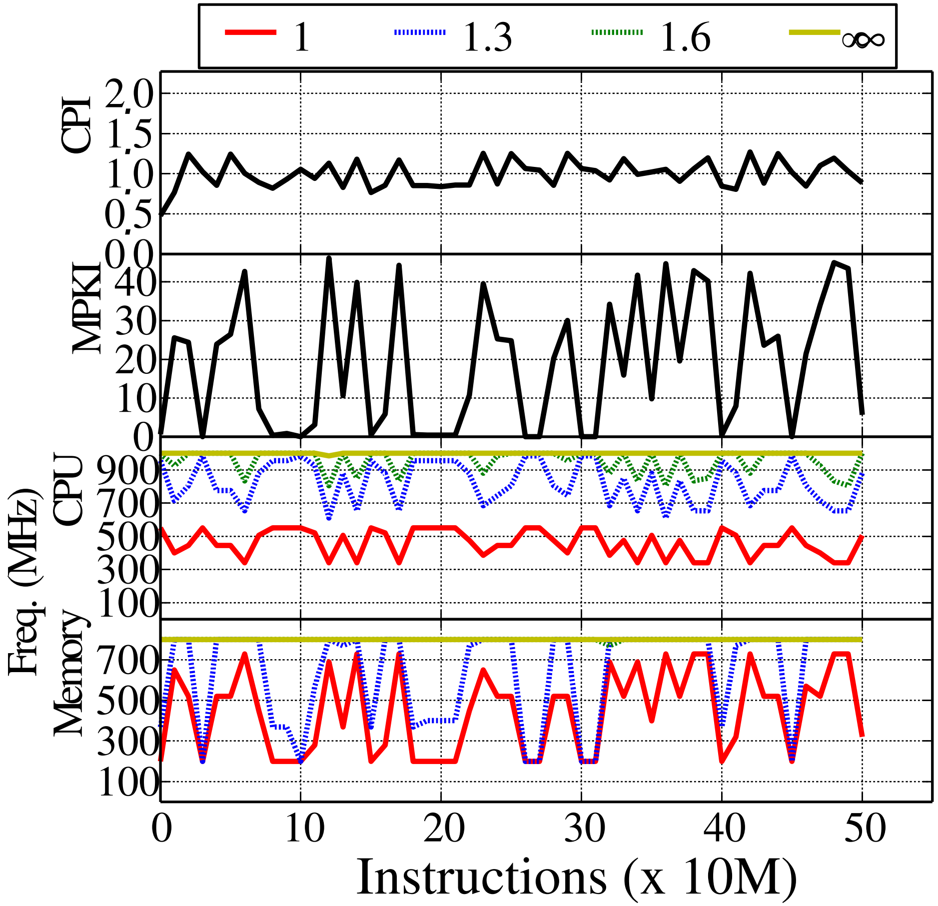

- It is expensive
- Limited energy performance trade-off options

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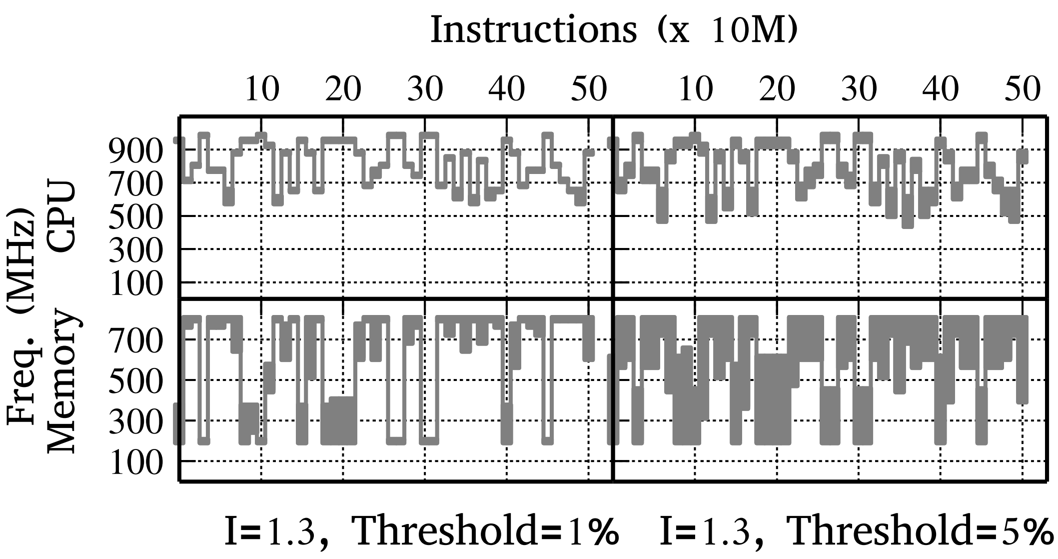

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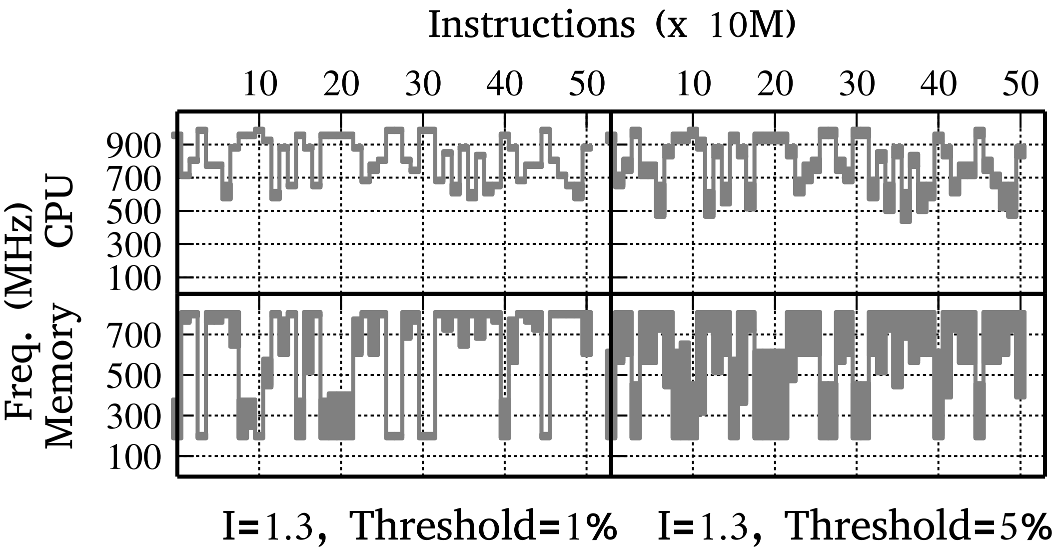

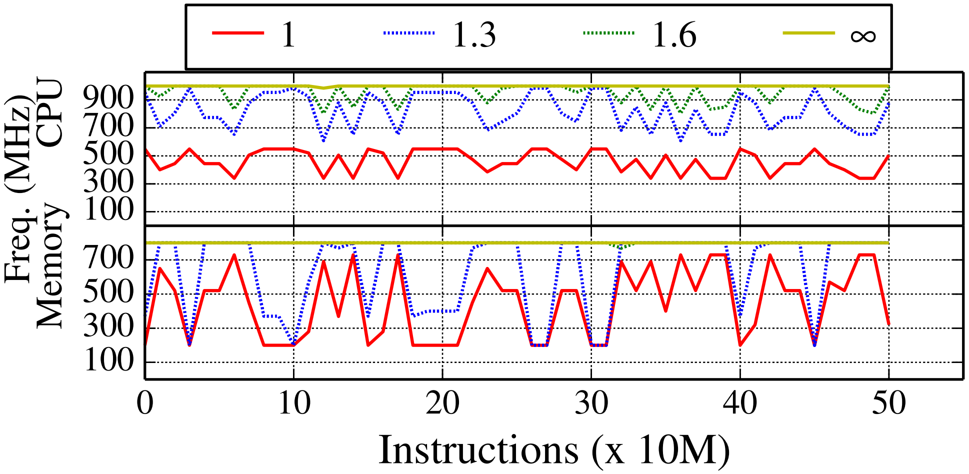

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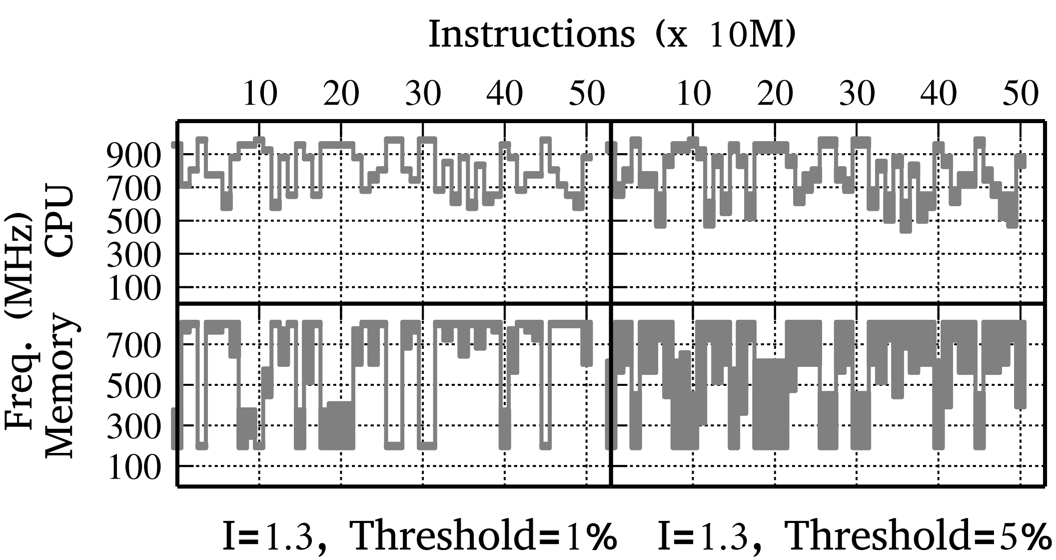

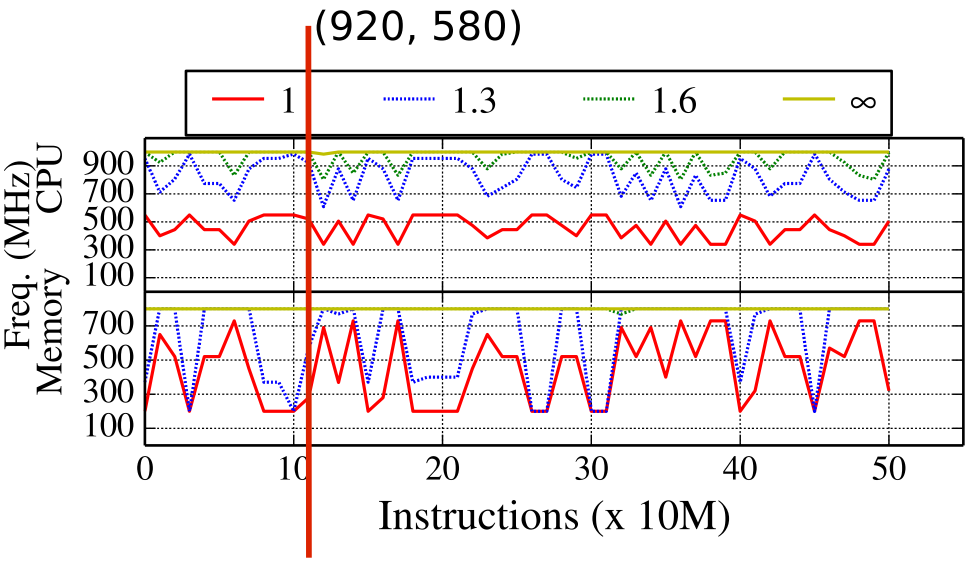

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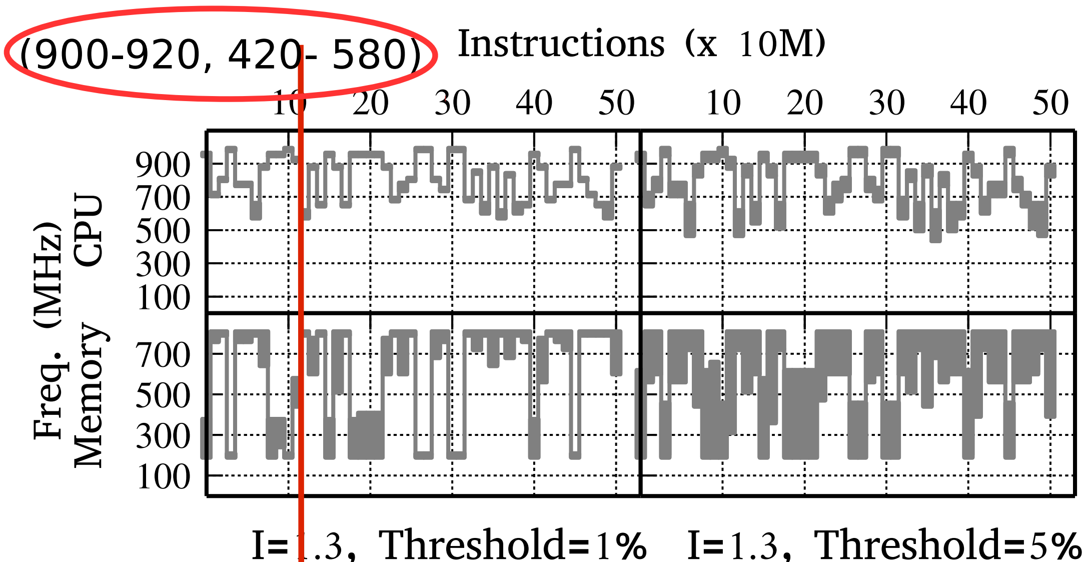

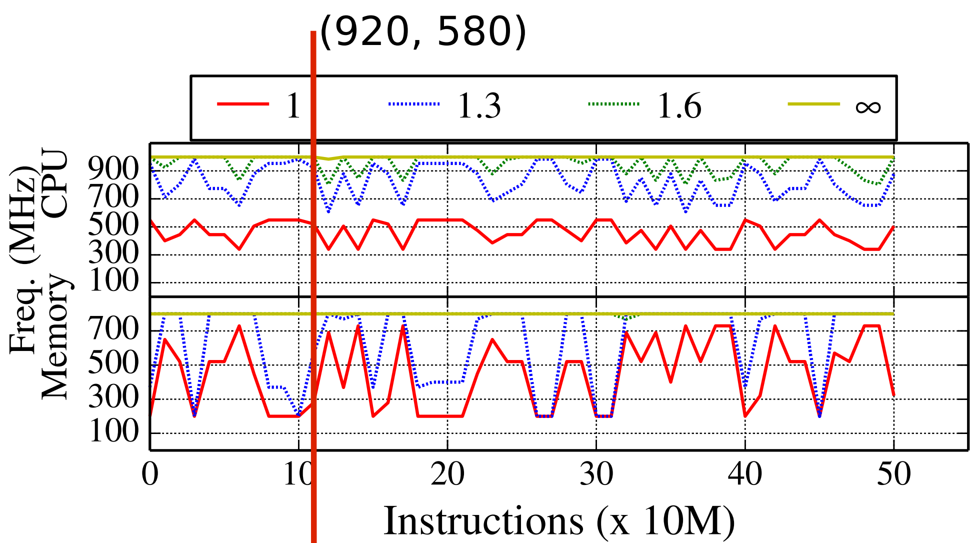

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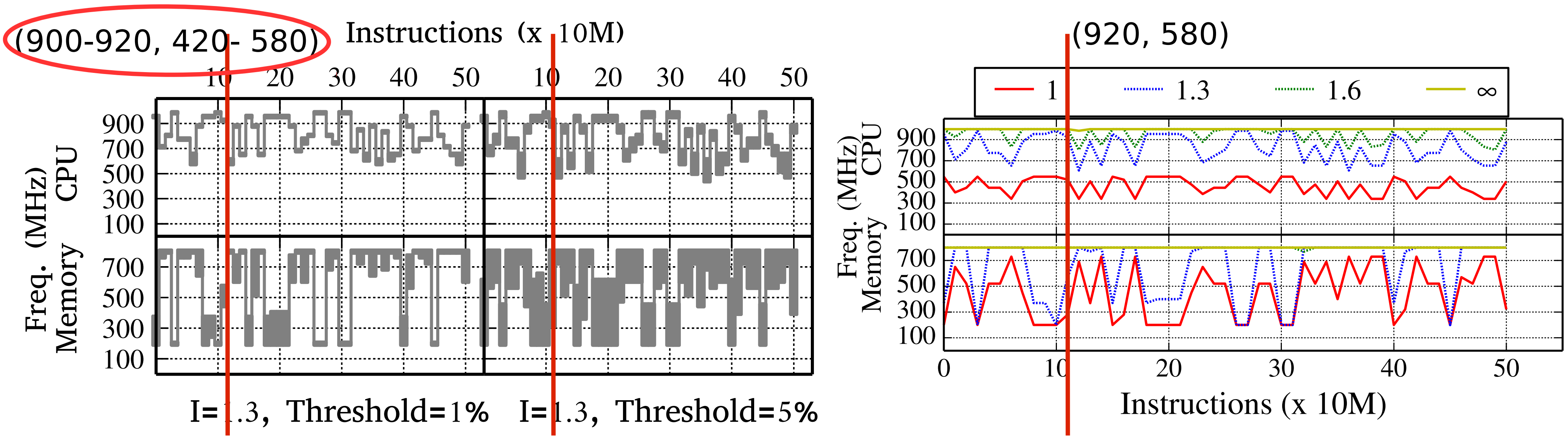

- Higher cluster thresholds result in higher range of available settings

Stable Regions

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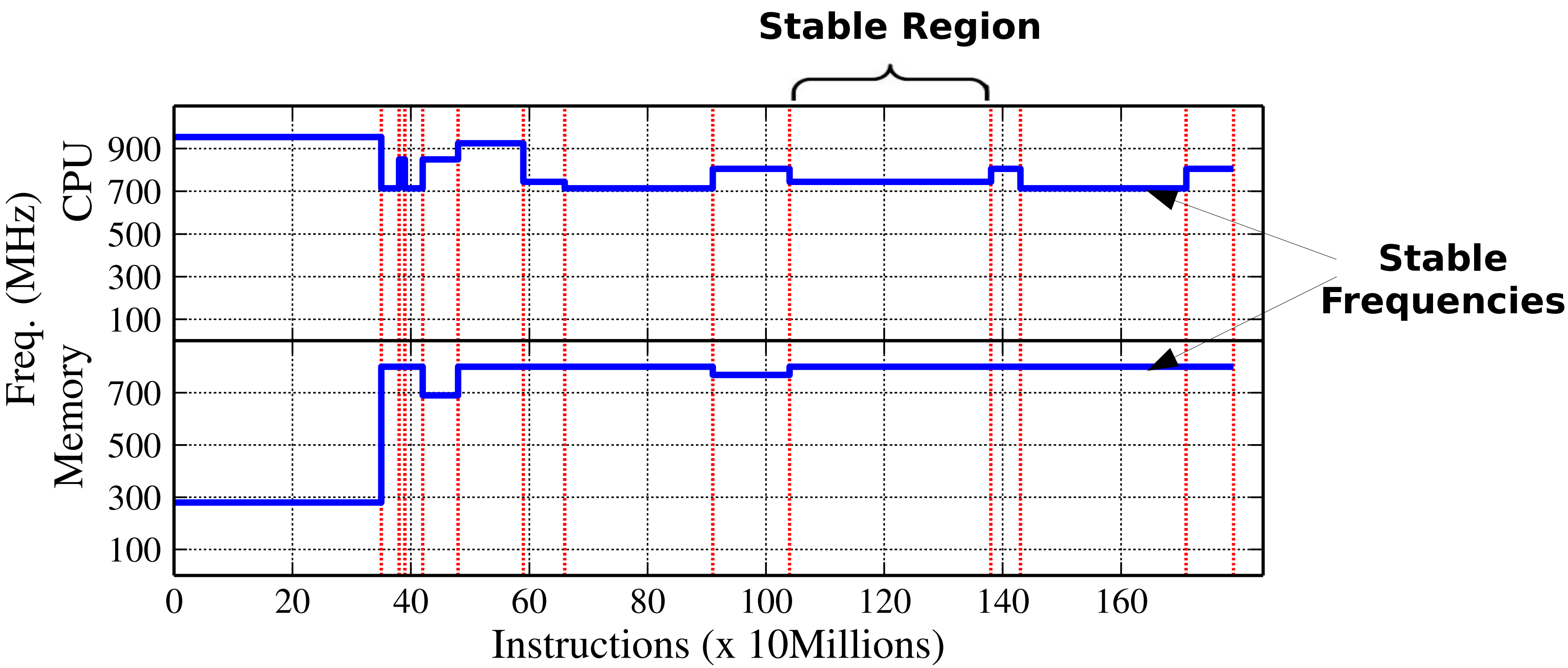

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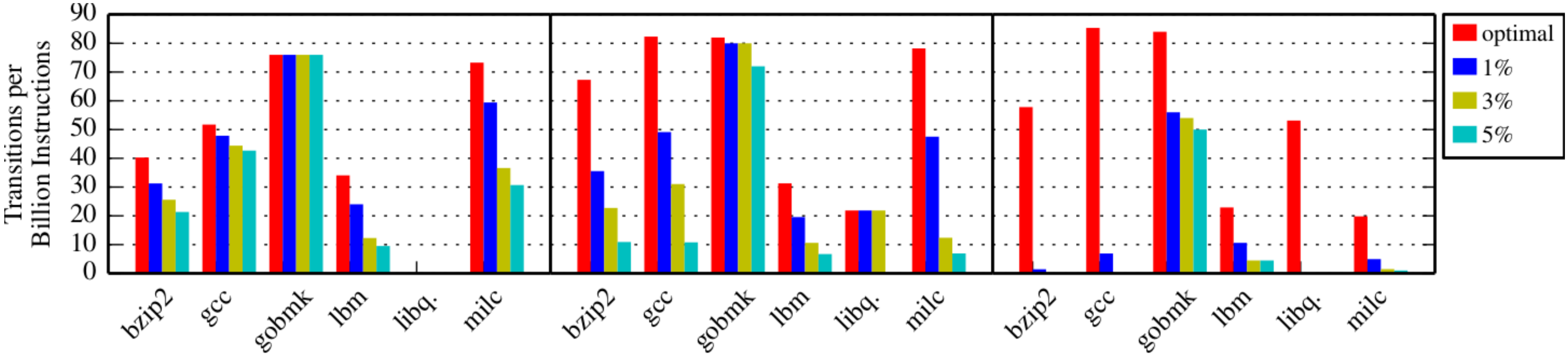

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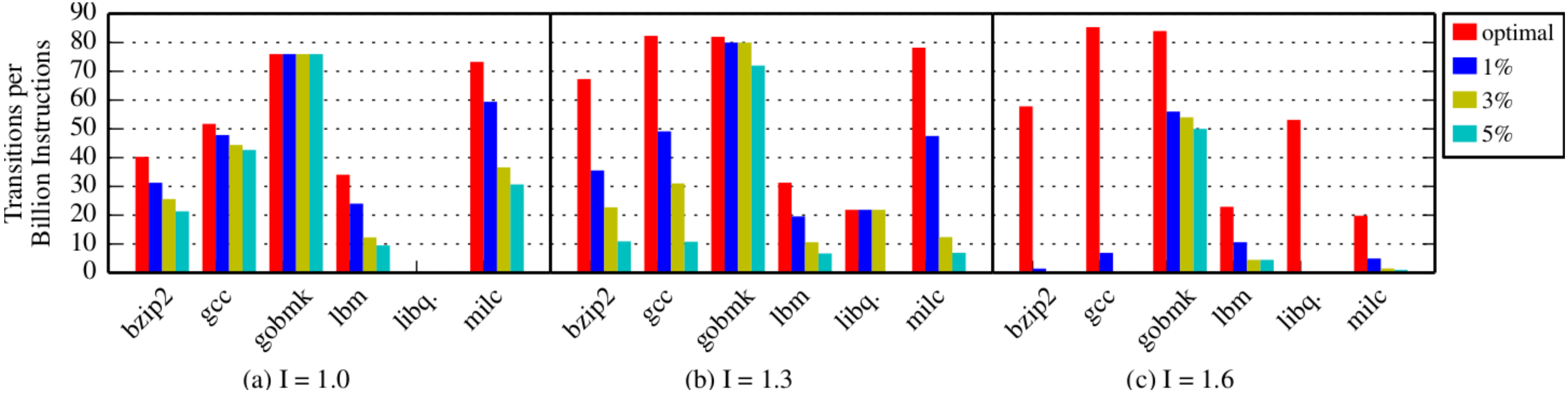
Stable Regions



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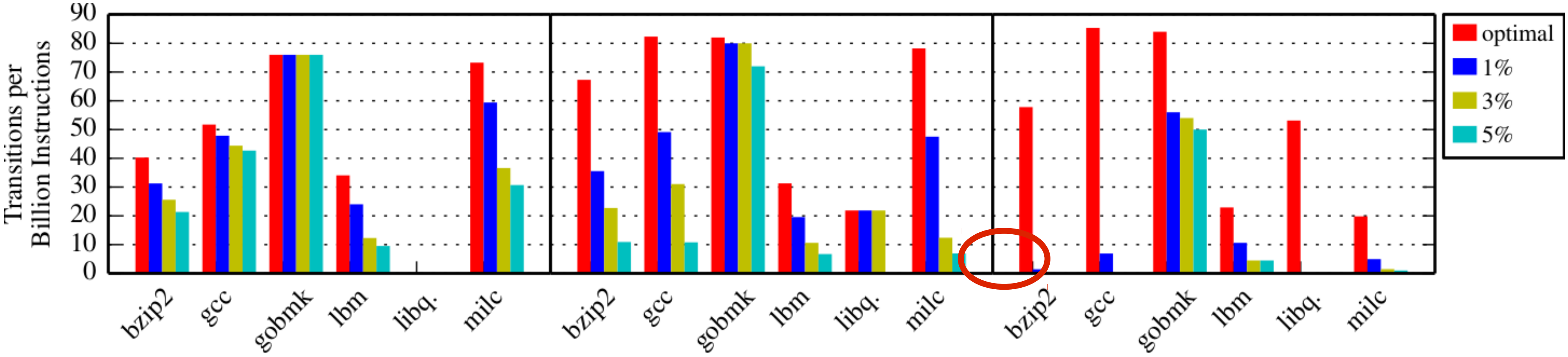

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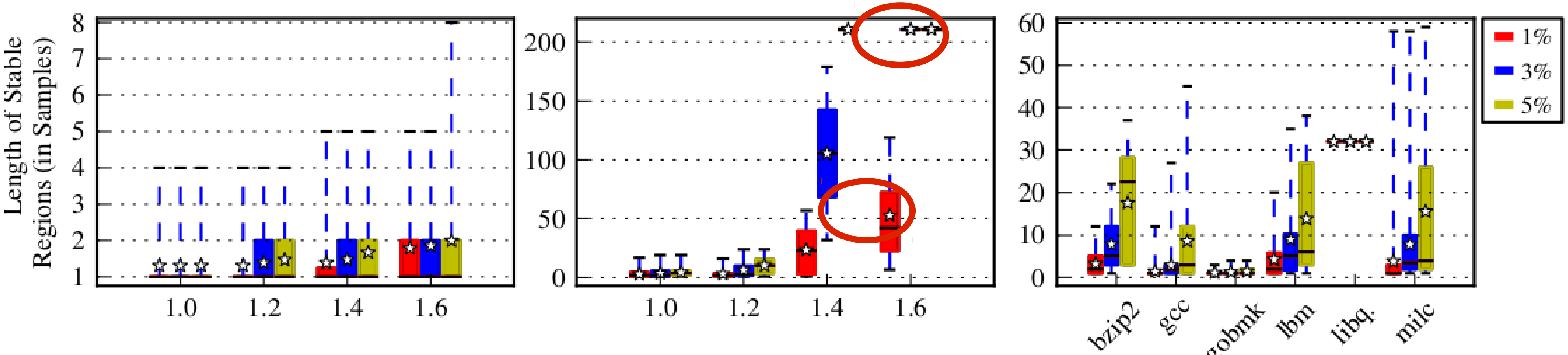

(a) Gobmk (b) Bzip2 (c)

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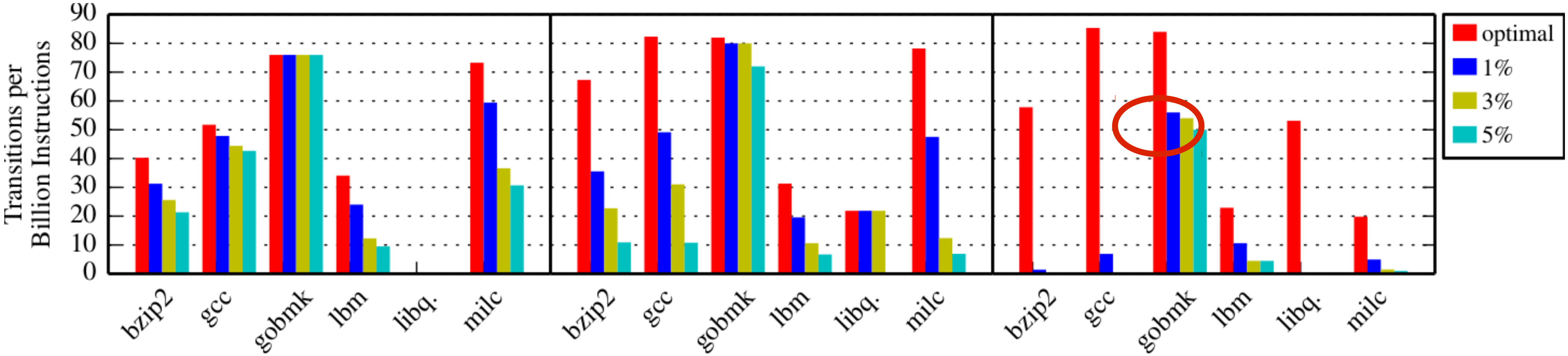

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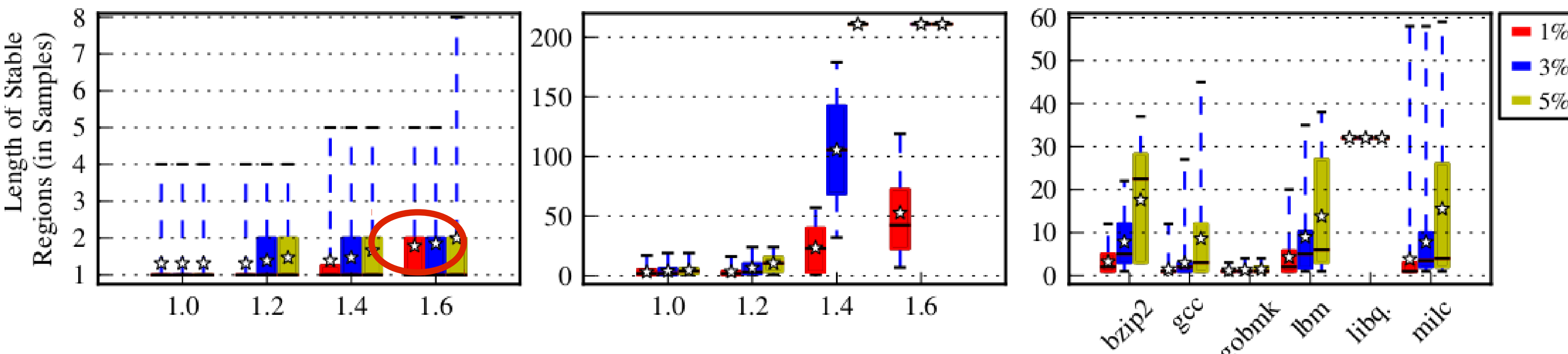
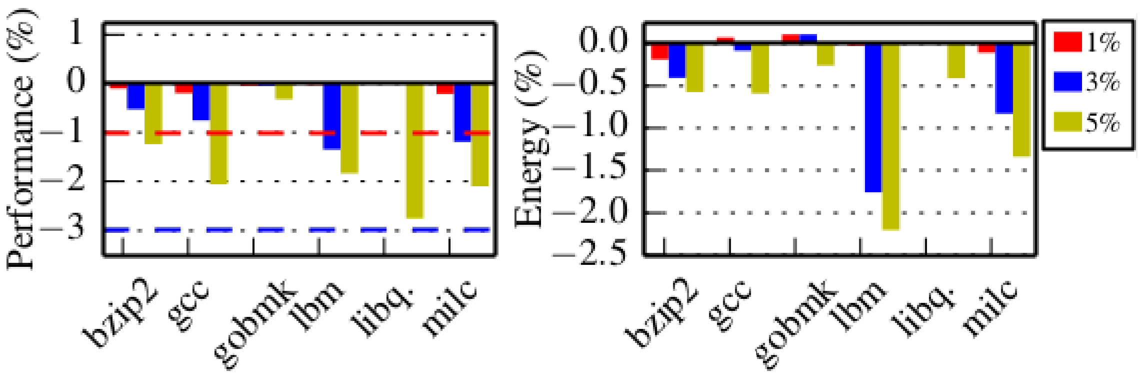


(a) Gobmk (b) Bzip2 (c)

- Number of transition decrease with in increase in cluster thresholds
- For *bzip2,* number of transitions are zero at higher inefficiencies
- *Rapidly changing phases of gobmk* result in only a slight decrease in number of transitions with cluster threshold

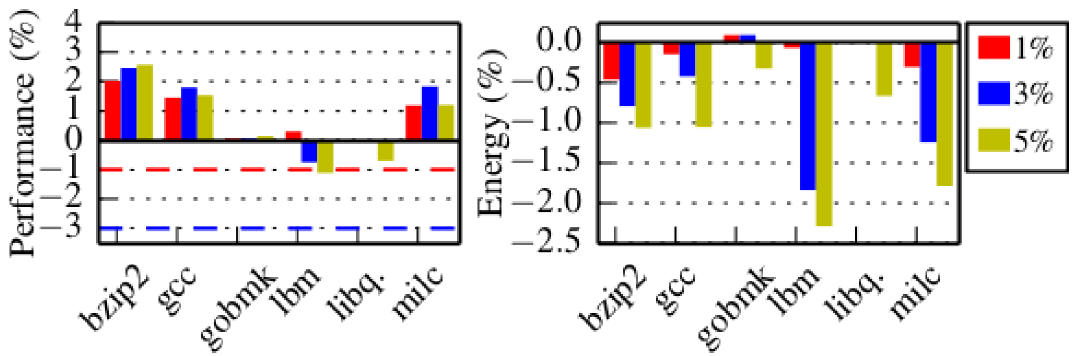
Energy, Performance Results



No Tuning Overhead

- Performance drop is within bounds --- always
- Energy consumption decreases with increase in cluster threshold --- lower frequency settings are selected

Energy, Performance Results



With Tuning Overhead

- Performance improves when tuning overhead is included --- due to decrease in number of transitions

Outline

- Inefficiency
- Inefficiency vs. Speedup
- Characteristics of Optimal Frequency Settings
- Performance Clusters and Stable Regions
- **Conclusions and Future Work**

Conclusion & Future Work

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Conclusion & Future Work

- Inefficiency
- Inefficiency and performance trade-offs ---CPU DVFS and memory DFS
- Tracking optimal frequency settings is expensive
- Performance clusters and stable regions help reduce the cost of frequent tuning
- We are building a system that is capable of tuning multiple components simultaneously while executing applications using the models and analysis of the performance clusters.

Questions?

References

1) Nachiappan, Nachiappan Chidambaram, et al. "Domain knowledge based energy management in handhelds." High Performance Computer Architecture (HPCA), 2015 IEEE 21st International Symposium on. IEEE, 2015.
2) Deng, Qingyuan, et al. "Memscale: active low-power modes for main memory." ACM SIGARCH Computer Architecture News 39.1 (2011): 225-238.
3) David, Howard, et al. "Memory power management via dynamic voltage/frequency scaling." Proceedings of the 8th ACM international conference on Autonomic computing. ACM, 2011.
4) Deng, Qingyuan, et al. "Coscale: Coordinating cpu and memory system dvfs in server systems." Microarchitecture (MICRO), 2012 45th Annual IEEE/ACM International Symposium on. IEEE, 2012.
5) Rumble, Stephen M., et al. "Apprehending joule thieves with cinder." ACM SIGCOMM Computer Communication Review 40.1 (2010): 106-111.
6) Binkert, Nathan, et al. "The gem5 simulator." ACM SIGARCH Computer Architecture News 39.2 (2011): 1-7.
7) Pandaboard, http://pandaboard.org/content/platform.
8) Micron, “Calculating Memory System Power for LPDDR2, May 2013.”
9) Isci, Canturk, Alper Buyuktosunoglu, and Margaret Martonosi. "Long-term workload phases: Duration predictions and applications to DVFS." Micro, IEEE 25.5 (2005): 39-51.
10) Lau, Jeremy, Erez Perelman, and Brad Calder. "Selecting software phase markers with code structure analysis." Proceedings of the International Symposium on Code Generation and Optimization. IEEE Computer Society, 2006.

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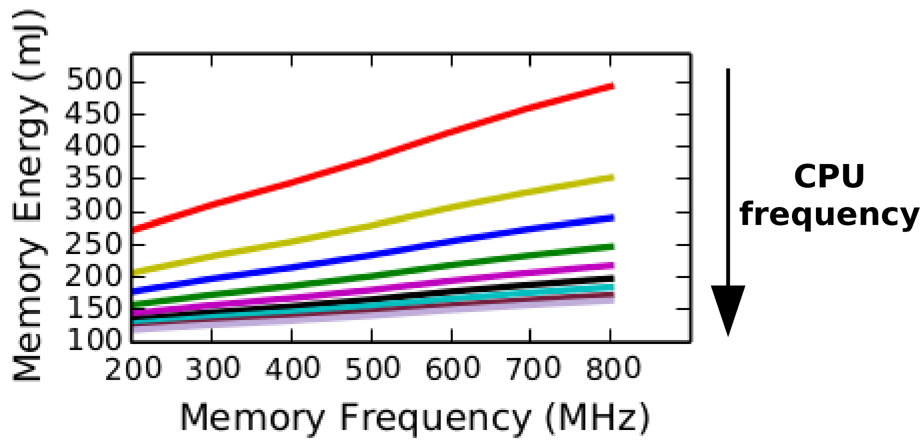

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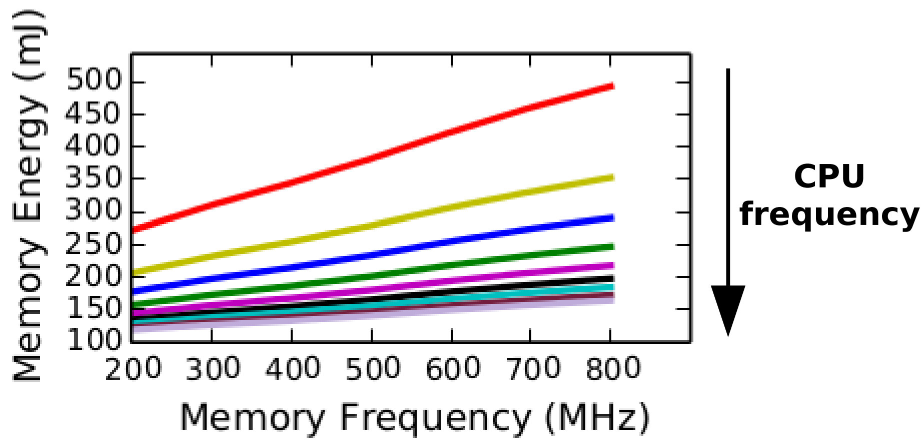

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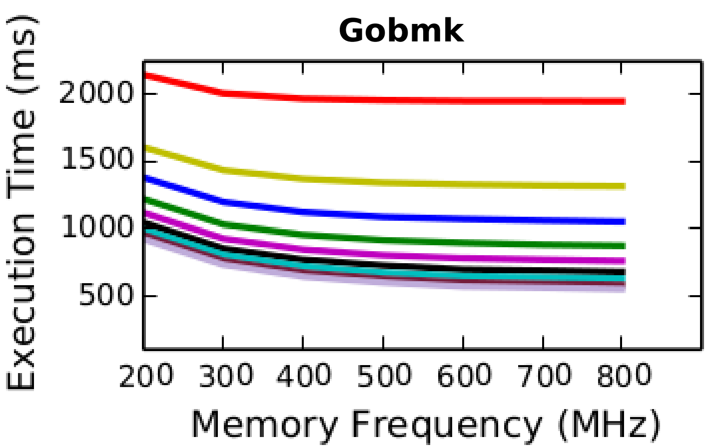

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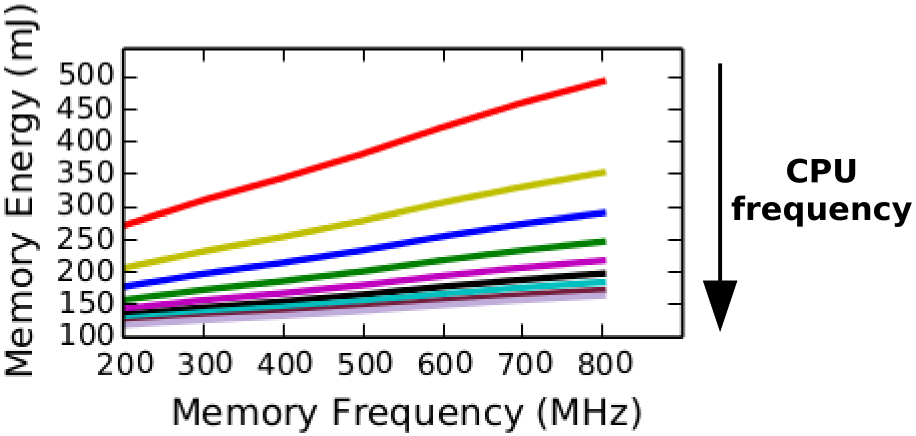

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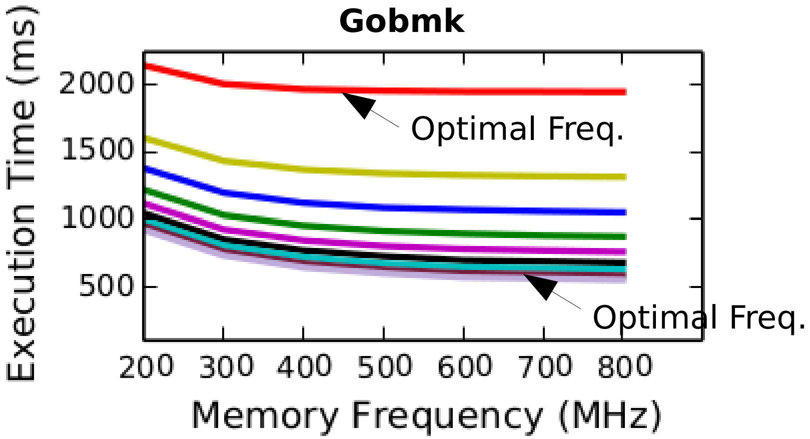

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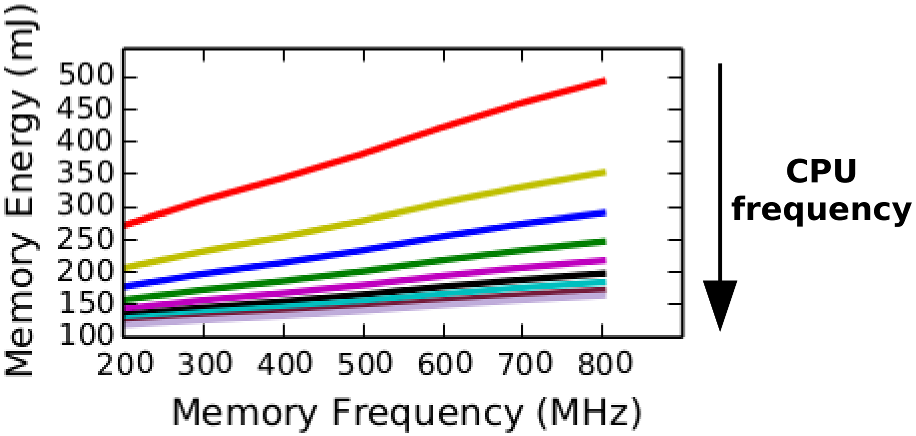

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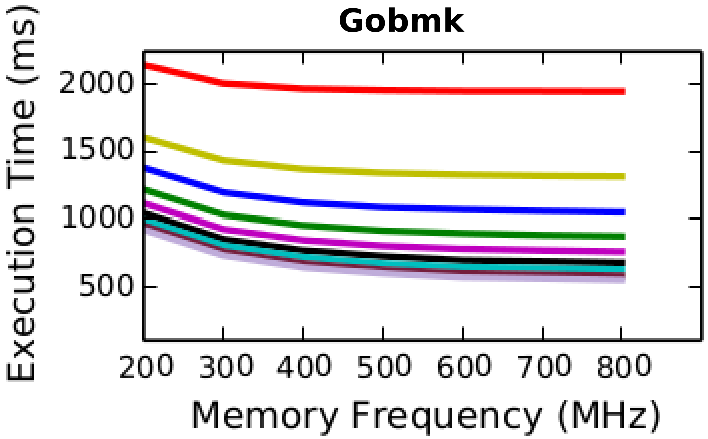
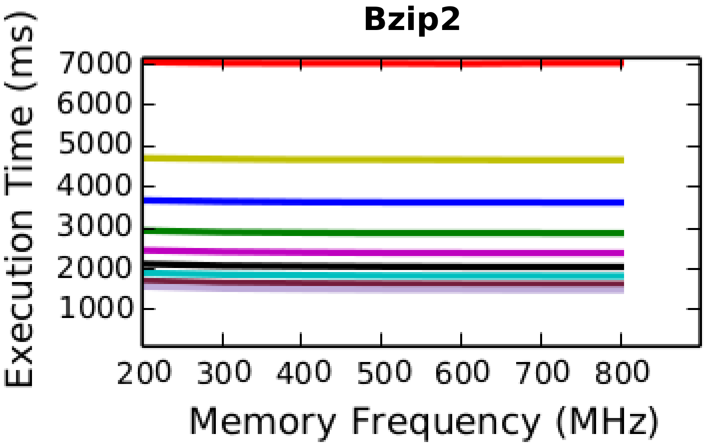
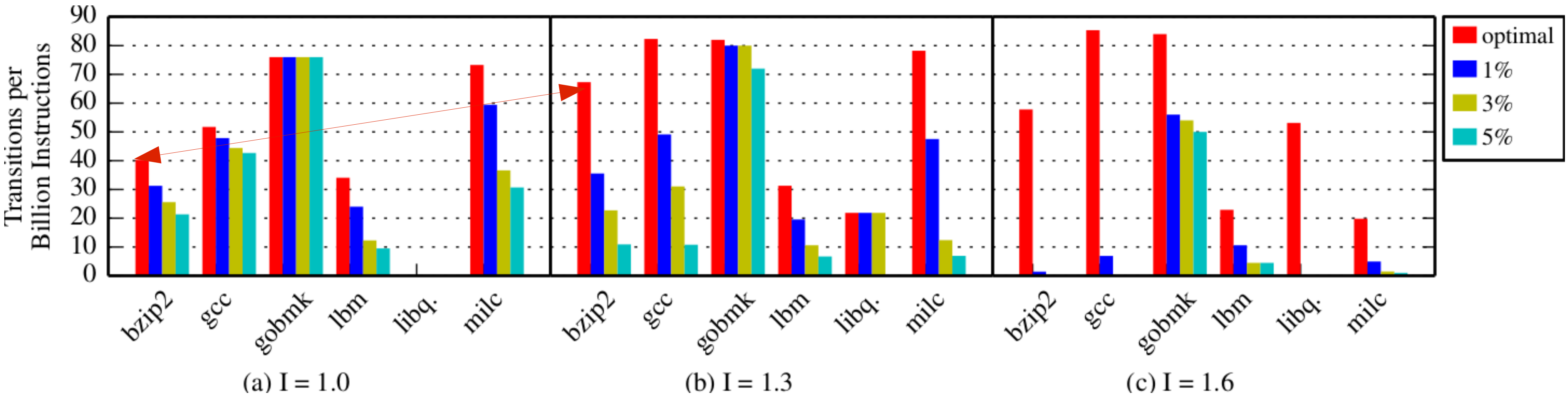




- Performance improvement with DRAM frequency varies across applications.

Stable Regions



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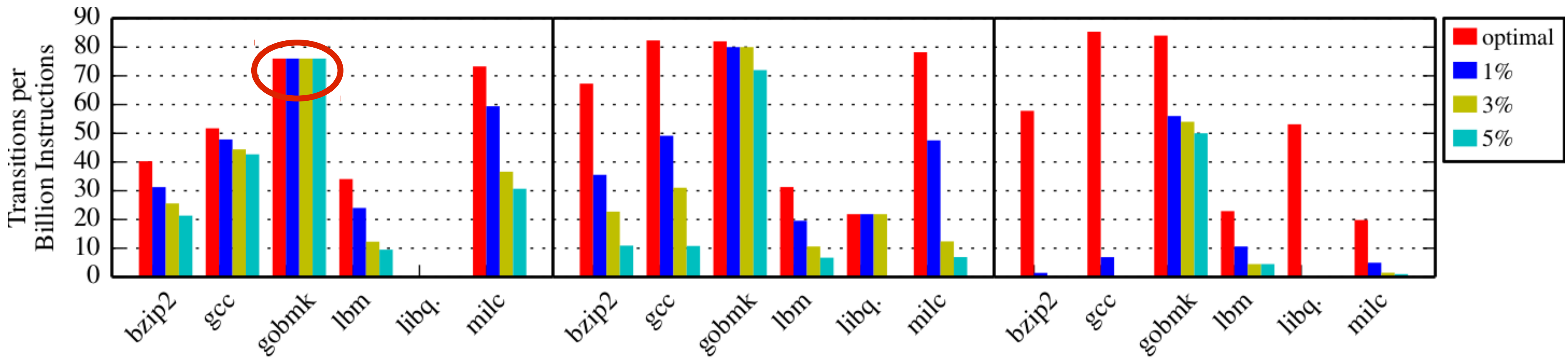

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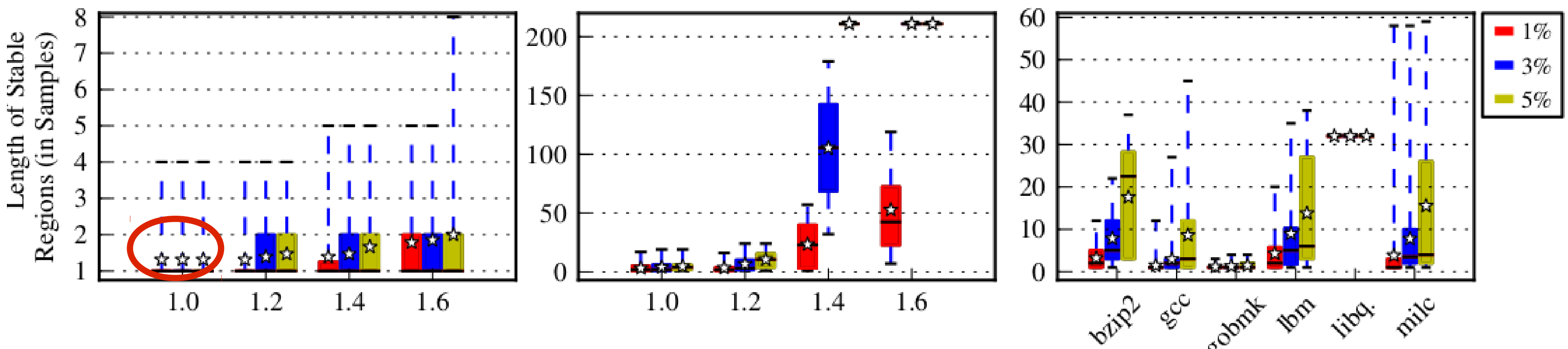

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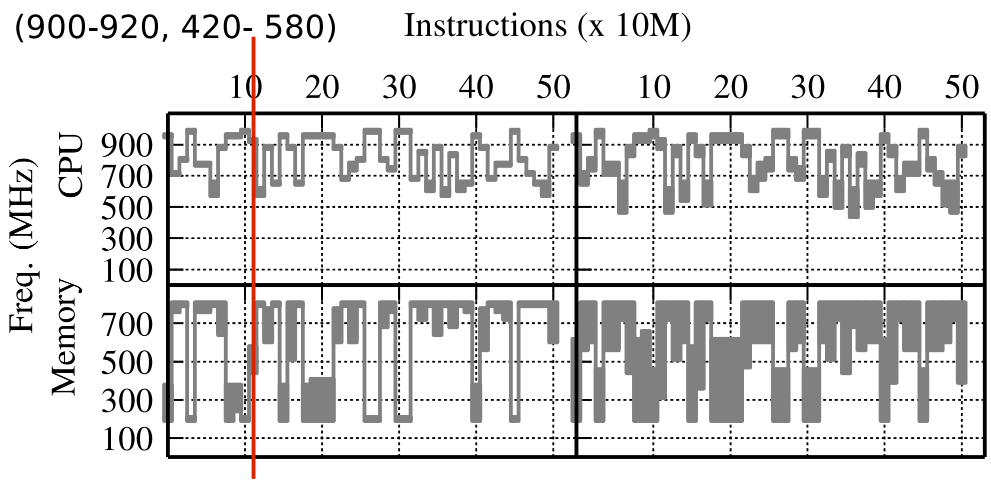
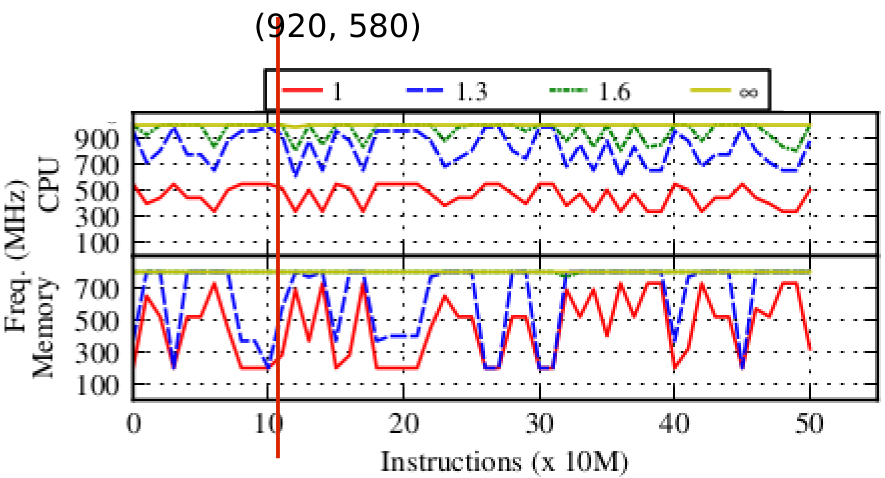


(c)I=1.3,Threshold = 1% (d) I= 1.3, Threshold =5%



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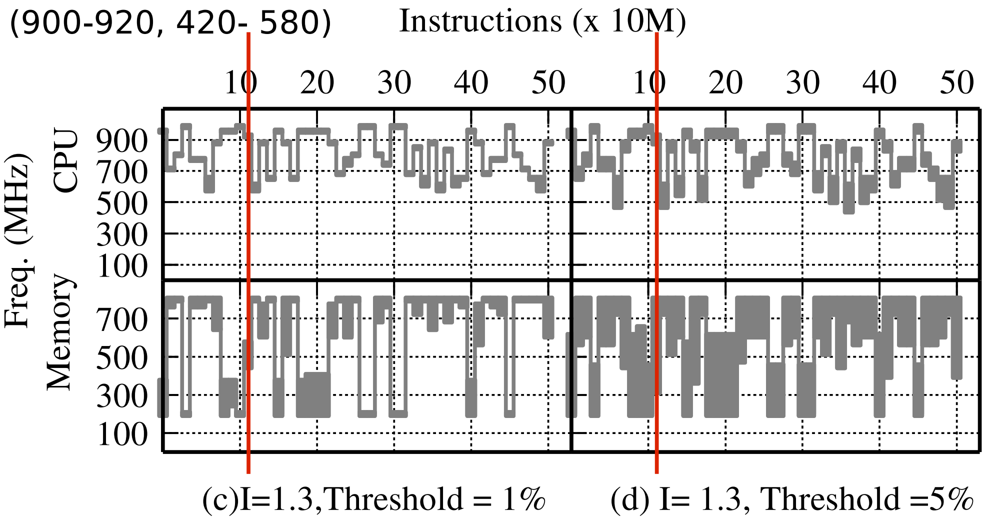
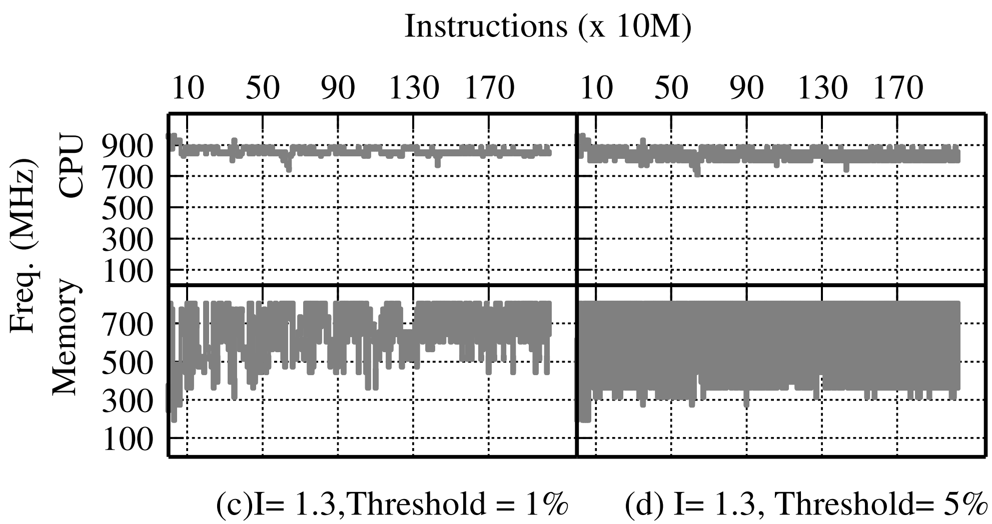
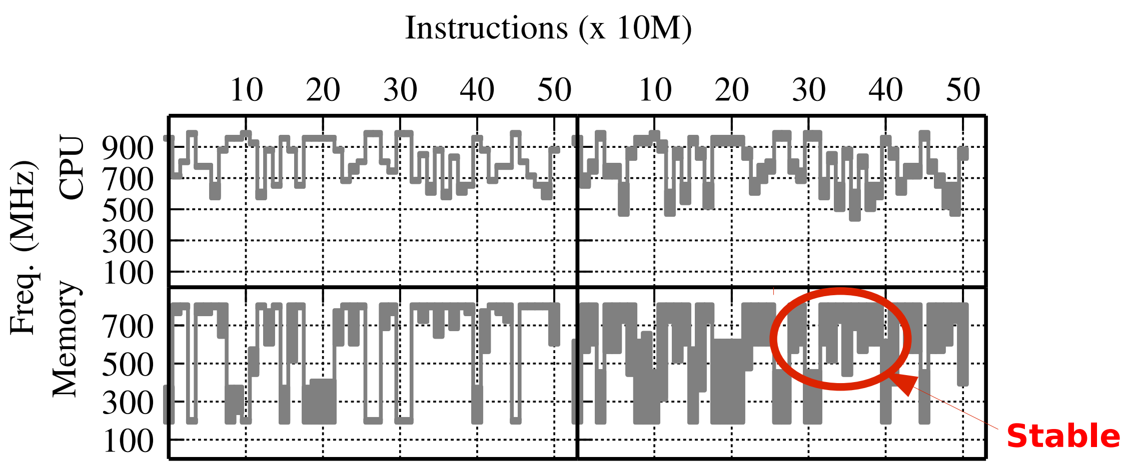


Gobmk



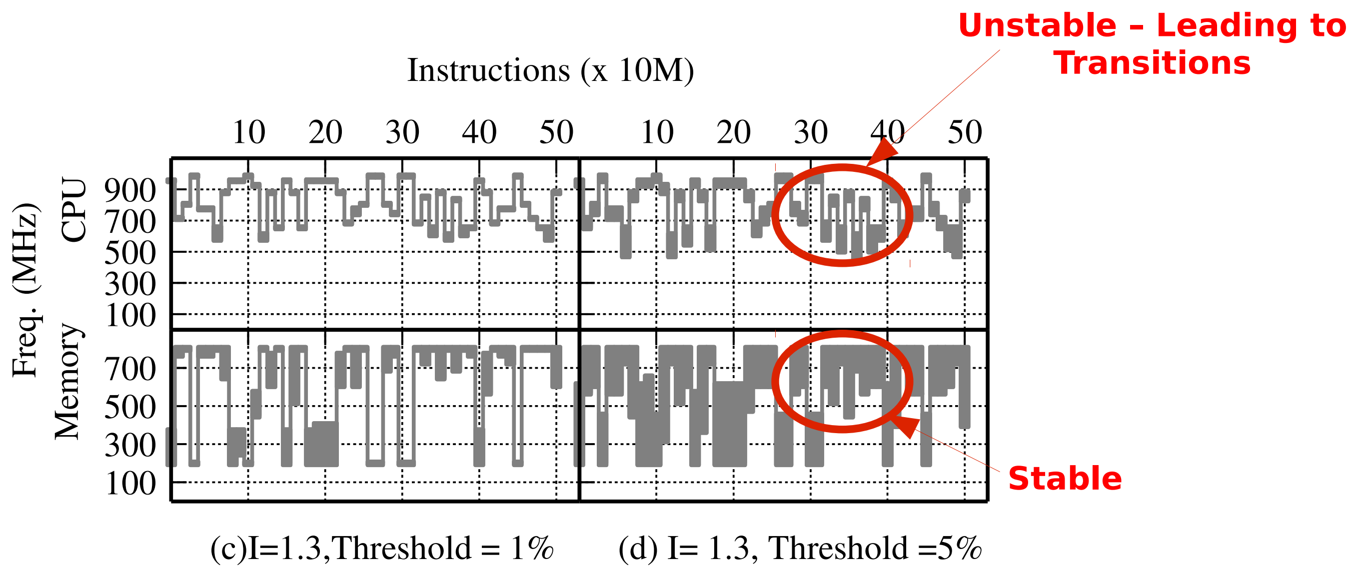
Milc

Performance Clusters



(c)I=1.3,Threshold = 1%　　(d) I= 1.3, Threshold =5%

Performance Clusters



➢ System doesn't need to transition to new set of frequencies only when ***both*** CPU and DRAM frequencies are stable.

Algorithm Implications

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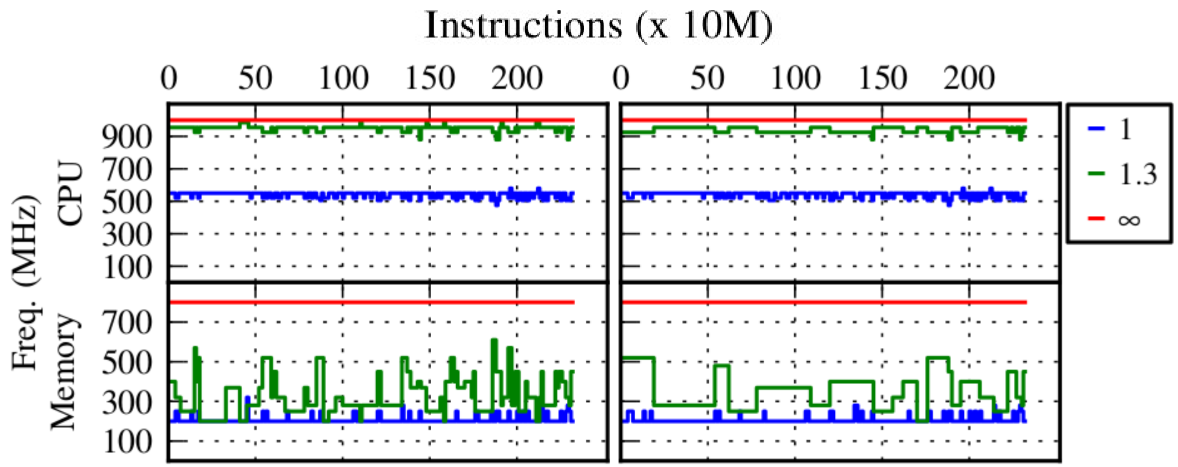
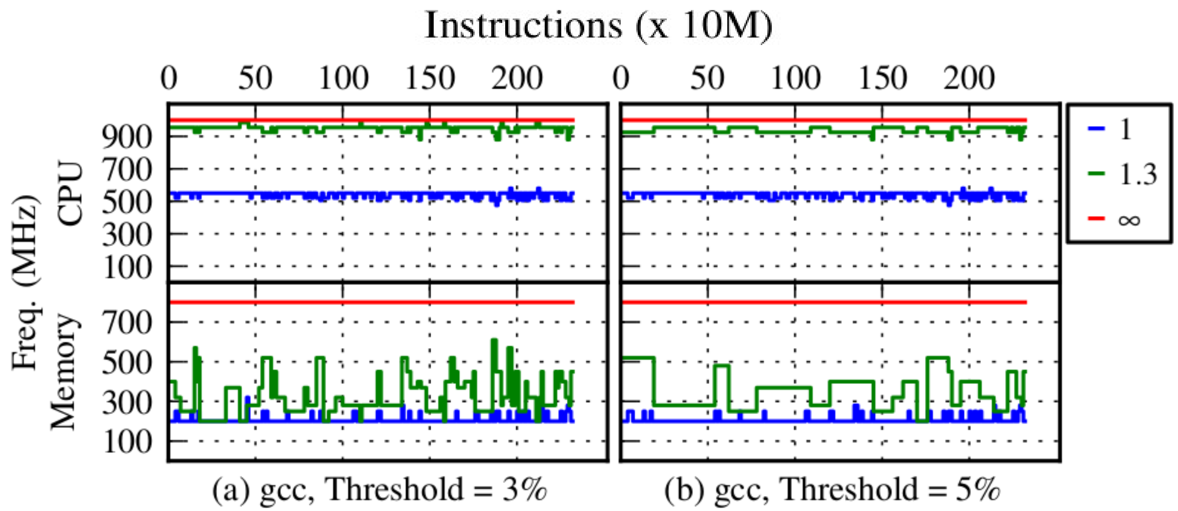


(a) gcc, Threshold = 3%
(b) gcc, Threshold = 5%

Stable Regions



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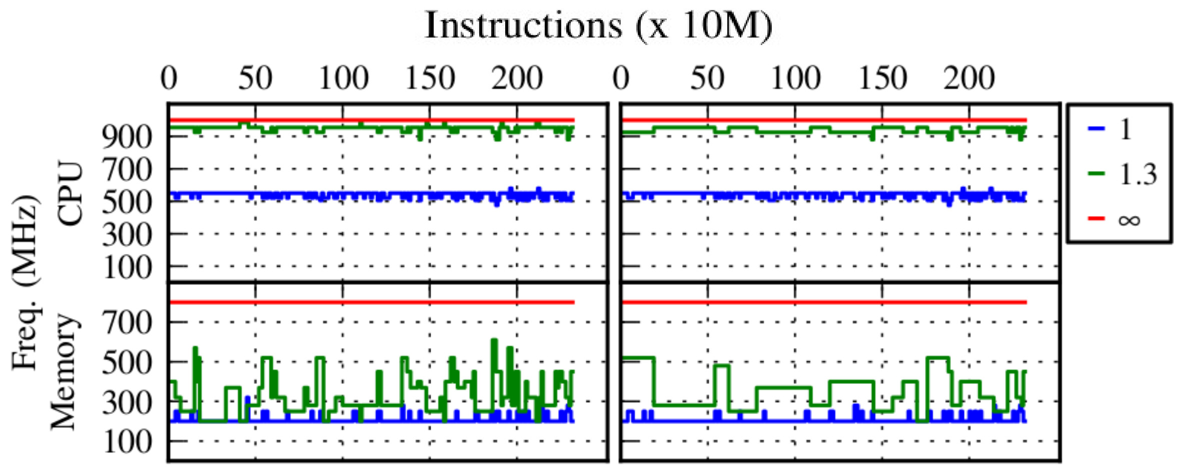

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- Number of transition made by gcc drop significantly at lower inefficiencies --- Higher inefficiencies allow the system to choose max-max always
- Increase in inefficiency also decreases the transitions --- function of application characteristics

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  - Offline profiling of applications[2] helps in pre determining the length and position of stable regions --- can be extended to other applications with similar phases

1) Isci et. al Micro 2005
2) Lau et. al International Symposium on Code Generation and Optimization. 2006.