A Refactoring Approach to Improve Energy Consumption of Parallel Software Systems

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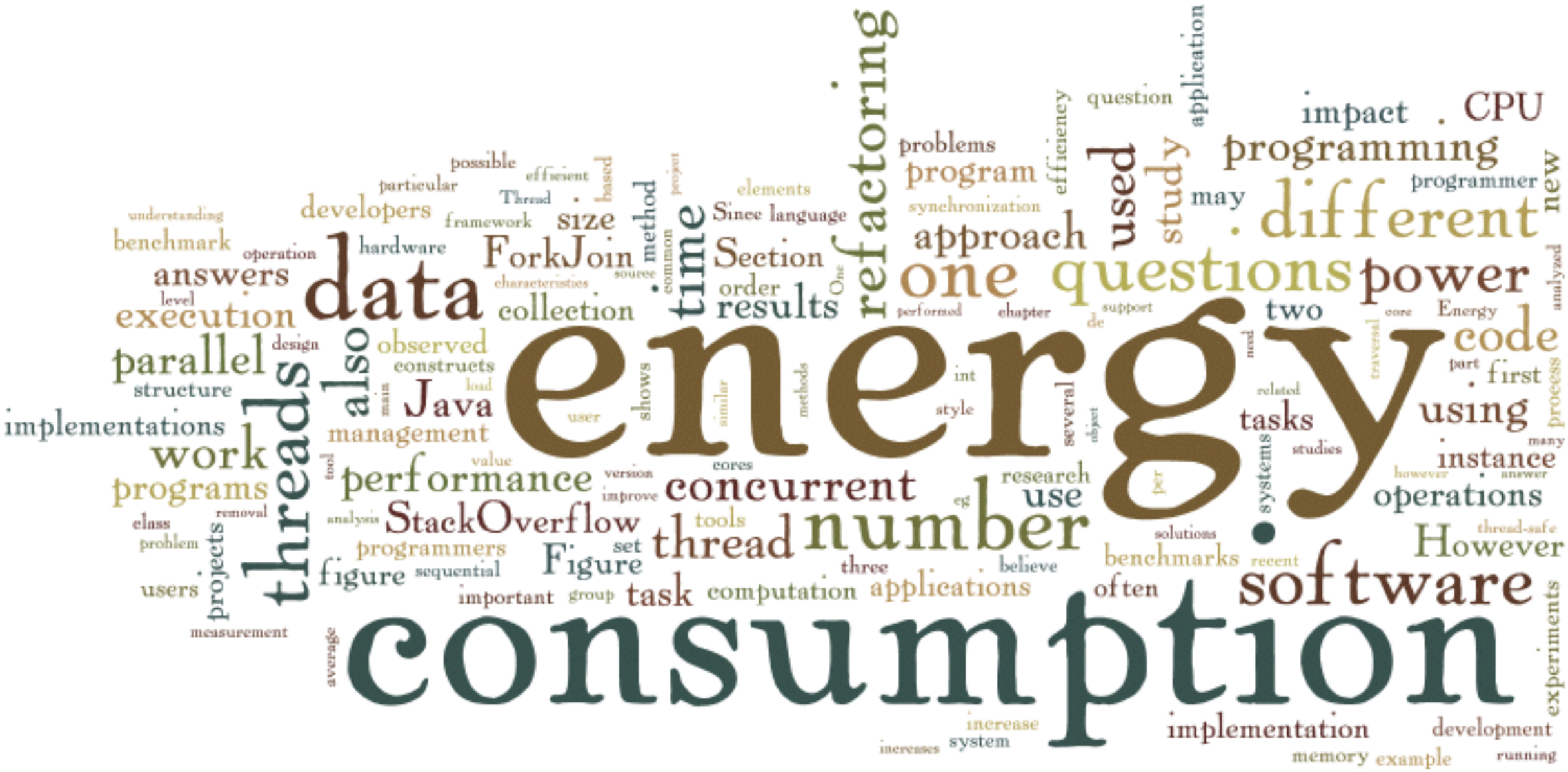
Federal University of Pernambuco

Recife, February/2015



Generated from 77,317 words

Motivation (1/2)

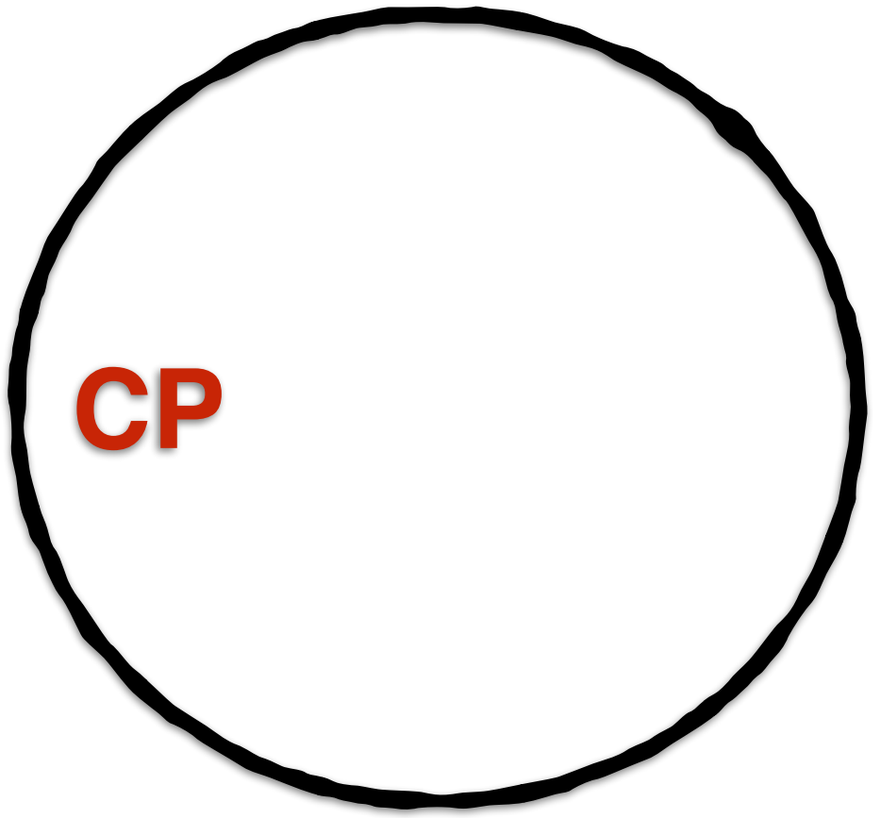
- **First**, **energy consumption** is a concern for unwired devices and also for data centers.

- **Second**, there is a large body of work in hardware/architecture, OS, runtime systems.

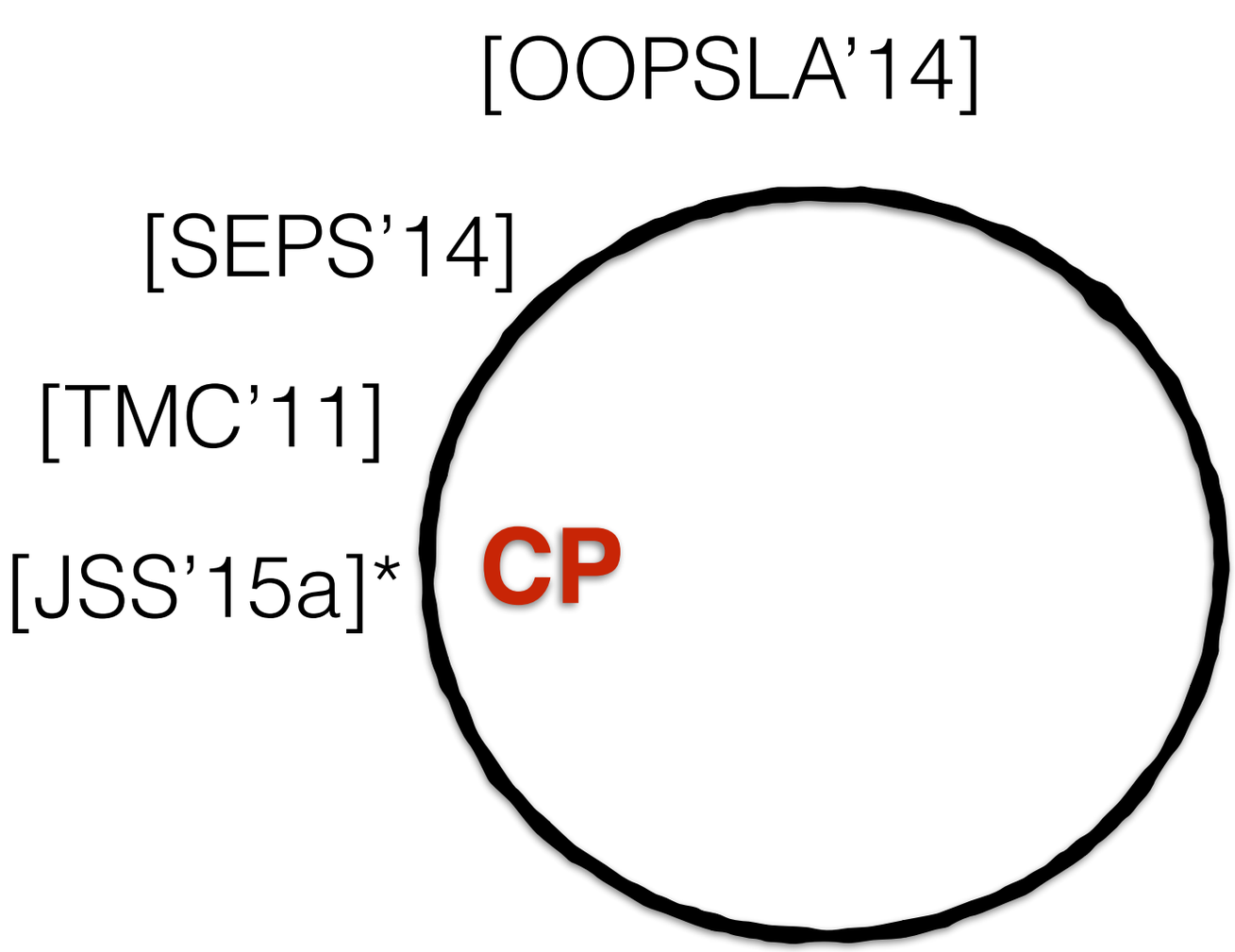
- **However**, little is known about the application level.

Motivation (2/2)

- **First, multicore** CPUs are ubiquitous
- **Second,** performance of the existing parallel software is reasonably well-understood
- **However**, little is known about **energy behaviors** of multi-threaded programs on the **application and programming language** level



CP: Concurrent Programming



CP: Concurrent Programming

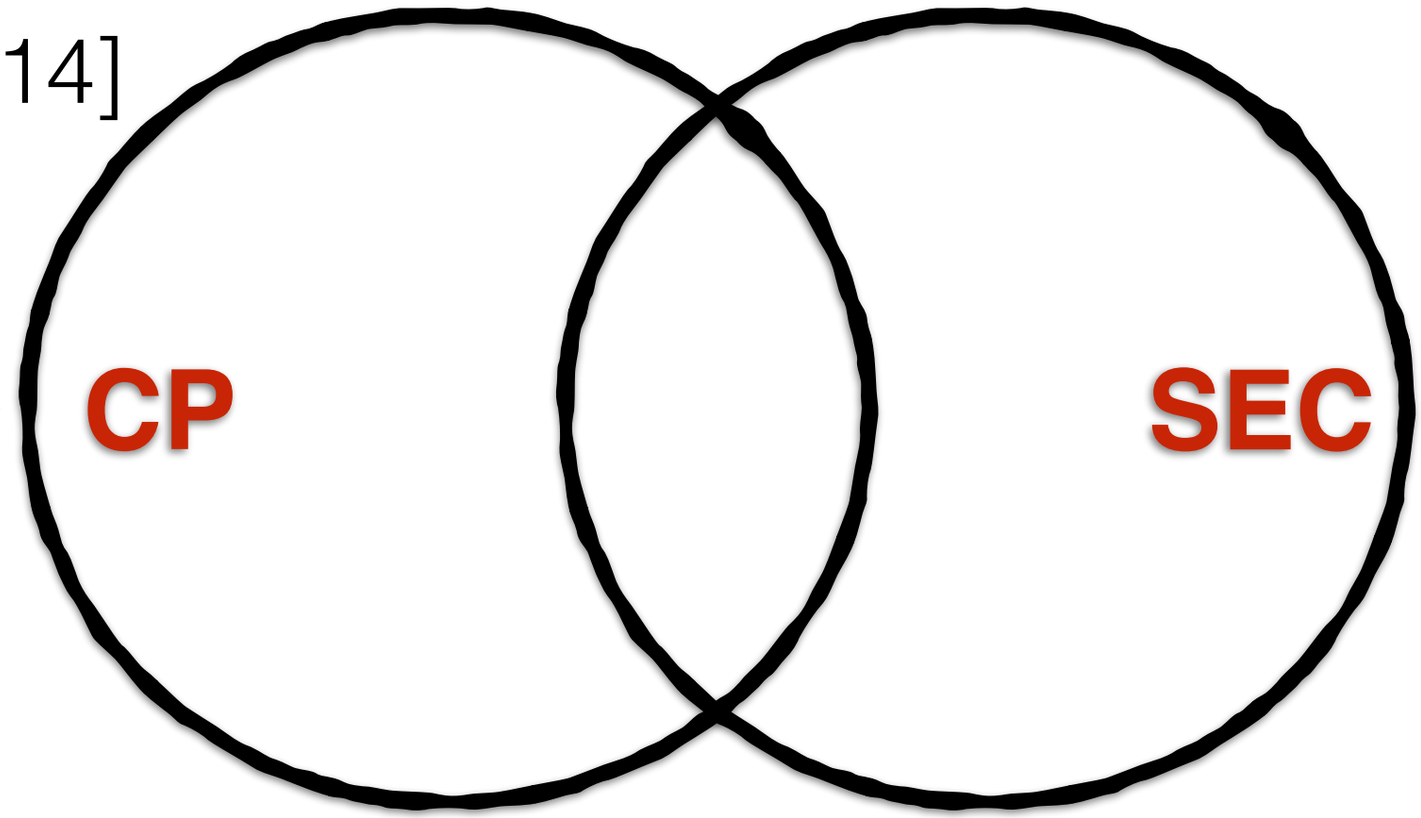
* Under submission

[OOPSLA'14]

[SEPS'14]

[TMC'11]

[JSS'15a]*



CP: Concurrent Programming
SEC: Software Energy Consumption

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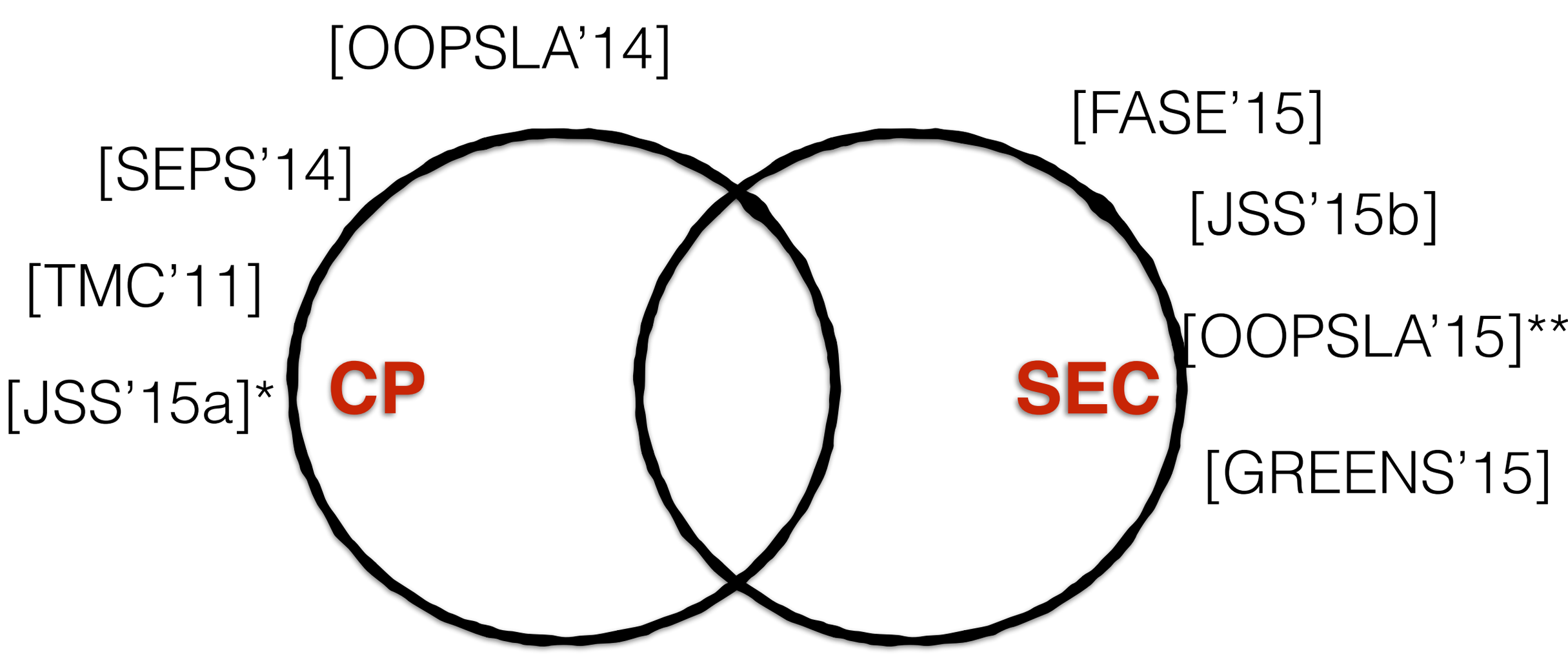

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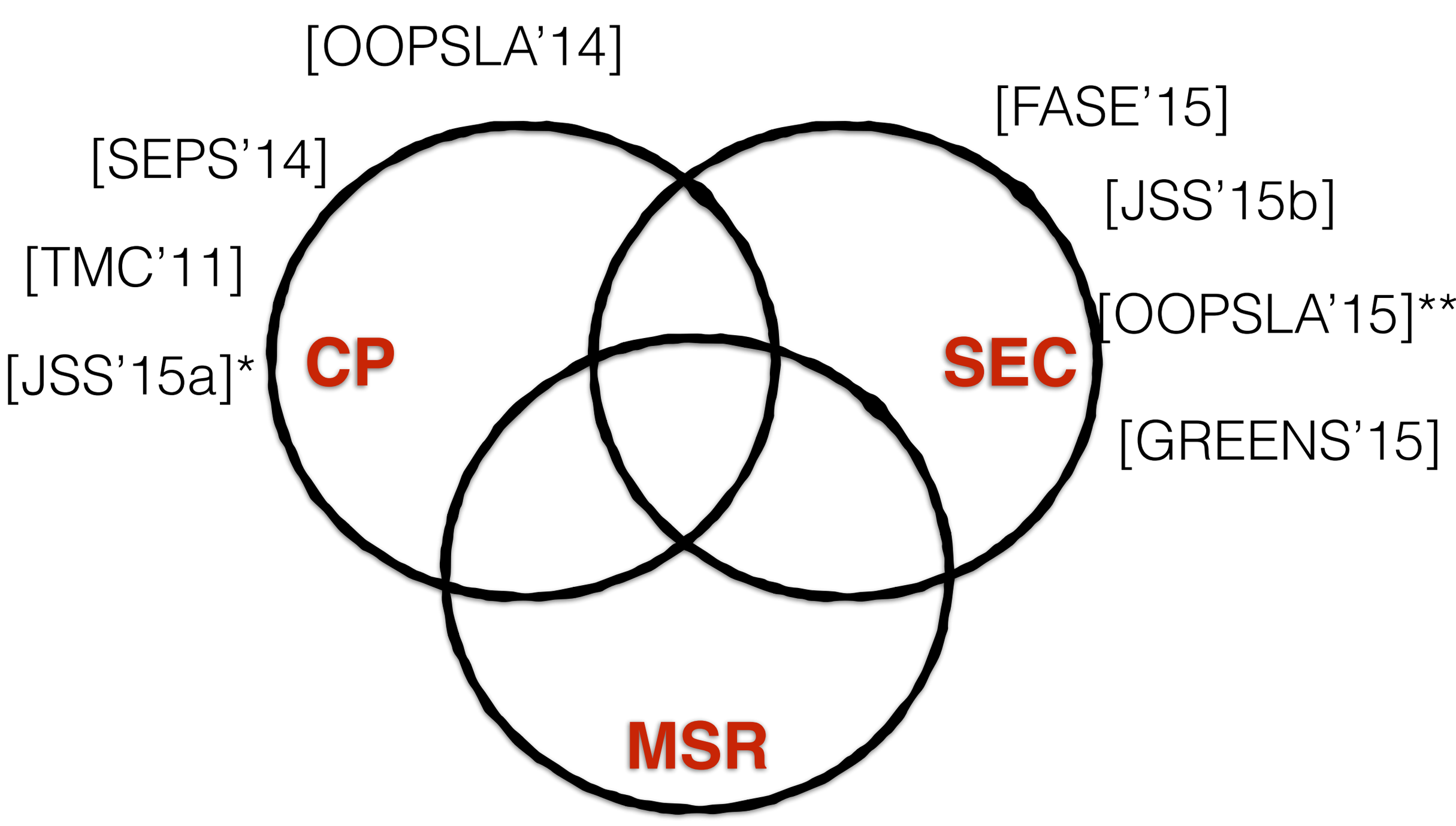
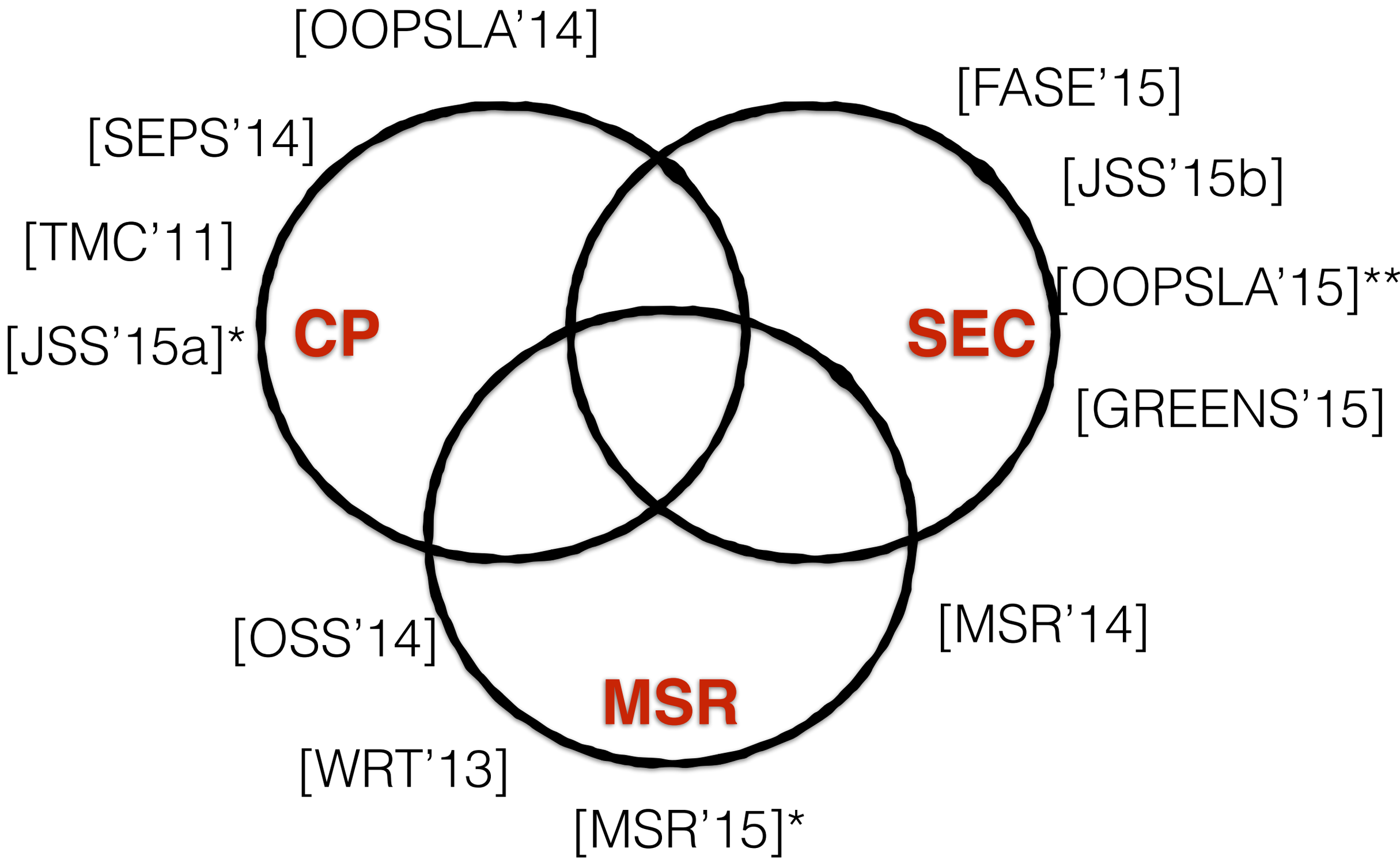


CP: Concurrent Programming
SEC: Software Energy Consumption
MSR: Mining Software Repositories

** Will be submitted
* Under submission



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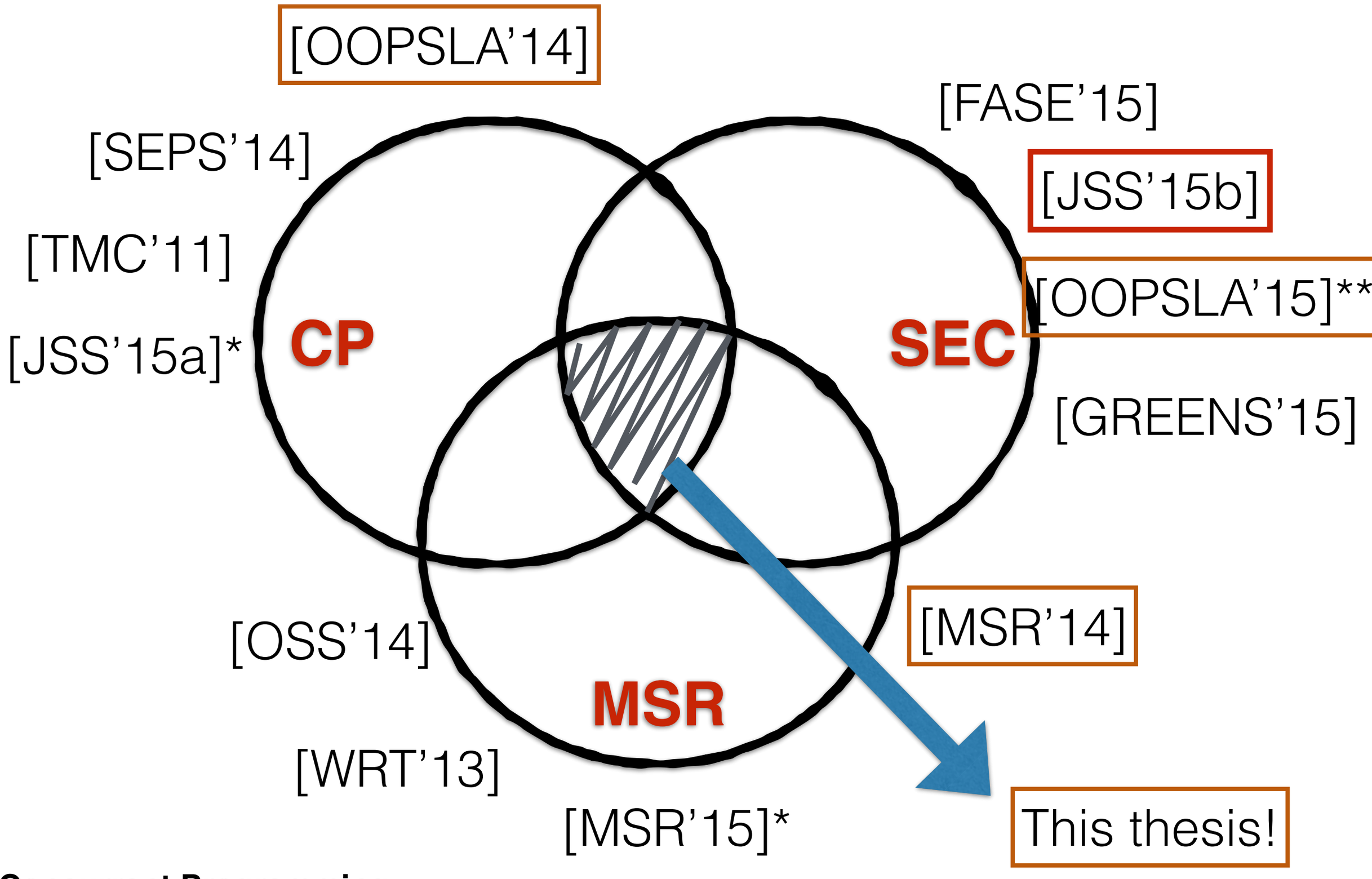

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The Problem

- The lack of knowledge
- The lack of tools

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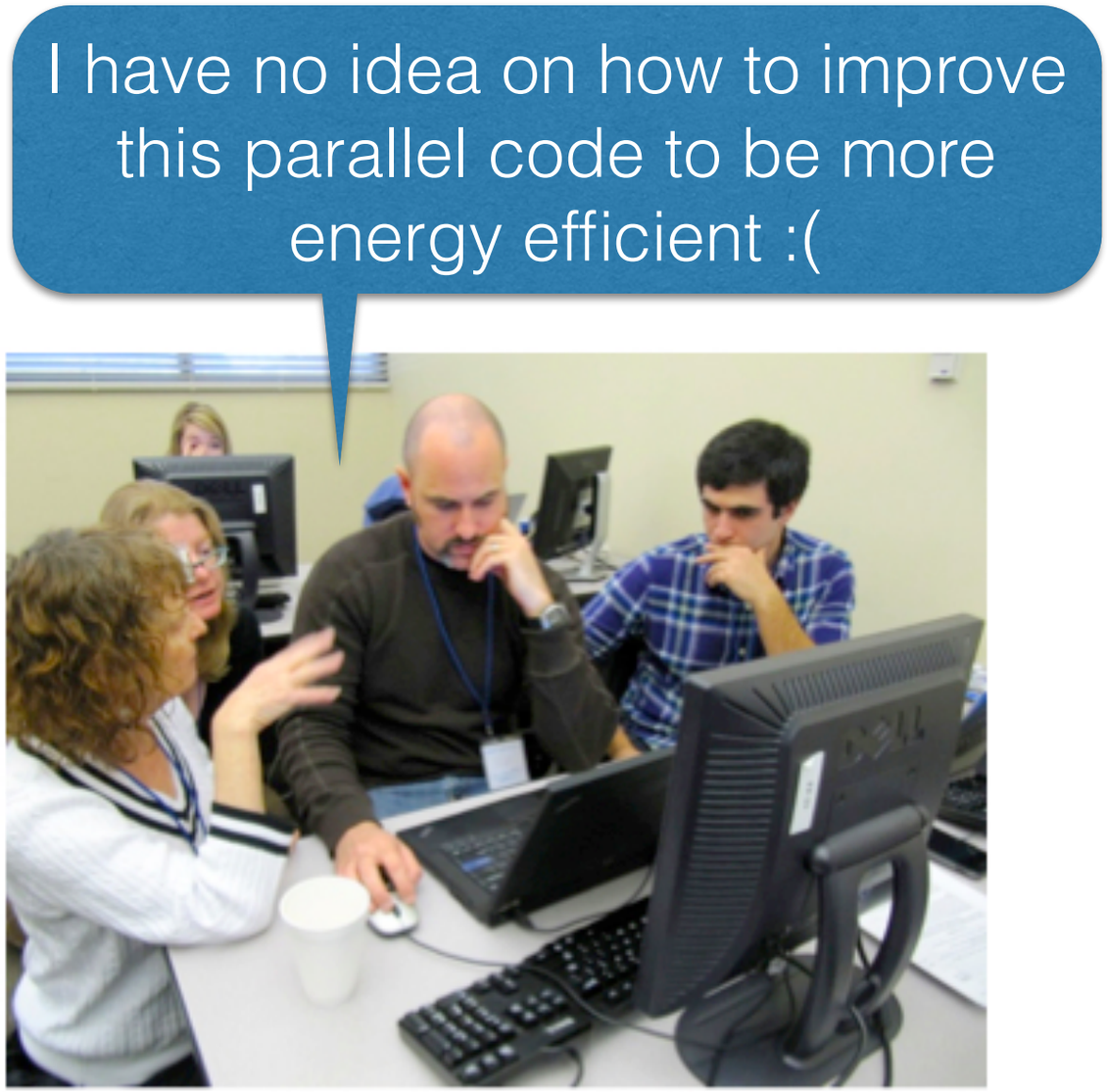

The Problem

- The lack of knowledge
- The lack of tools

The Contributions

1. To understand how software developers are dealing with energy consumption issues;

2. To characterize the energy-consumption behavior of
    1. Thread-safe collections
    2. Thread management techniques

3. To derive a refactoring to (1) identify and (2) refactor one energy-consumption anti-pattern;

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2M+ Users

5M+ Questions

10M+ Answers

50GB+ of data

“The most used Q&A website in the world”

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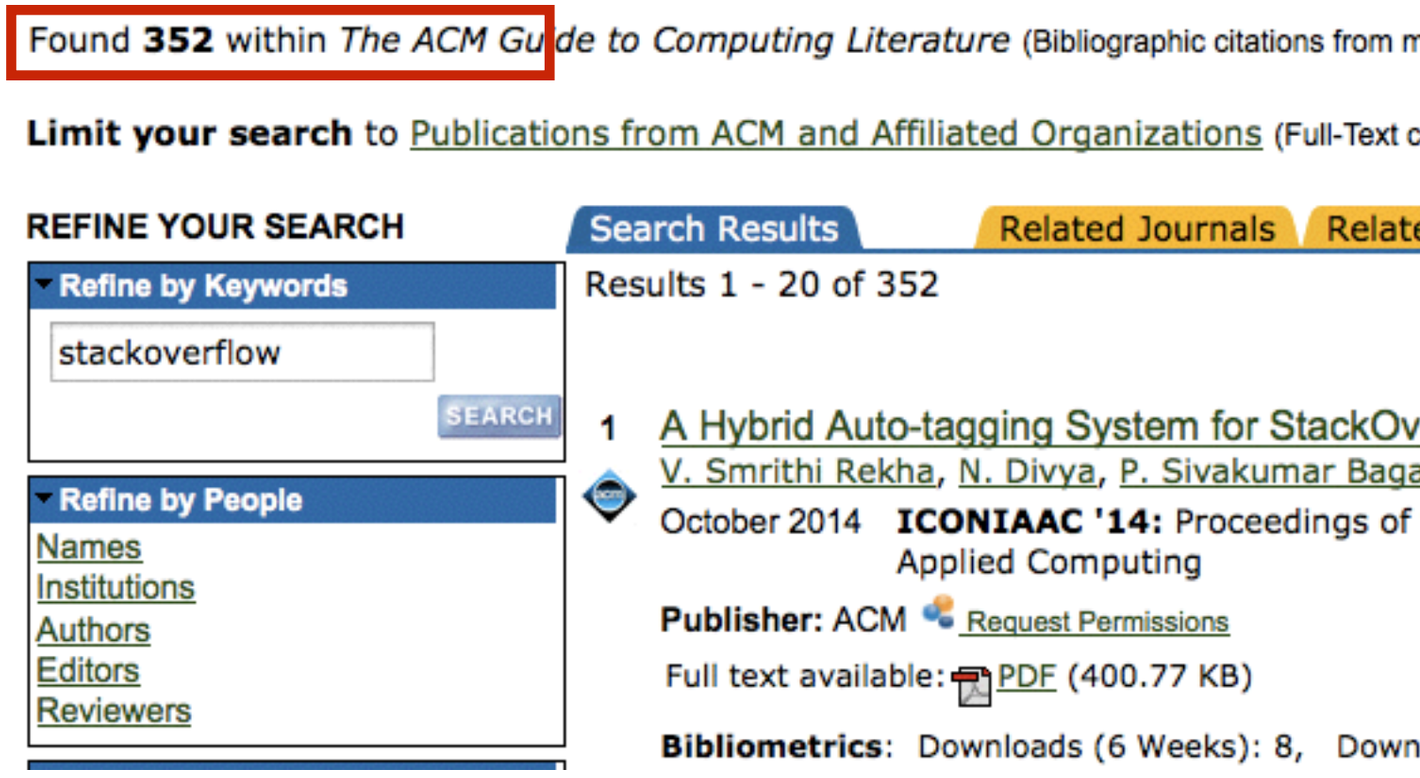
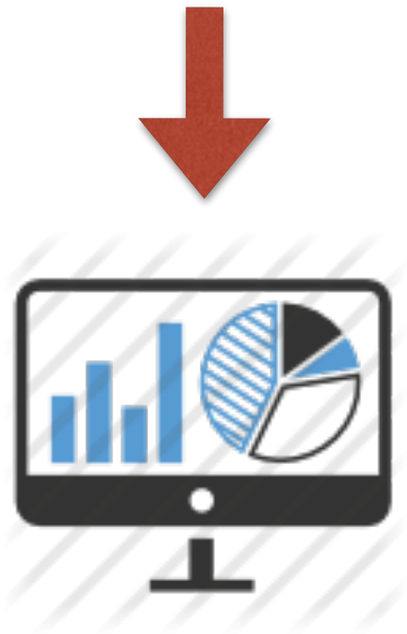


"The most used Q&A website in the world"

5M Questions

Automatic Filter

Manual Filter



Final Data

5M Questions

Automatic Filter

615 Questions
1,197 Answers

Manual Filter

Final Data

5M Questions

Automatic Filter

Manual Filter

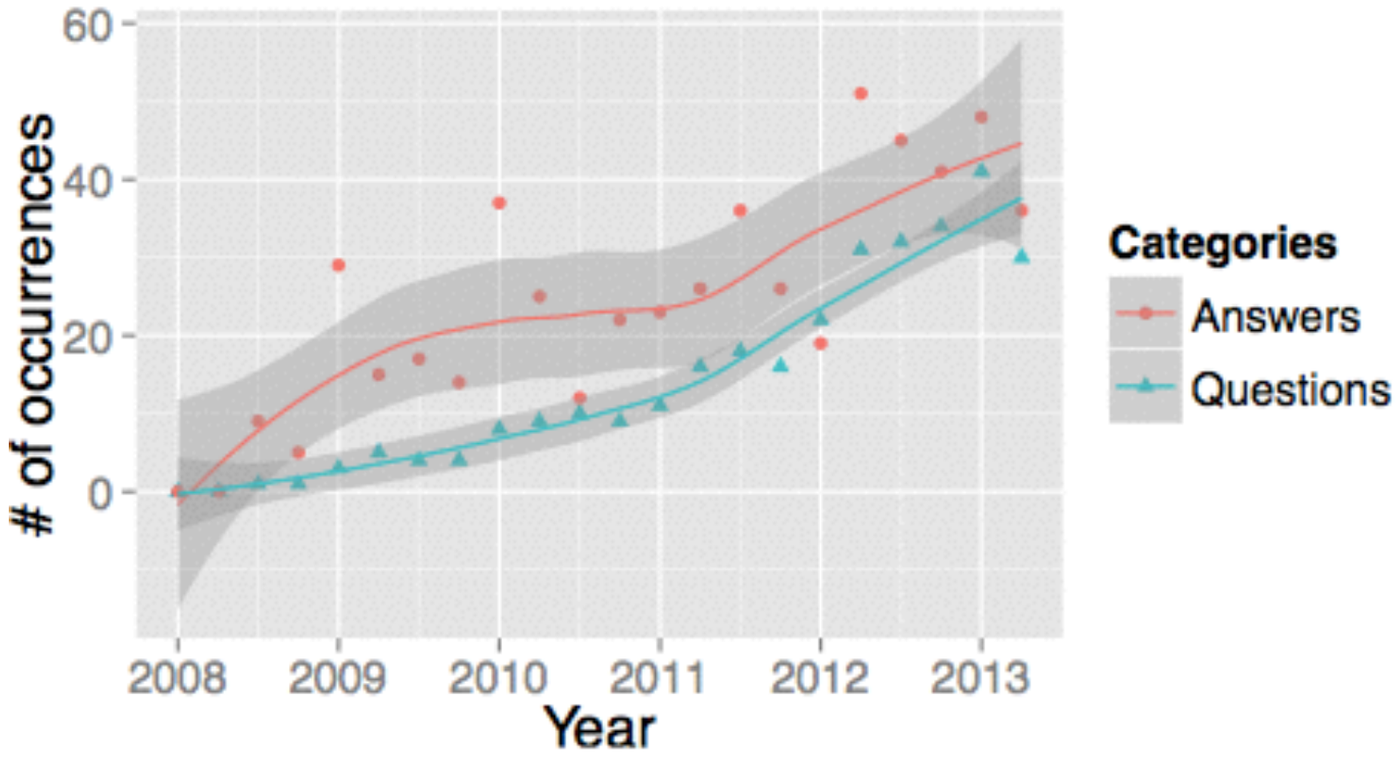
Final Data

325 Questions
558 Answers

Base Group

from 2008 to 2013

Characteristics



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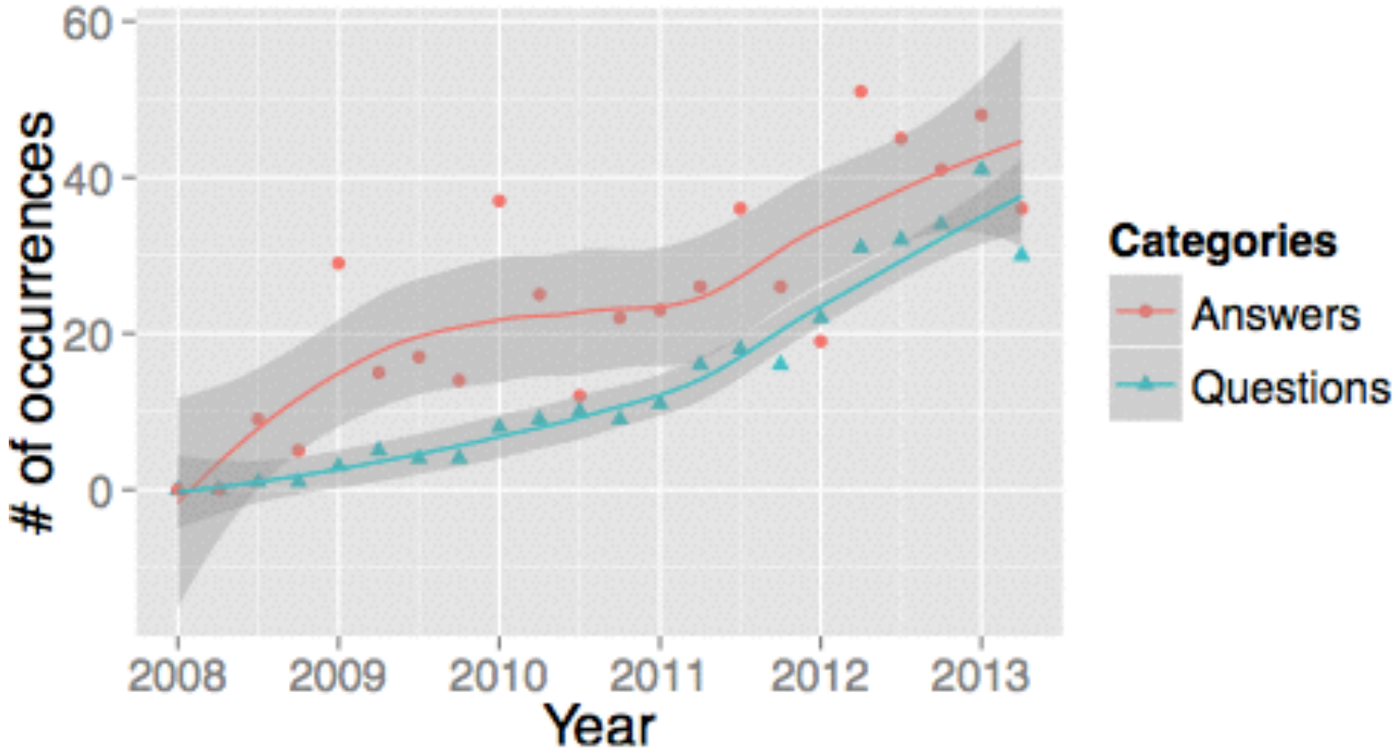

85% of Q. have A.
(45% are answered successfully)

No obvious “energy expert”

1/4 of questions are from mobile dev.

Problems

- Measurements (59/97 — Q/A)
- General Knowledge (40/84 — Q/A)
- Code design (36/133 — Q/A)
- Context-specific (83/110 — Q/A)
- Noise (107/134 — Q/A)

“I want to measure the energy consumption of my own application (which I can modify) [...] on Windows CE 5.0 and Windows Mobile 5/6. Is there some kind of API for this?”

- Measurements (59/97 — Q/A)
- General Knowledge (40/84 — Q/A)
- Code design (36/133 — Q/A)
- Context-specific (83/110 — Q/A)
- Noise (107/134 — Q/A)

“Are there any s/w high level design considerations […] to make the code as power efficient as possible?”

- Measurements (59/97 — Q/A)
- General Knowledge (40/84 — Q/A)
- Code design (36/133 — Q/A)
- Context-specific (83/110 — Q/A)
- Noise (107/134 — Q/A)

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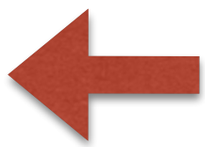

— Highest popularity
— Highest A per Q ratio
— Highest success rate

Causes

- Unnecessary resource usage (49 occurrences)
- Fault GPS behavior (42 occurrences)
- Background activities (40 occurrences)
- Excessive synchronization (32 occurrences)
- Background wallpapers (17 occurrences)
- Advertisement (11 occurrences)

"to have a background application that monitors device usage, identifies unused/idle resources, and acts appropriately"

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- Fault GPS behavior (42 occurrences)
- Background activities (40 occurrences)
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"When there are bugs that keep the GPS turned on too long they go to the top of the list to get fixed"

- Unnecessary resource usage (49 occurrences)
- Fault GPS behavior (42 occurrences)
- Background activities (40 occurrences)
- Excessive synchronization (32 occurrences)
- Background wallpapers (17 occurrences)
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Solutions

- Keep IO to a minimum (29 occurrences)
- Bulk operations (24 occurrences)
- Avoid polling (17 occurrences)
- Hardware Coordination (11 occurrences)
- Concurrent Programming (9 occurrences)
- Race to idle (7 occurrences)

“do not flood the output stream with null values”

- Keep IO to a minimum (29 occurrences)
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- Hardware Coordination (11 occurrences)
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“Don’t transfer say 1 file, and then wait for a bit to do another transfer. Instead, transfer right after the other.”

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- Hardware Coordination (11 occurrences)
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Do researchers agree?

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Do researchers agree?

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16 Collections

List
ArrayList
Vector
Collections.syncList()
CopyOnWriteArrayList

Set
LinkedHashSet
Collections.syncSet()
CopyOnWriteArraySet
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Non thread-safe

Thread-safe

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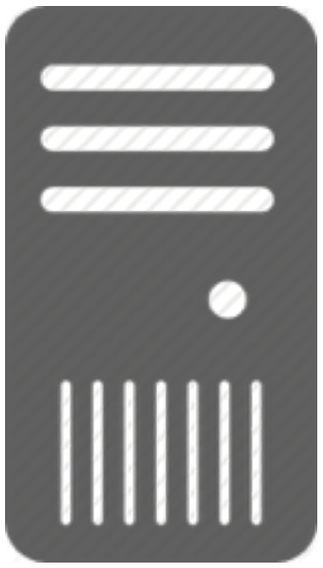
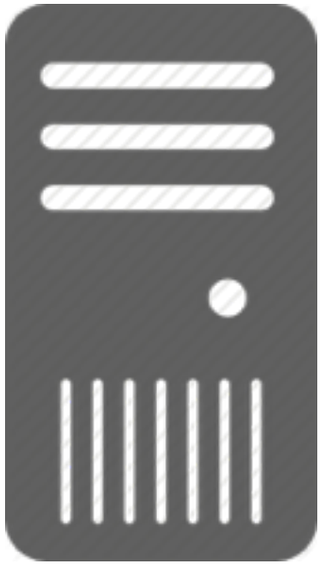
x 3 Operations

Traversal	Insertion	Removal

Experimental Environment

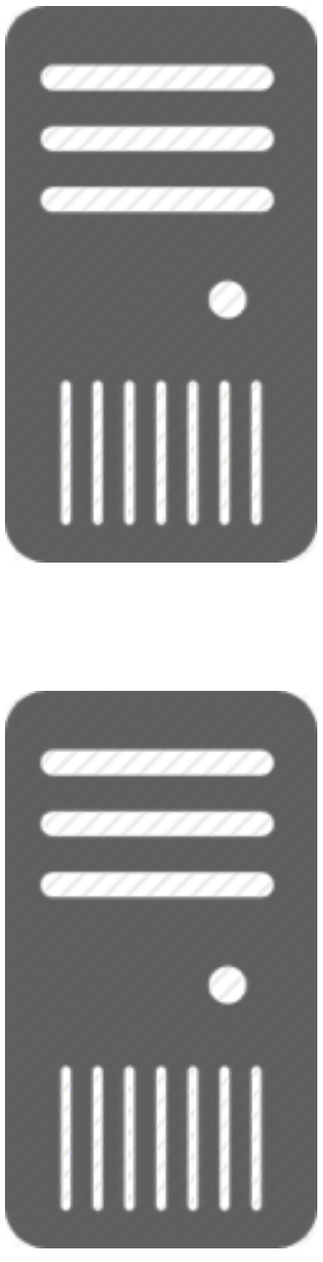


System#1: A 2×16-core **AMD CPUs**, running Debian, 2.4 GHz, 64GB of memory, JDK version 1.7.0 11, build 21.



System#2: A 2×8-core (32-cores w/ hyper-threading) **Intel CPU**,running Debian, 2.60GHz, with 64GB of memory, JDK version 1.7.0 71, build 14.

Experimental Environment



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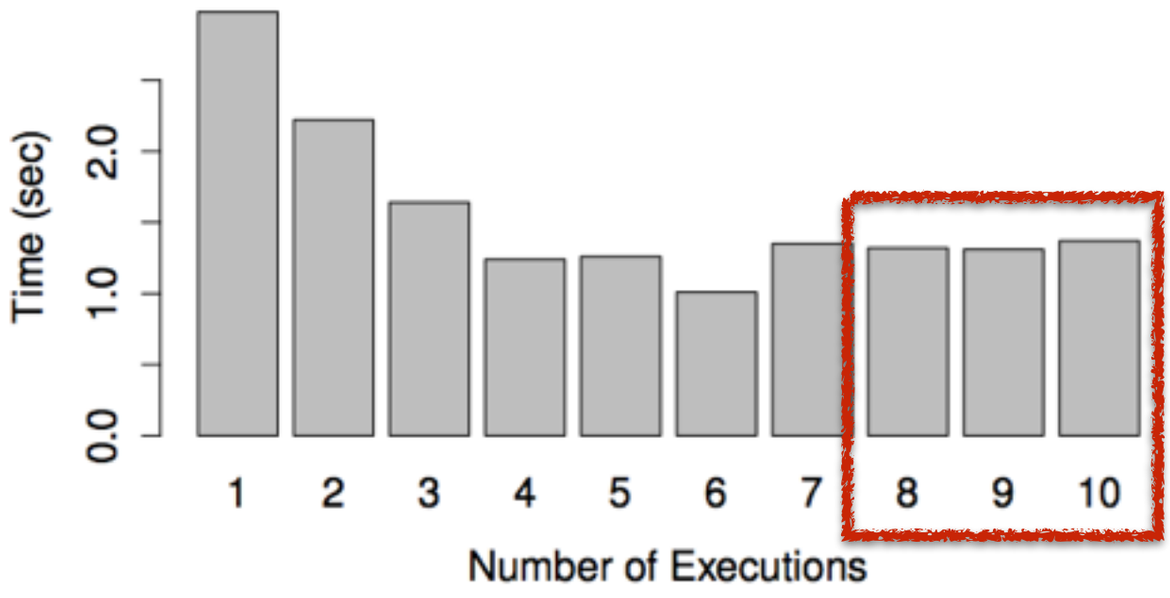

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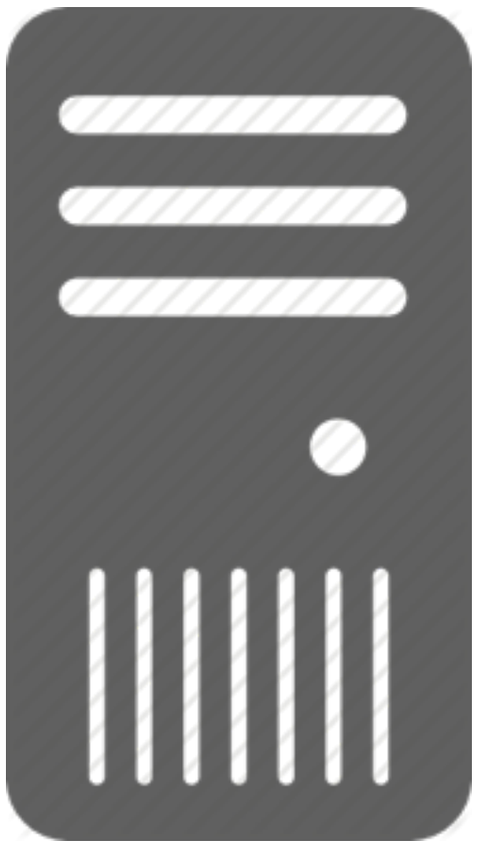
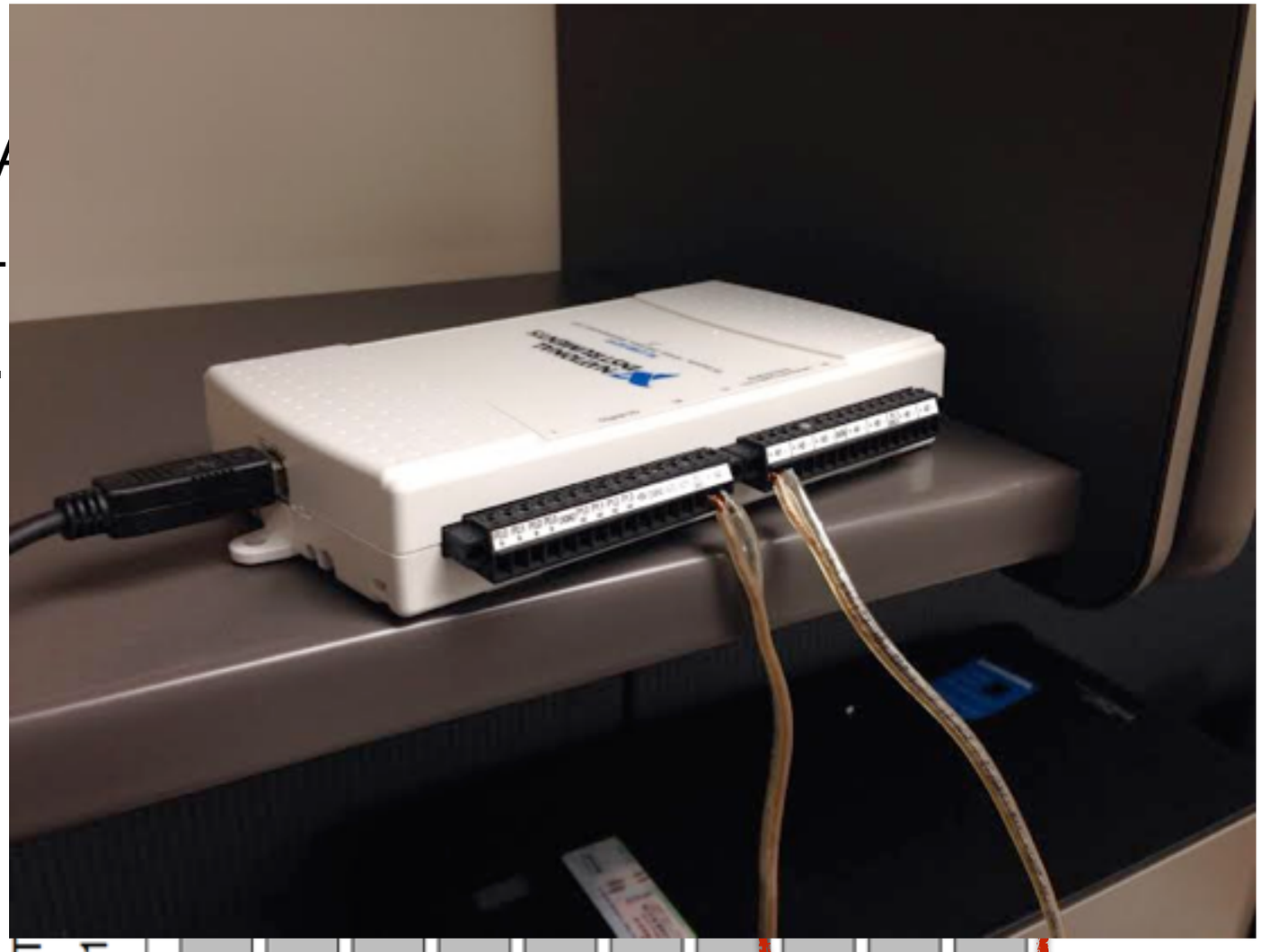
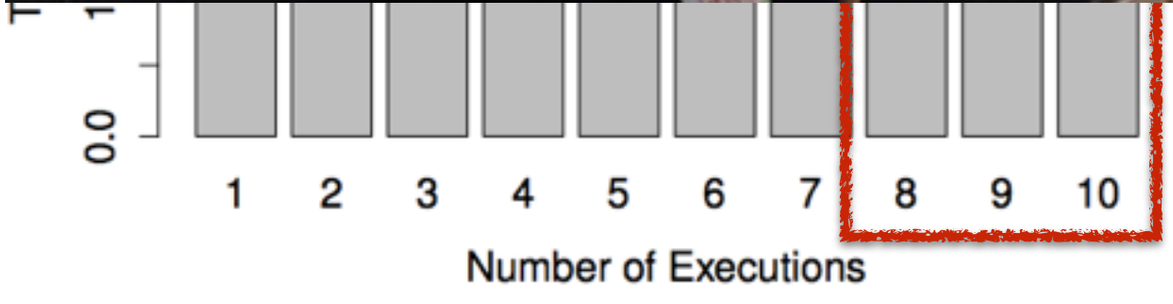


System#1: A
Debian, 2.4
version 1.7.





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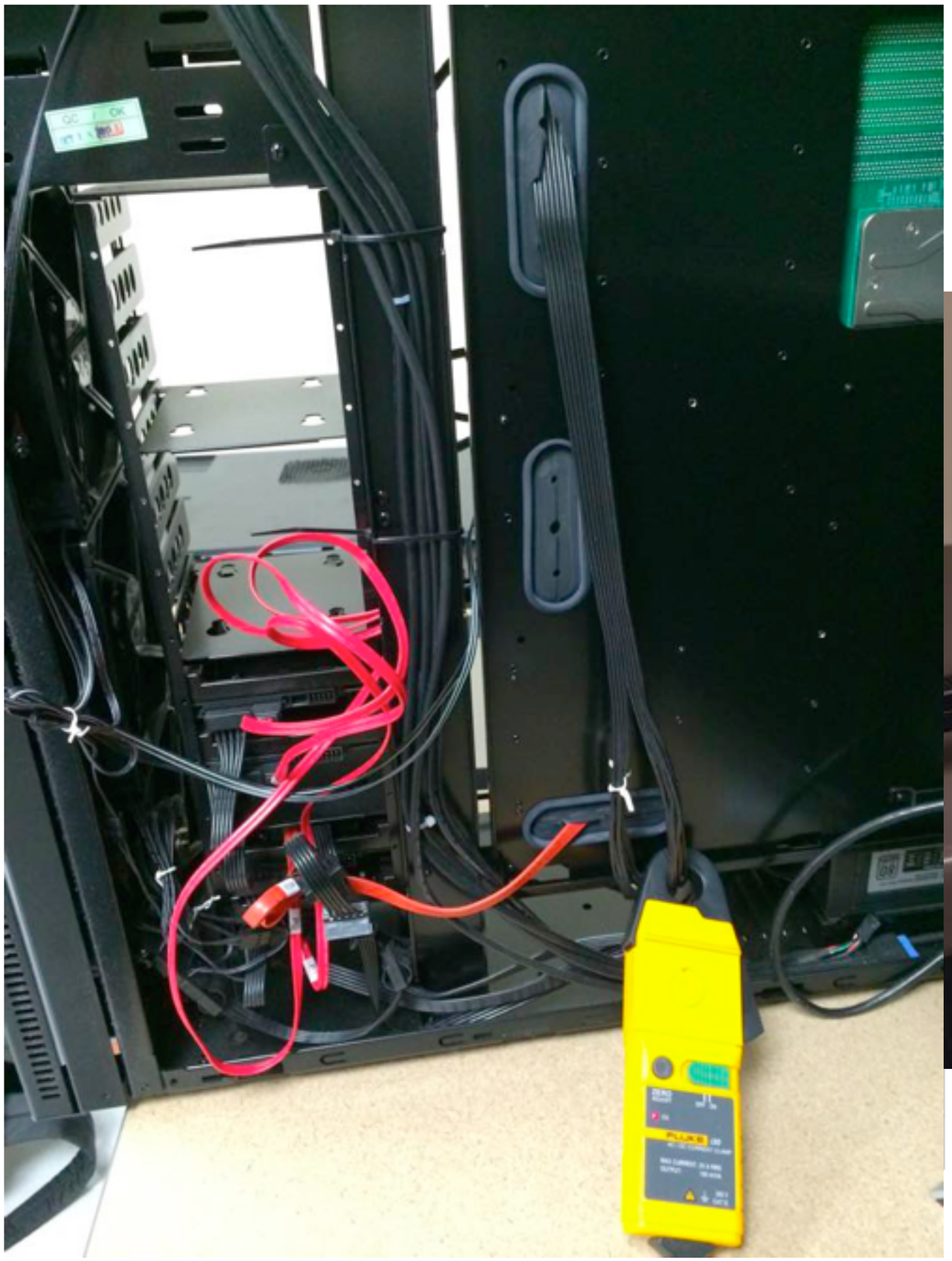

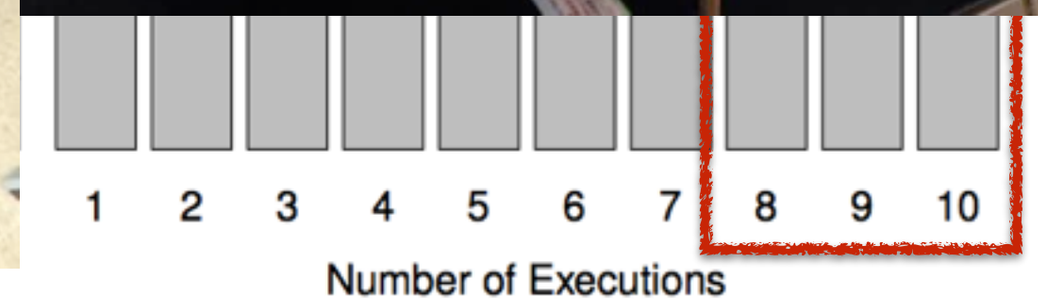

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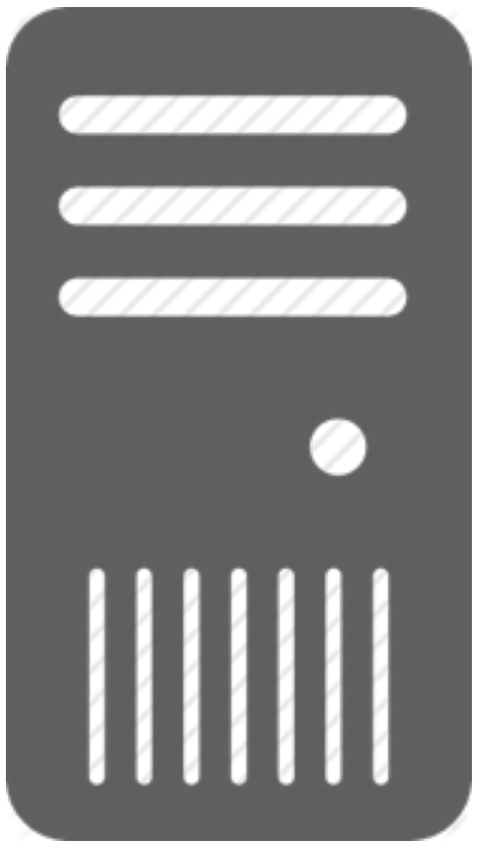

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jRAPL -- A framework for profiling energy consumption of Java programs

What is jRAPL?

jRAPL is framework for profiling Java programs running on CPUs with Running Average Power Limit (RAPL) support.

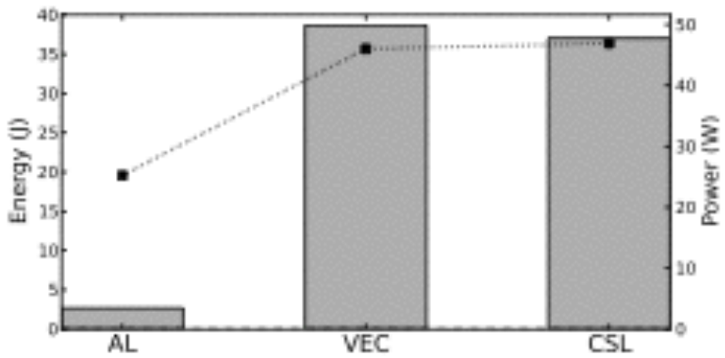
But, what is RAPL?

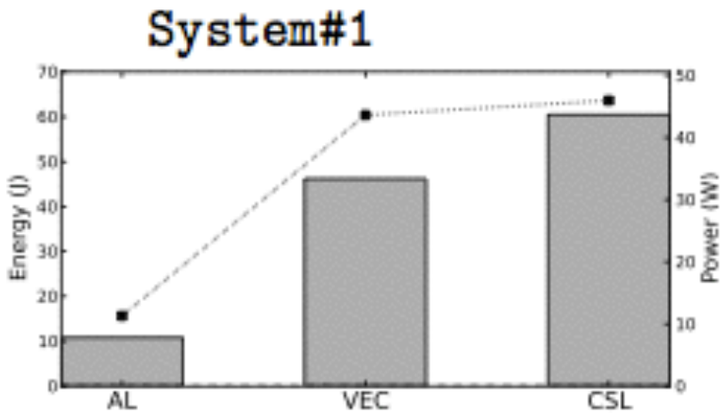
RAPL is a set of low-level interfaces with the ability to monitor, control, and get notifications of energy and power consumptio

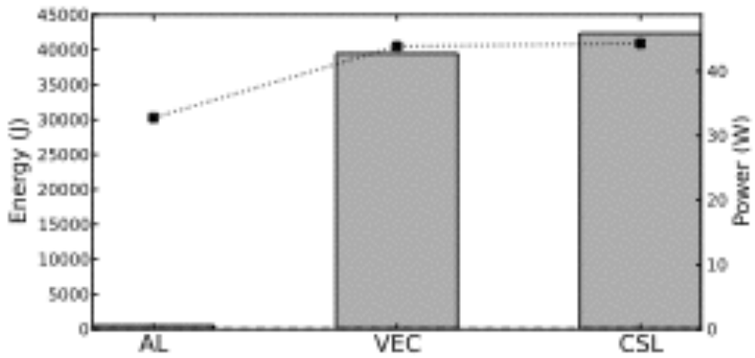
Originally designed by Intel for enabling chip-level power management, RAPL is widely supported in today's Intel architecture popular i5 and i7.

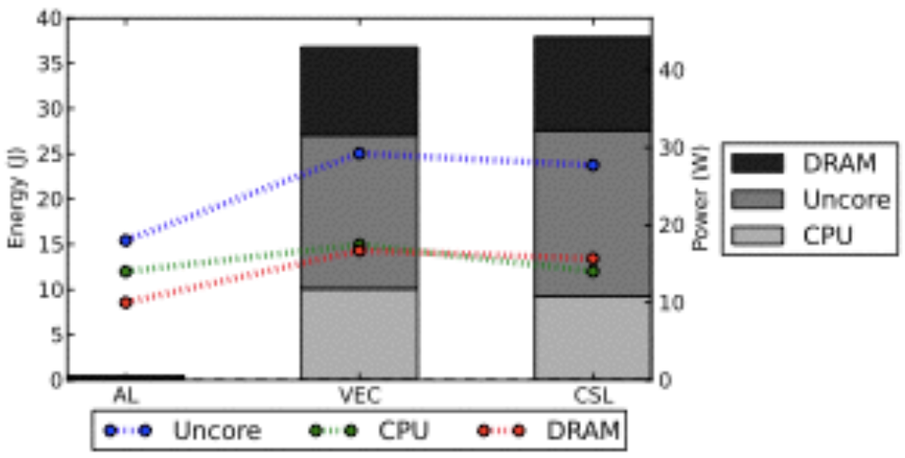
http://kliu20.github.io/jRAPL/

Lists

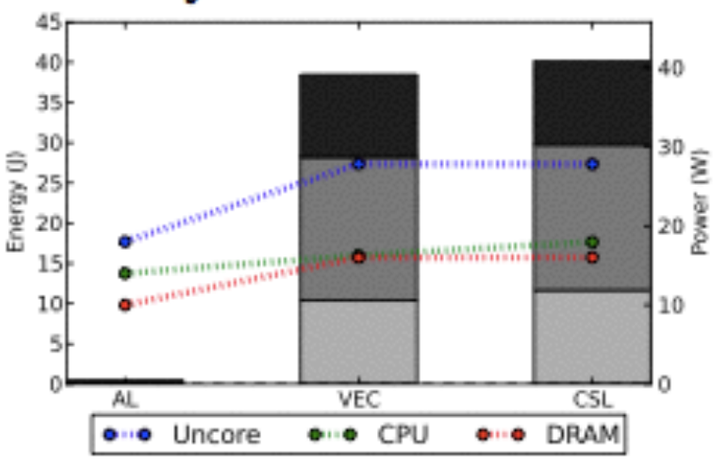




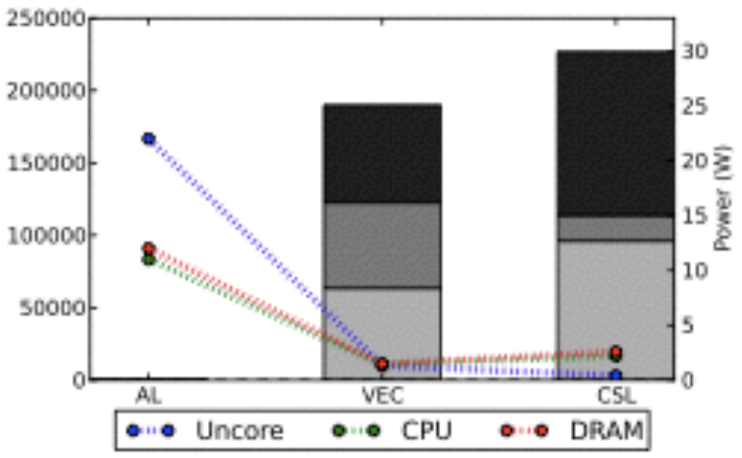




Traversal

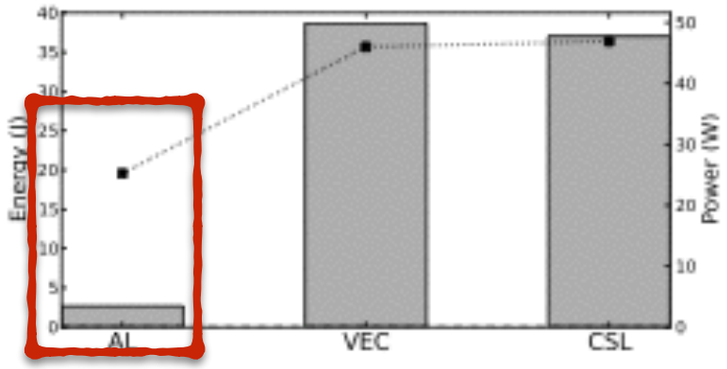


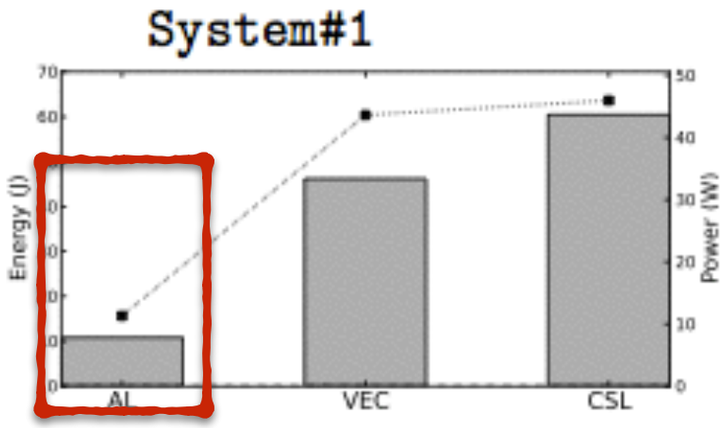
Insertion

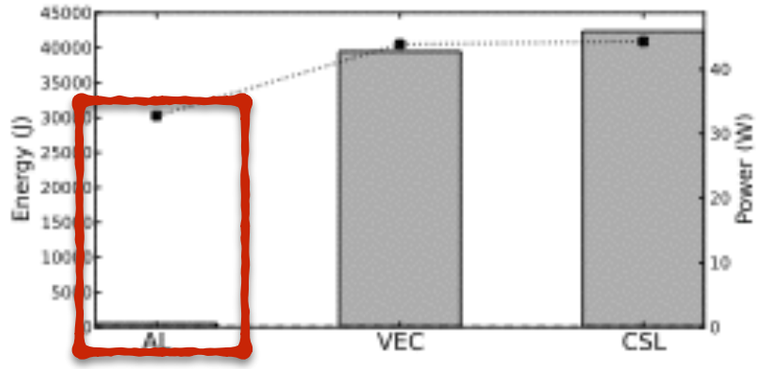


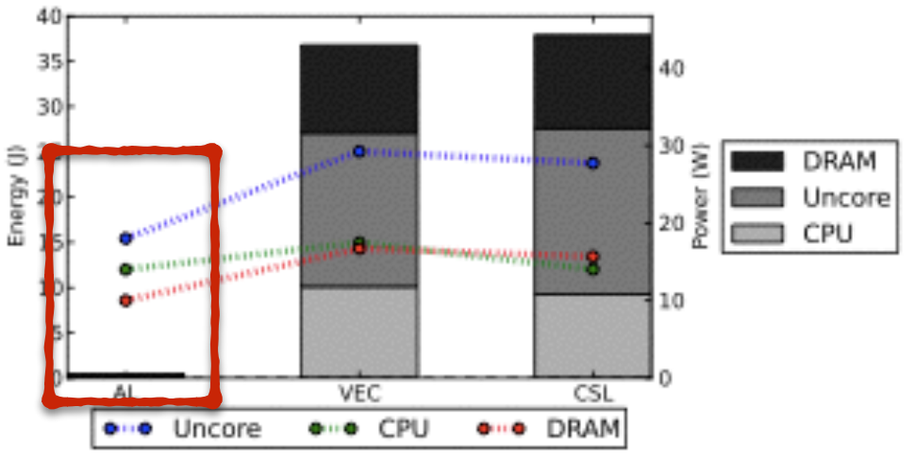
Removal

Lists









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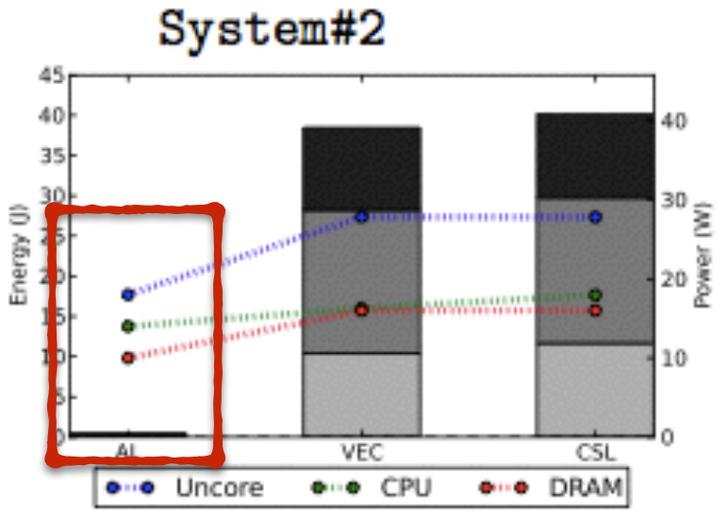

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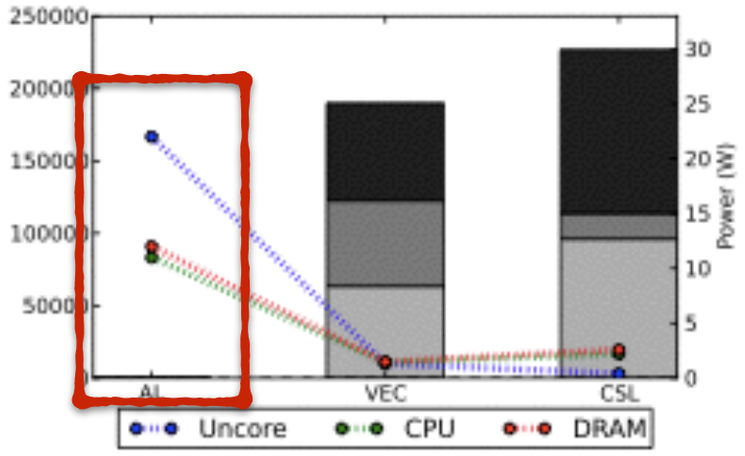

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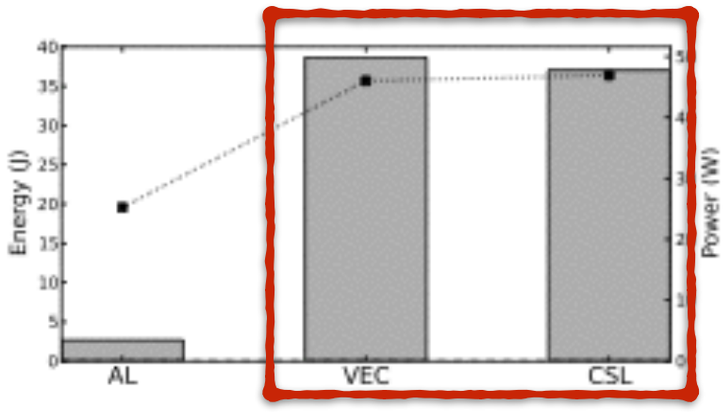

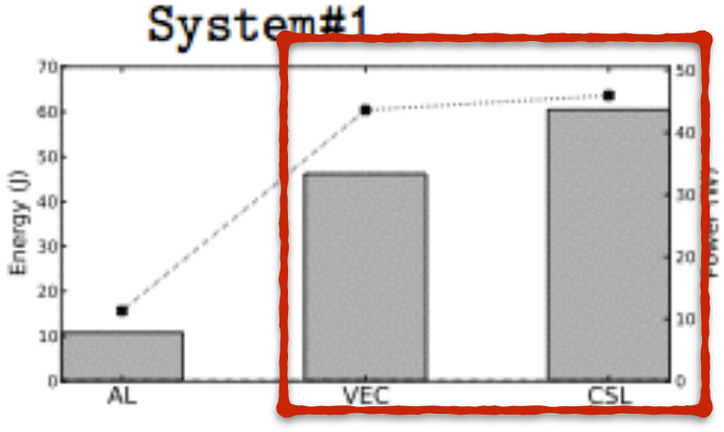

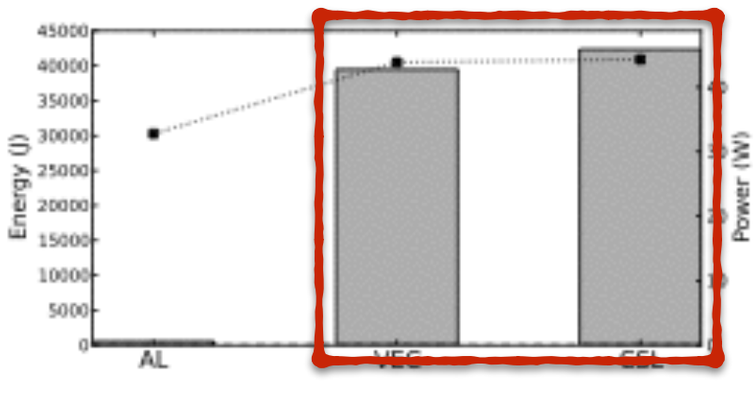

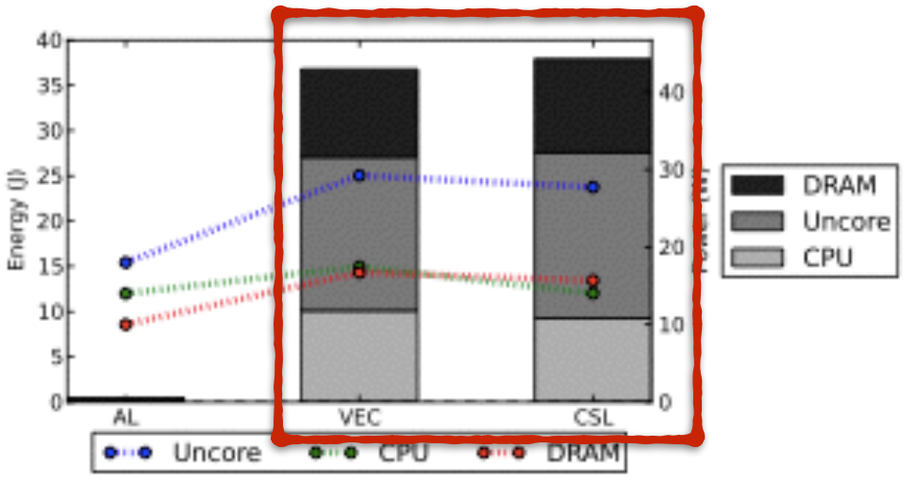

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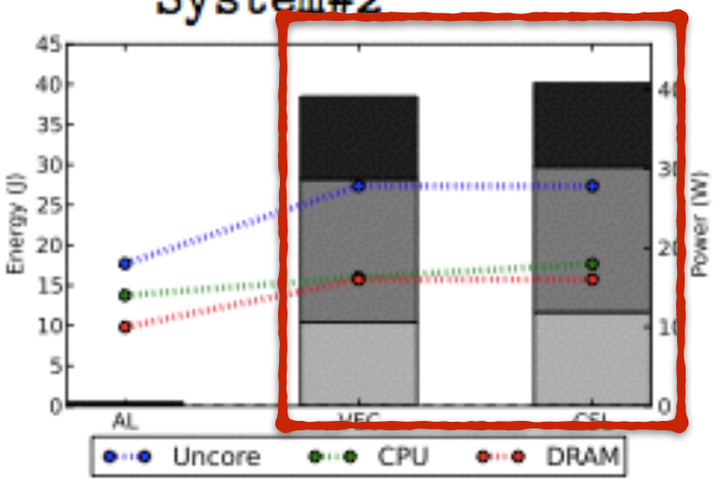
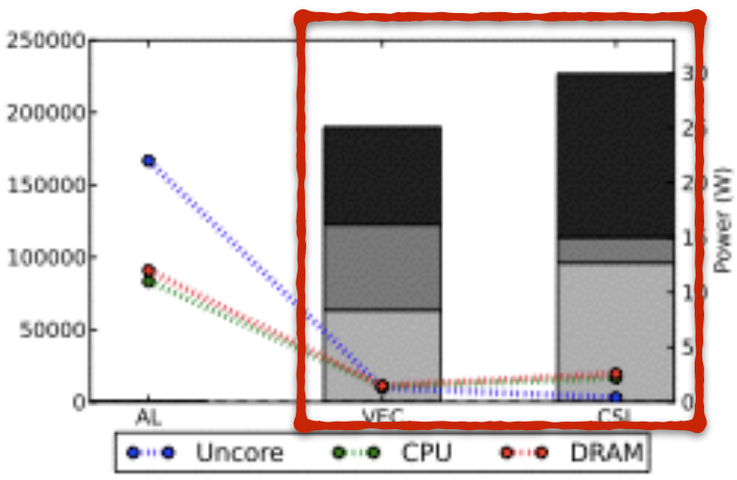


Insertion

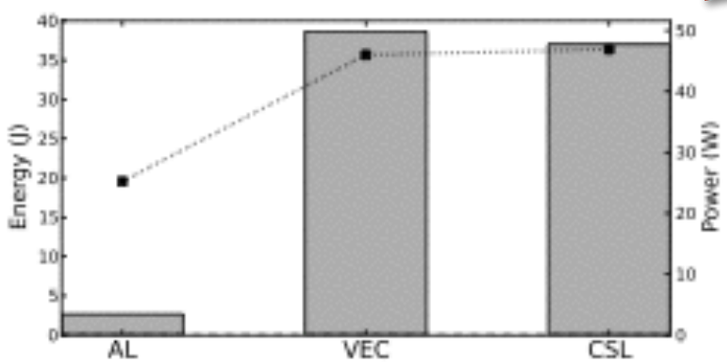


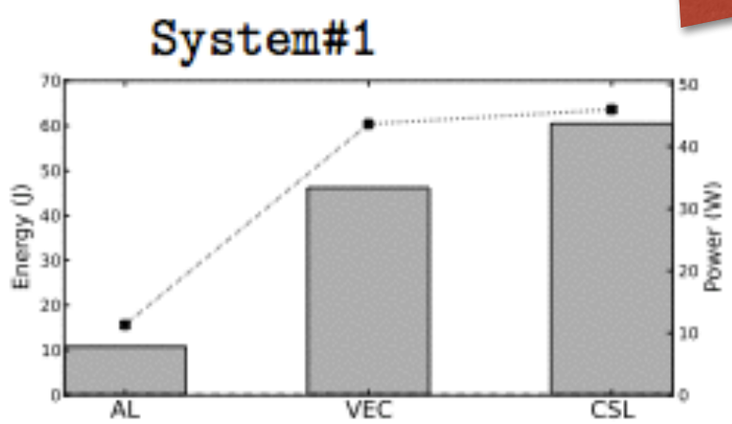
Removal

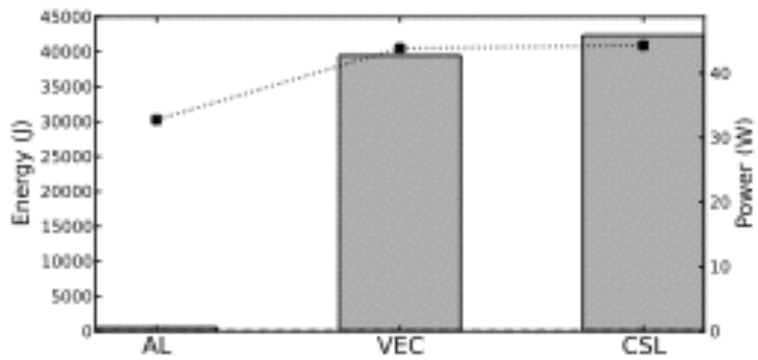
Lists

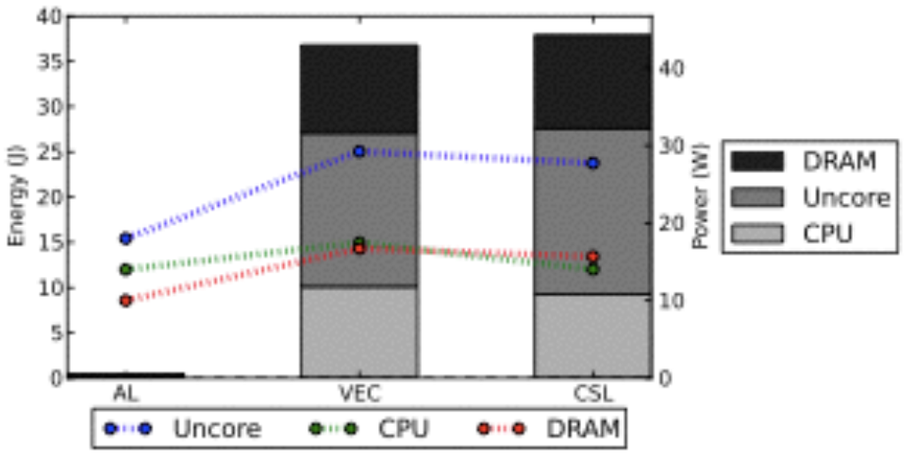
COW: -46x

COW: +152x

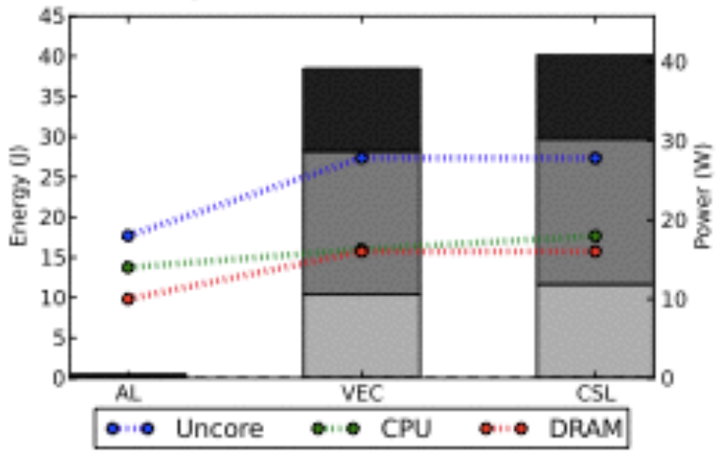




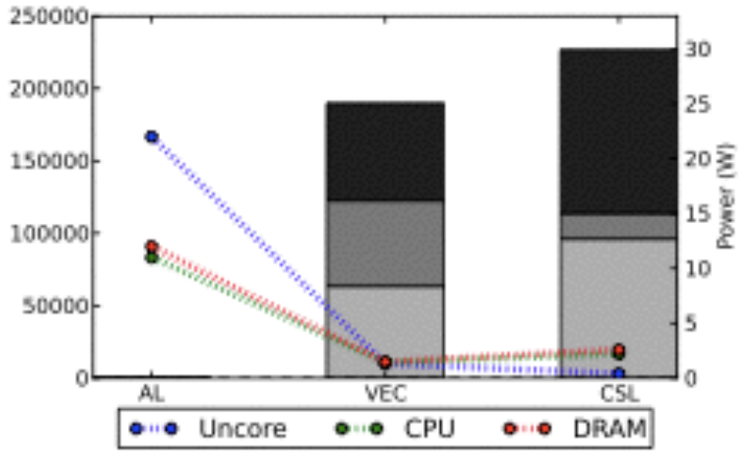




Traversal

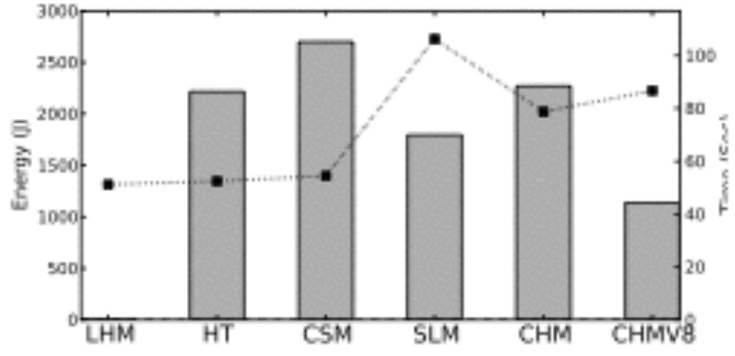


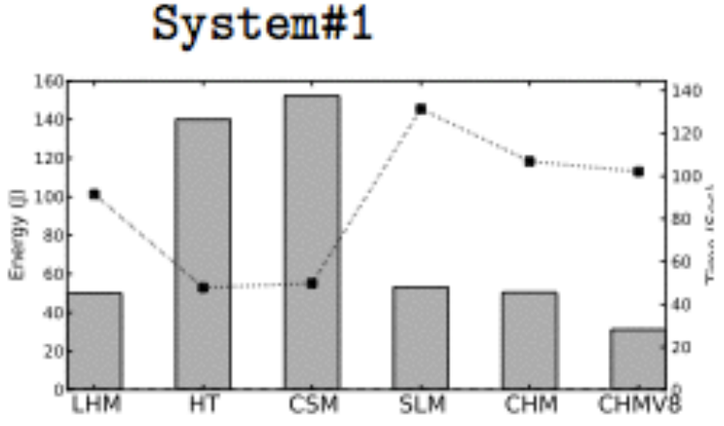
Insertion

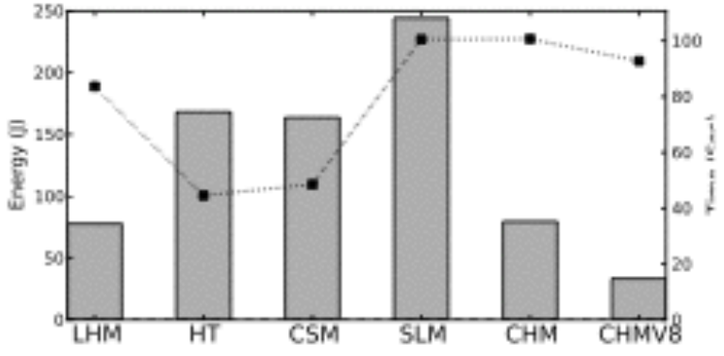


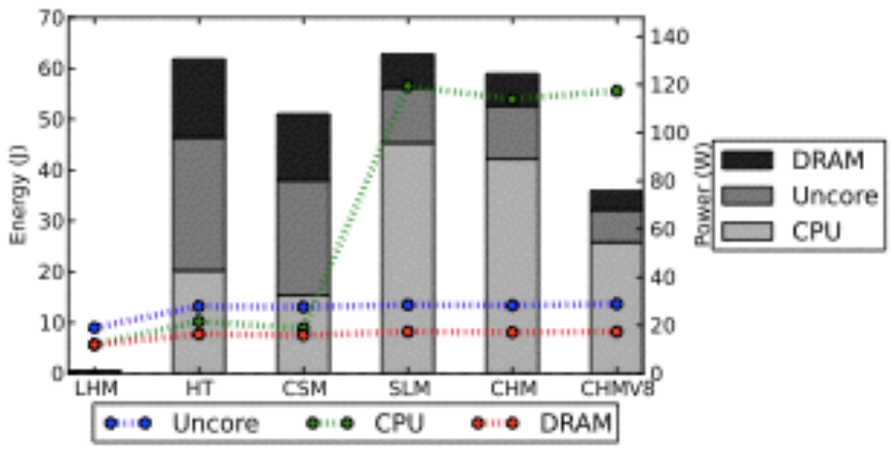
Removal

Maps

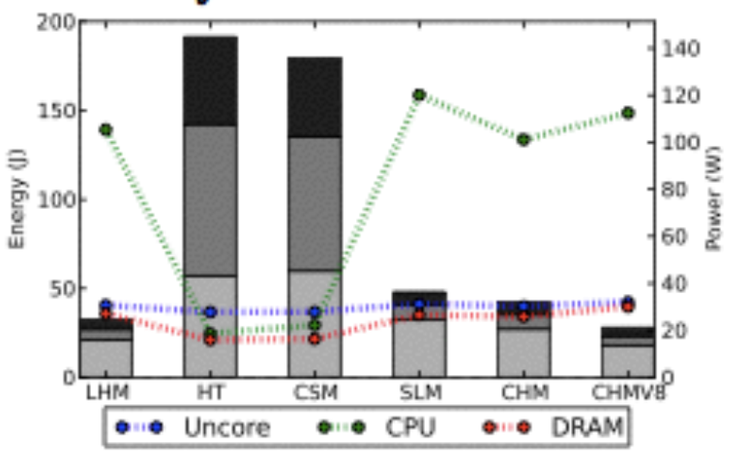




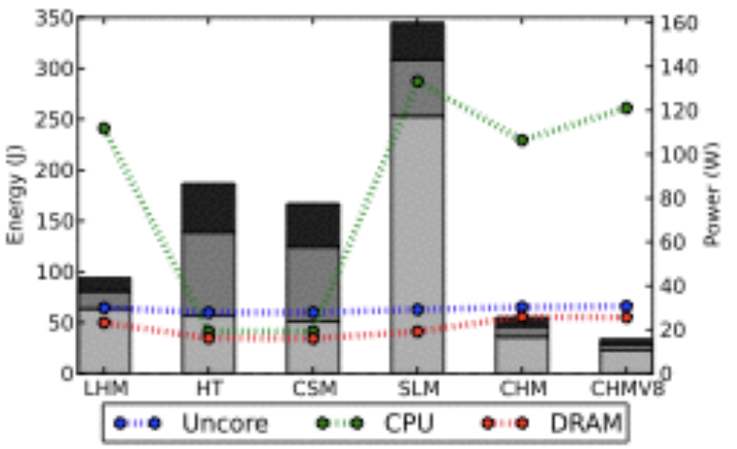




Traversal

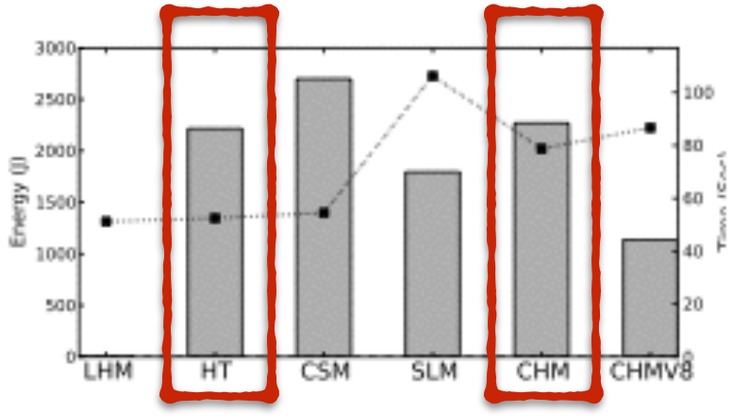


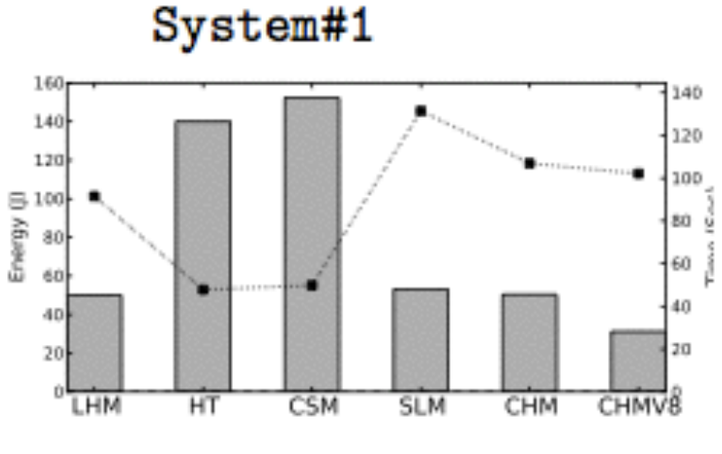
Insertion

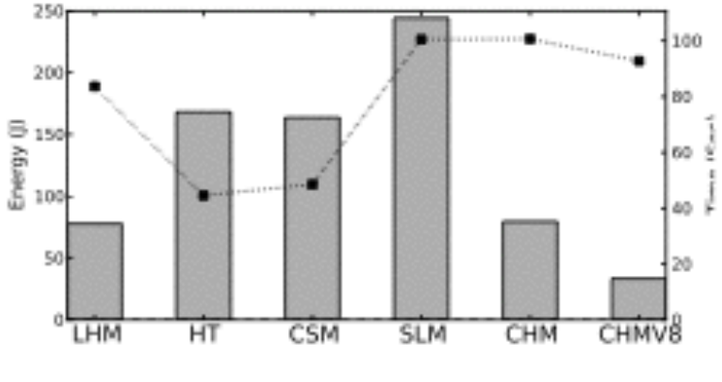


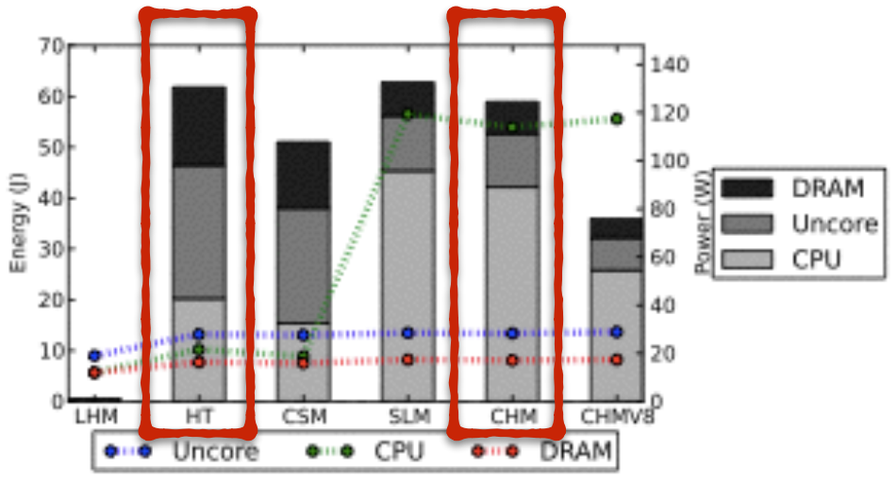
Removal

Maps

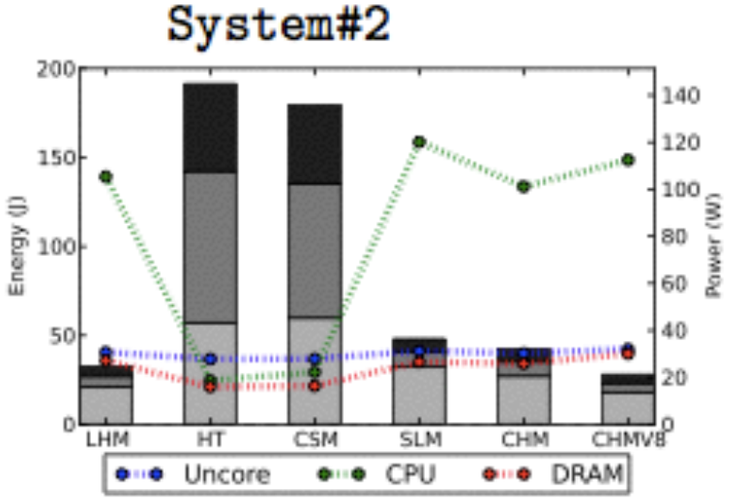




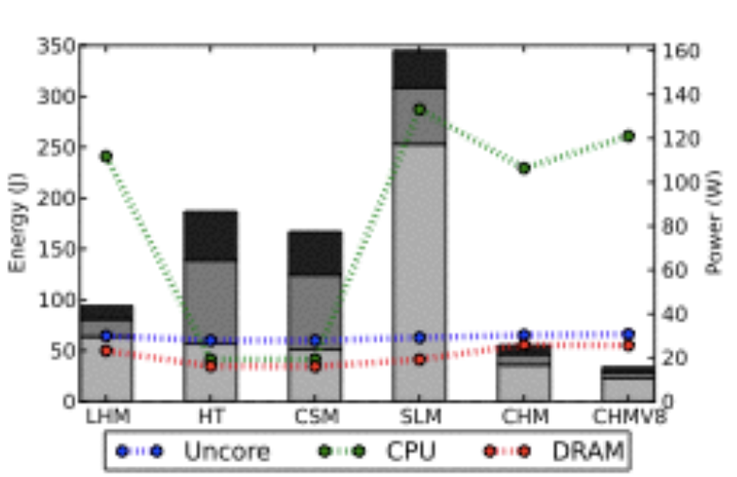




Traversal

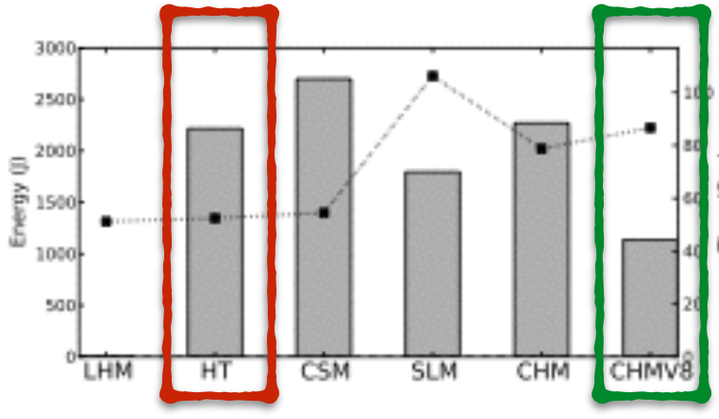


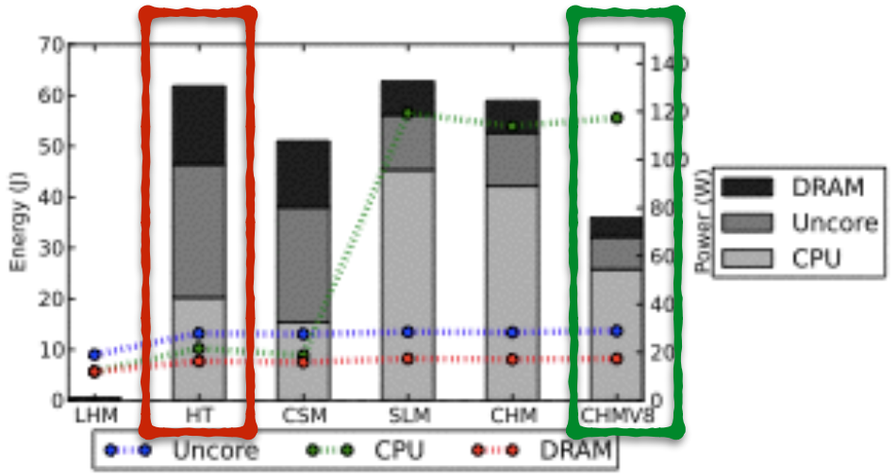
Insertion



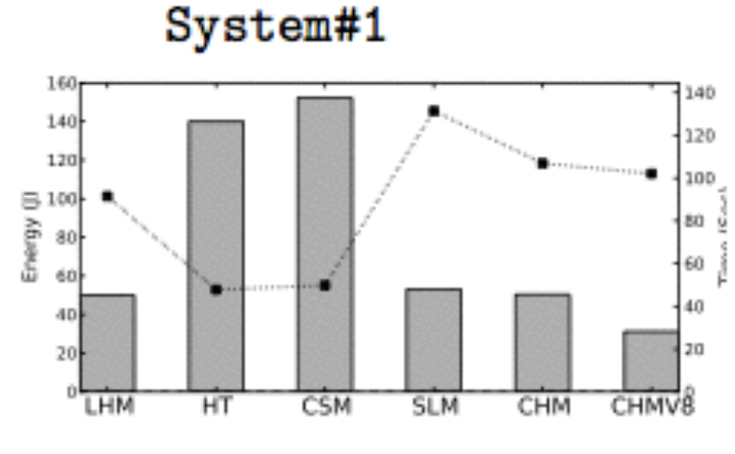
Removal

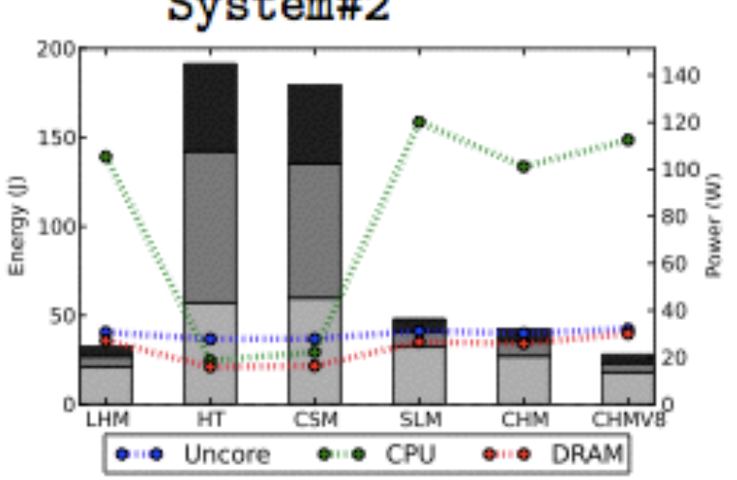
Maps





Traversal





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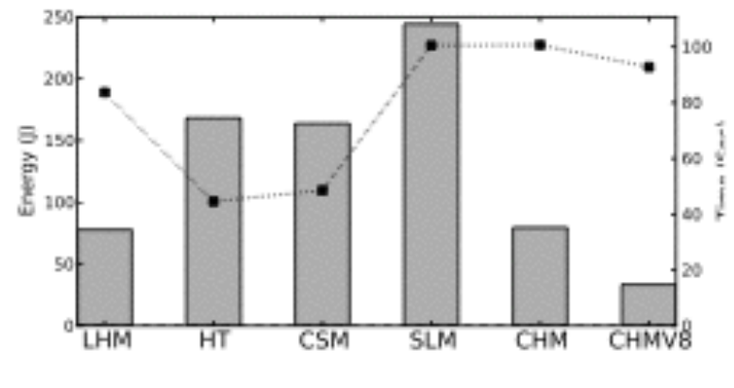
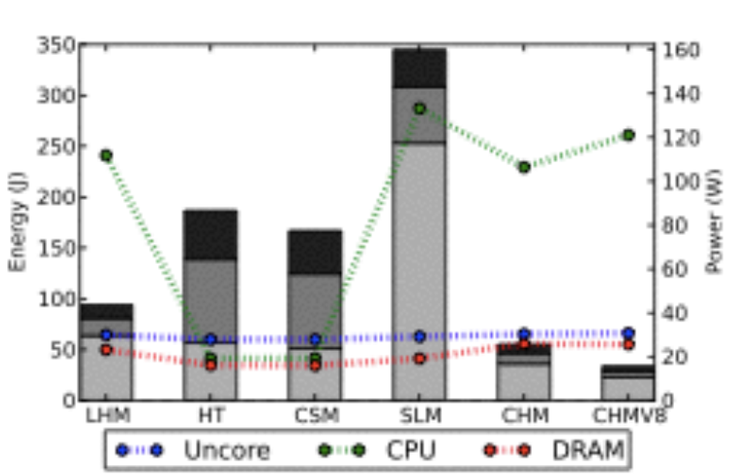
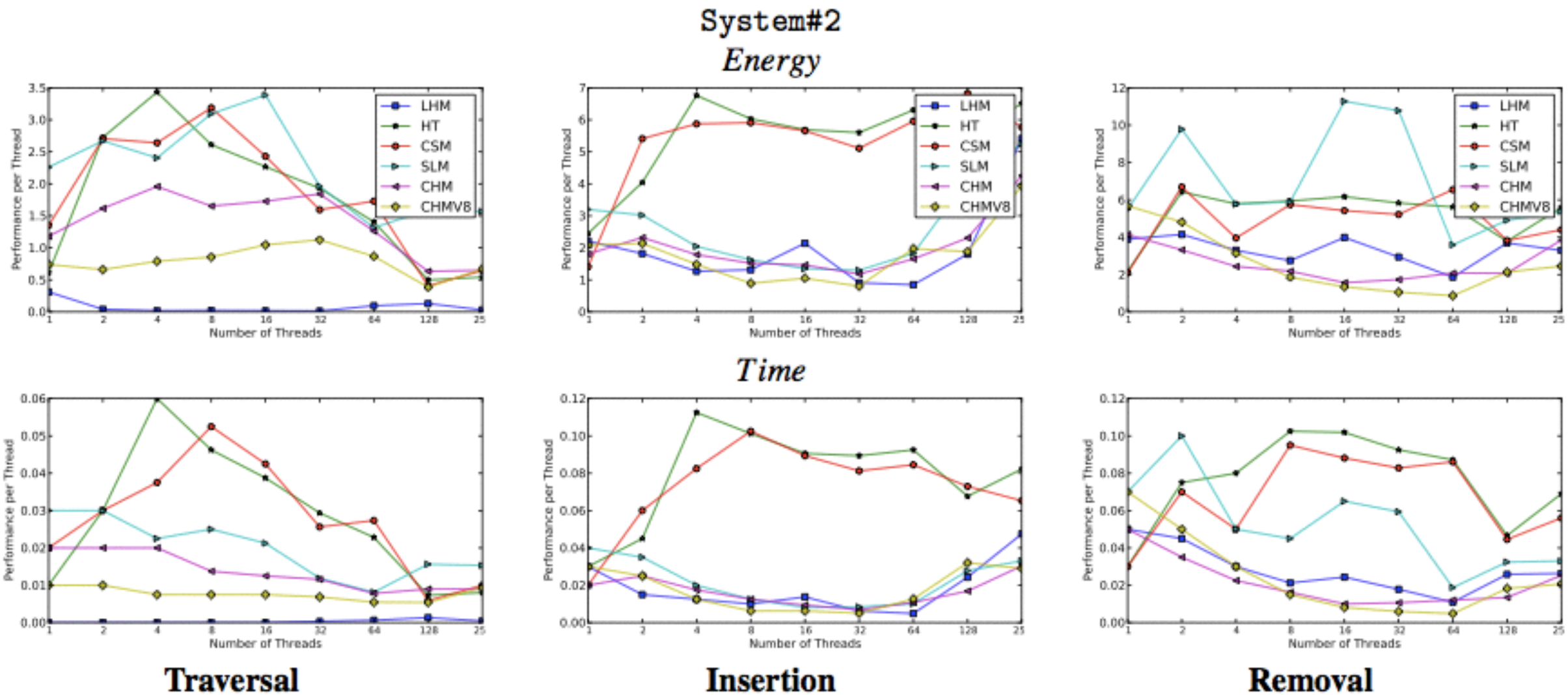


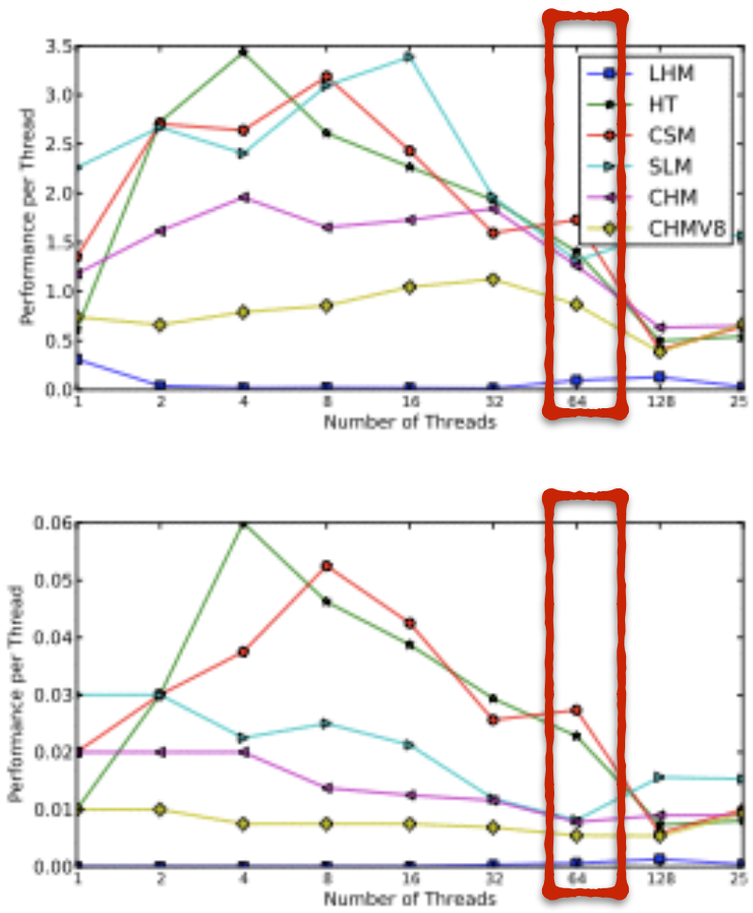


Removal

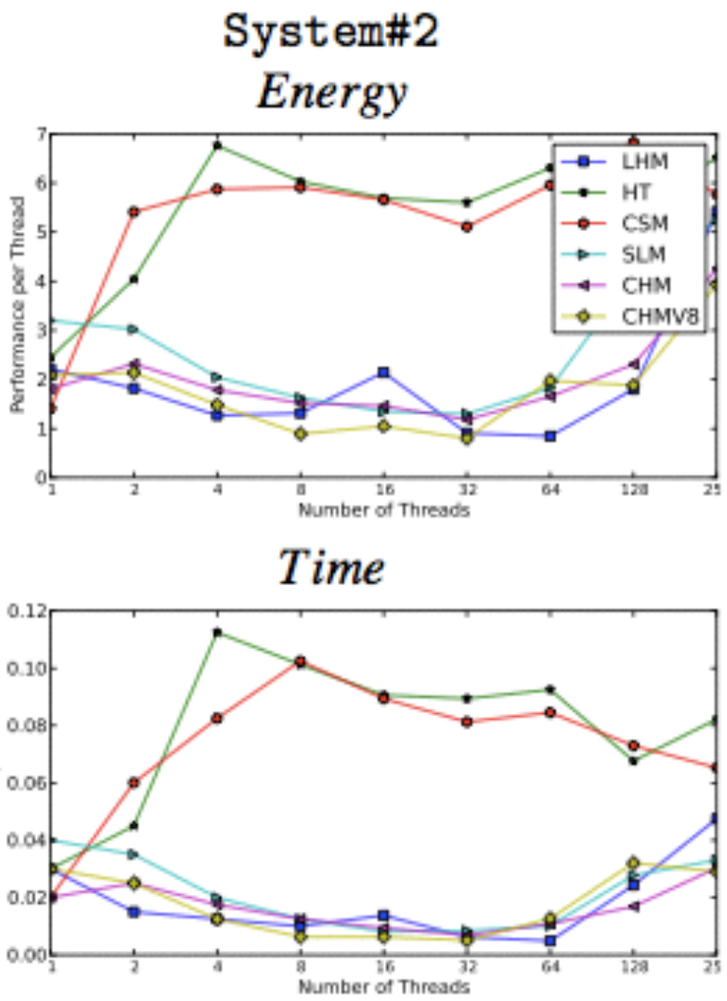
Do Maps Scale?



Do Maps Scale?



Traversal



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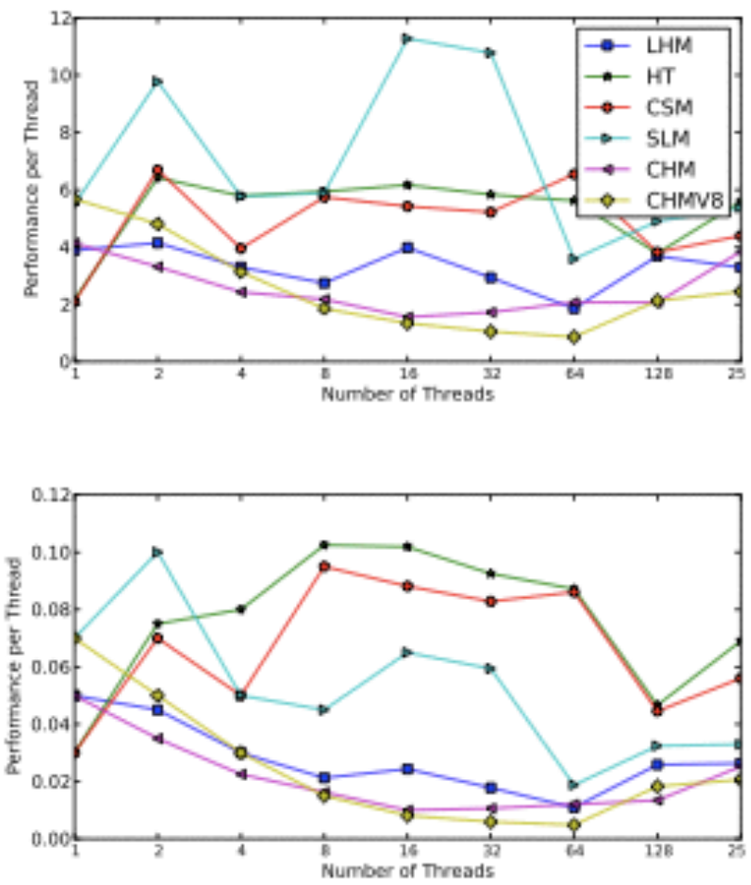
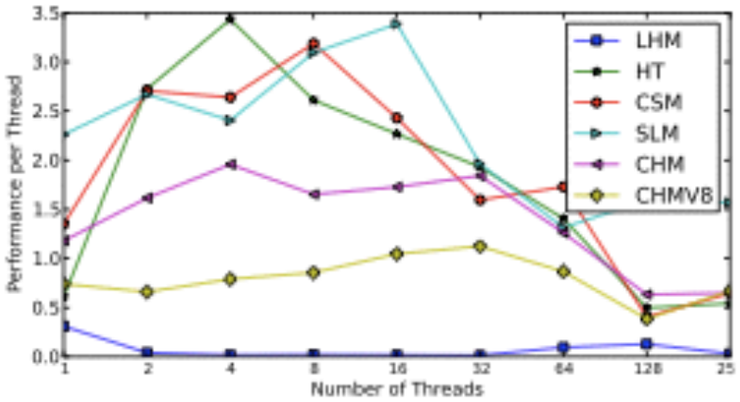


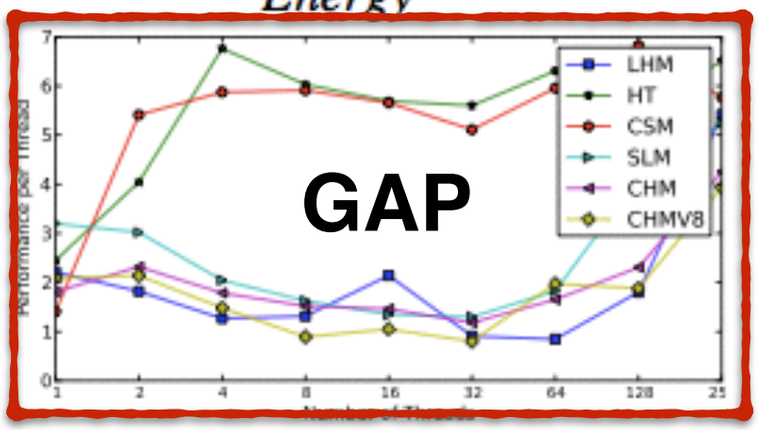
Removal

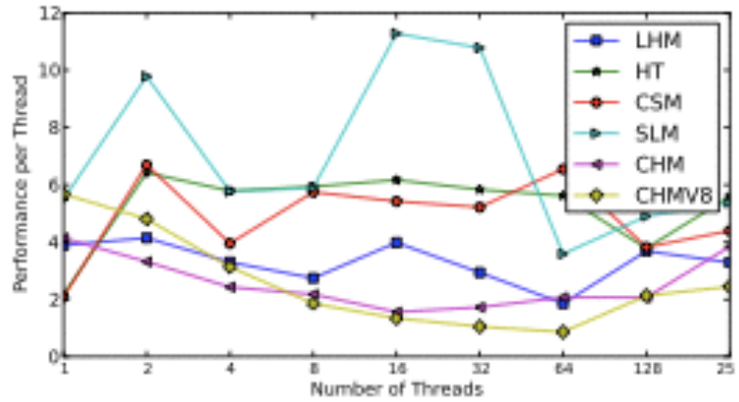
Do Maps Scale?

System#2

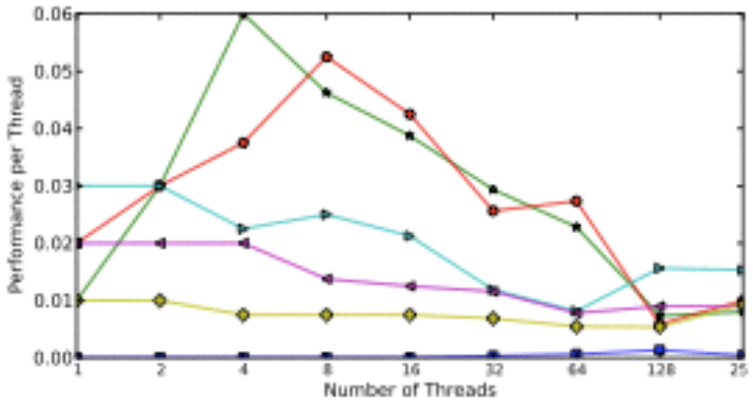
Energy



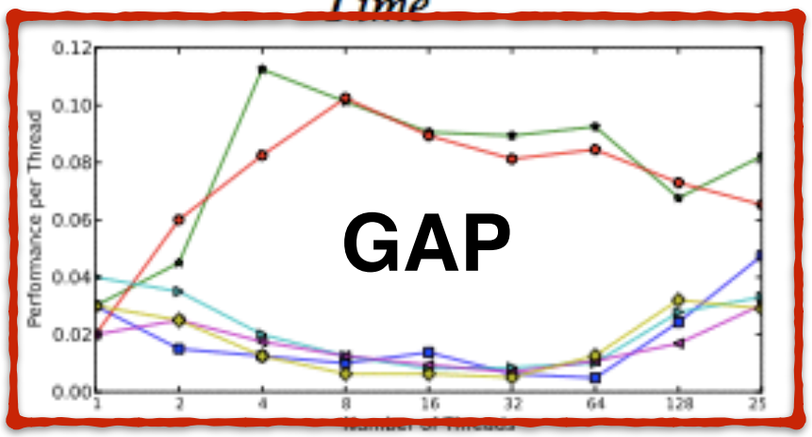




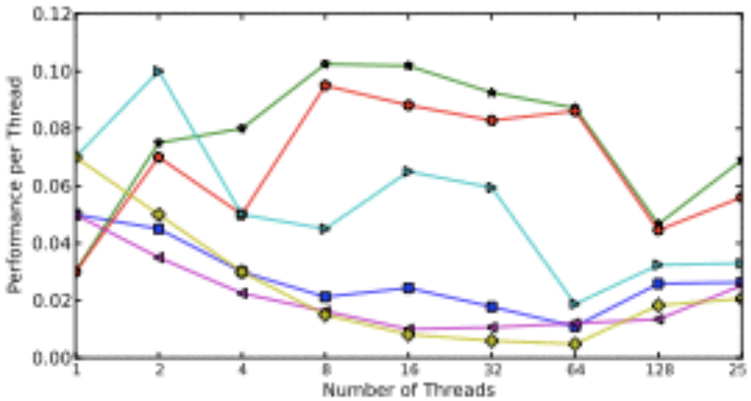
Time



Traversal



Insertion



Removal

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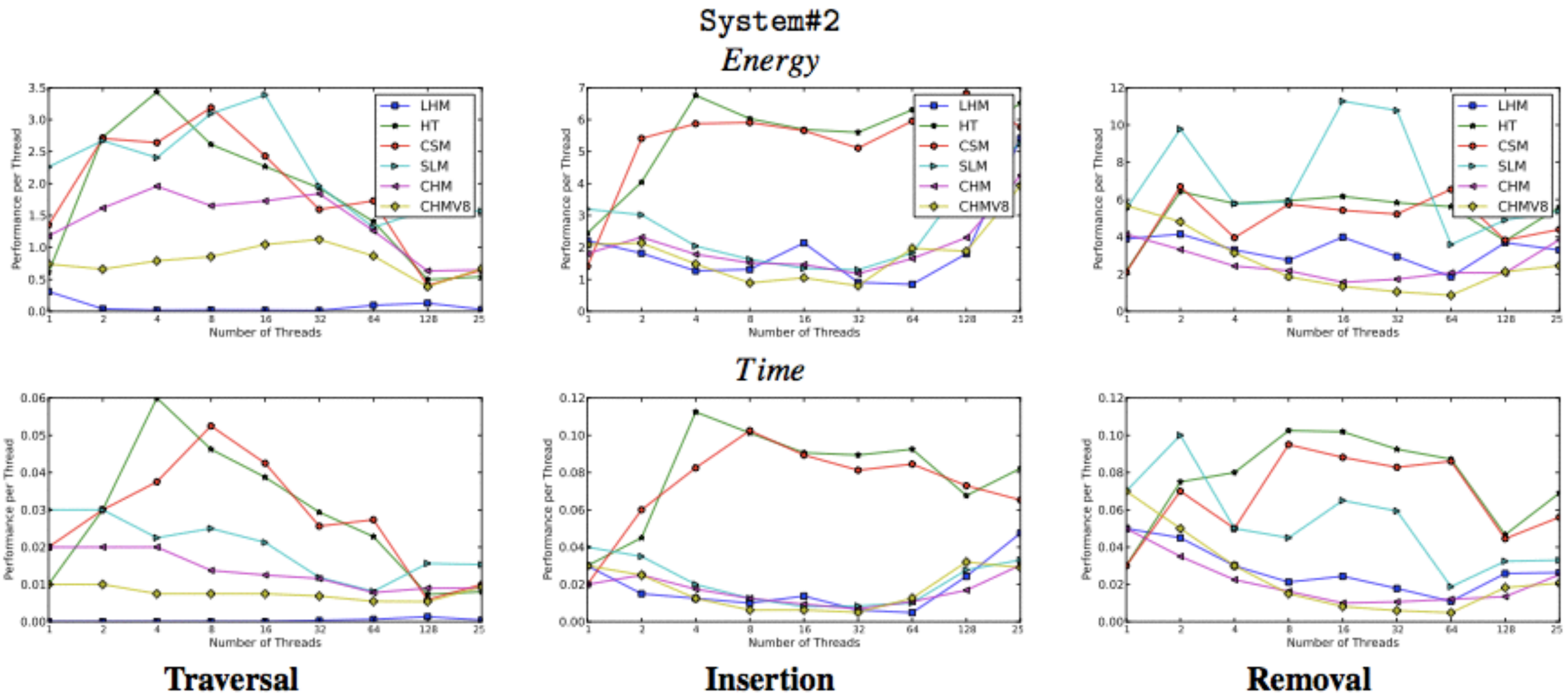

If you are in doubt, go for CHMV8!

The Goal

1. To understand how software developers are dealing with energy consumption issues;

2. To characterize the energy-consumption behavior of
    1. Thread-safe collections

    2. Thread management techniques
3. To derive a refactoring to (1) identify and (2) refactor one energy-consumption anti-pattern;

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    2. <u>Thread management techniques</u>

3. To derive a refactoring to (1) identify and (2) refactor one energy-consumption anti-pattern;

Thread management constructs

- **Explicit threading (the Thread-style):** Using the *java.lang.Thread* class

- **Thread pooling (the Executor-style):** Using the *java.util.concurrent.Executor** framework

- **Working Stealing (the ForkJoin-style):** Using the *java.util.concurrent.ForkJoin** framework

Benchmarks

- **Embarrassingly parallel:** spectralnorm, sunflow, n-queens
- **Leaning parallel:** xalan, knucleotide, tomcat
- **Leaning serial:** mandelbrot, largestImage
- **Embarrassingly serial:** h2

Benchmarks

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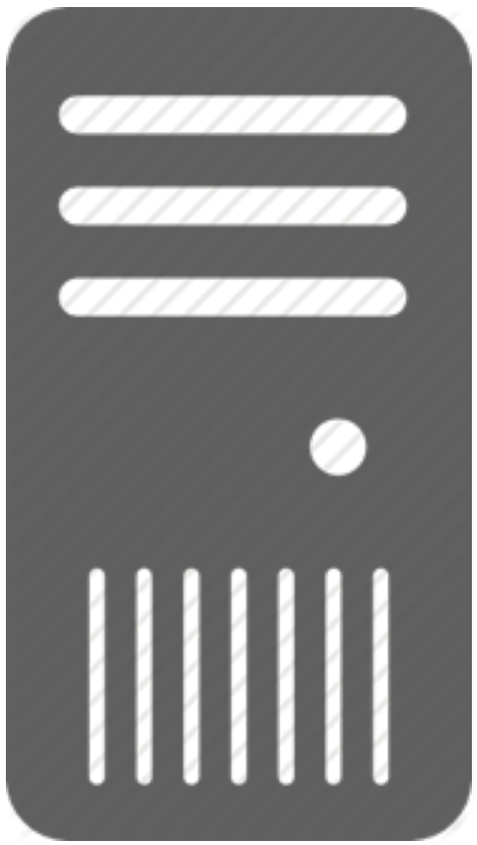
Micro-benchmarks

DaCapo benchmarks

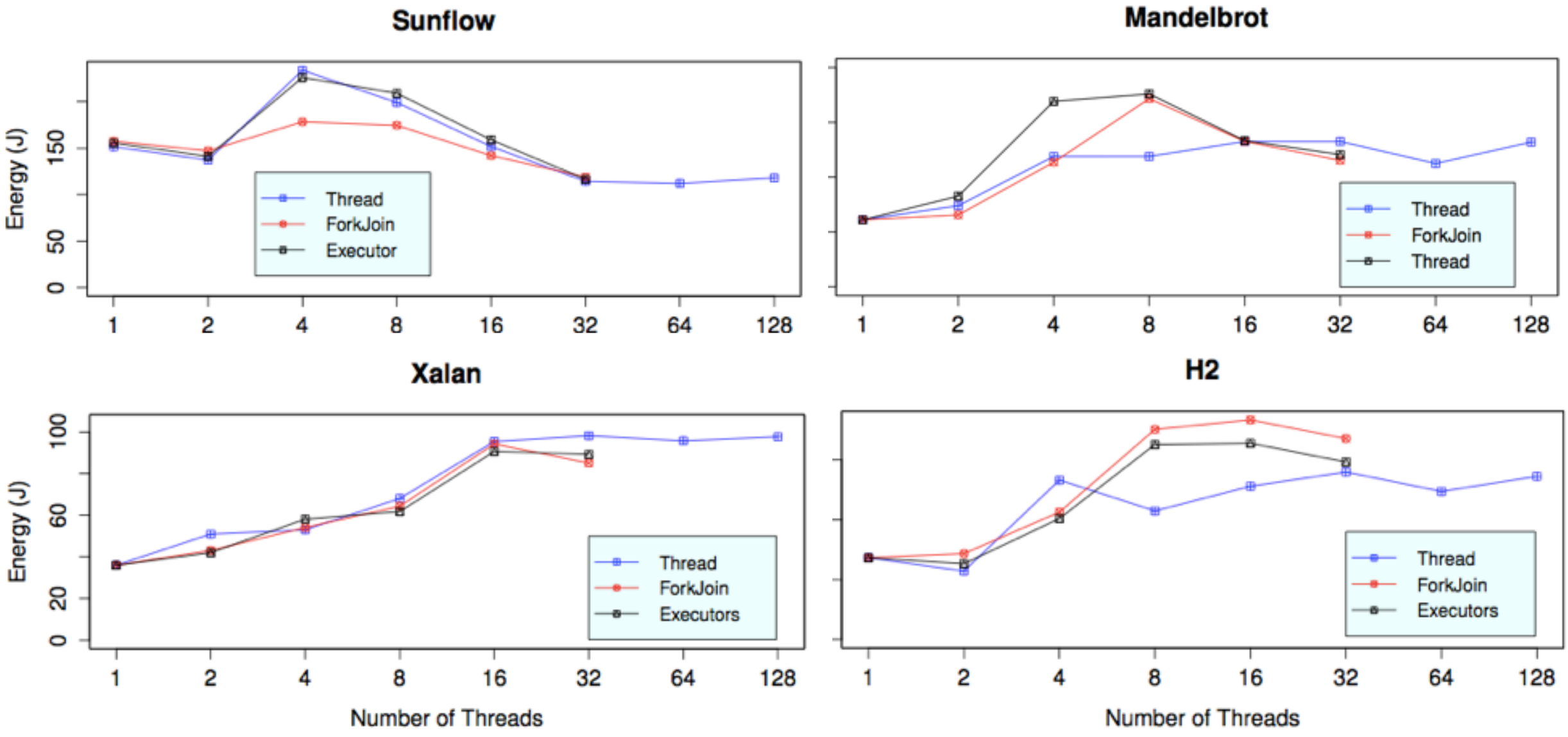
the DaCapo benchmark suite

Experimental Environment

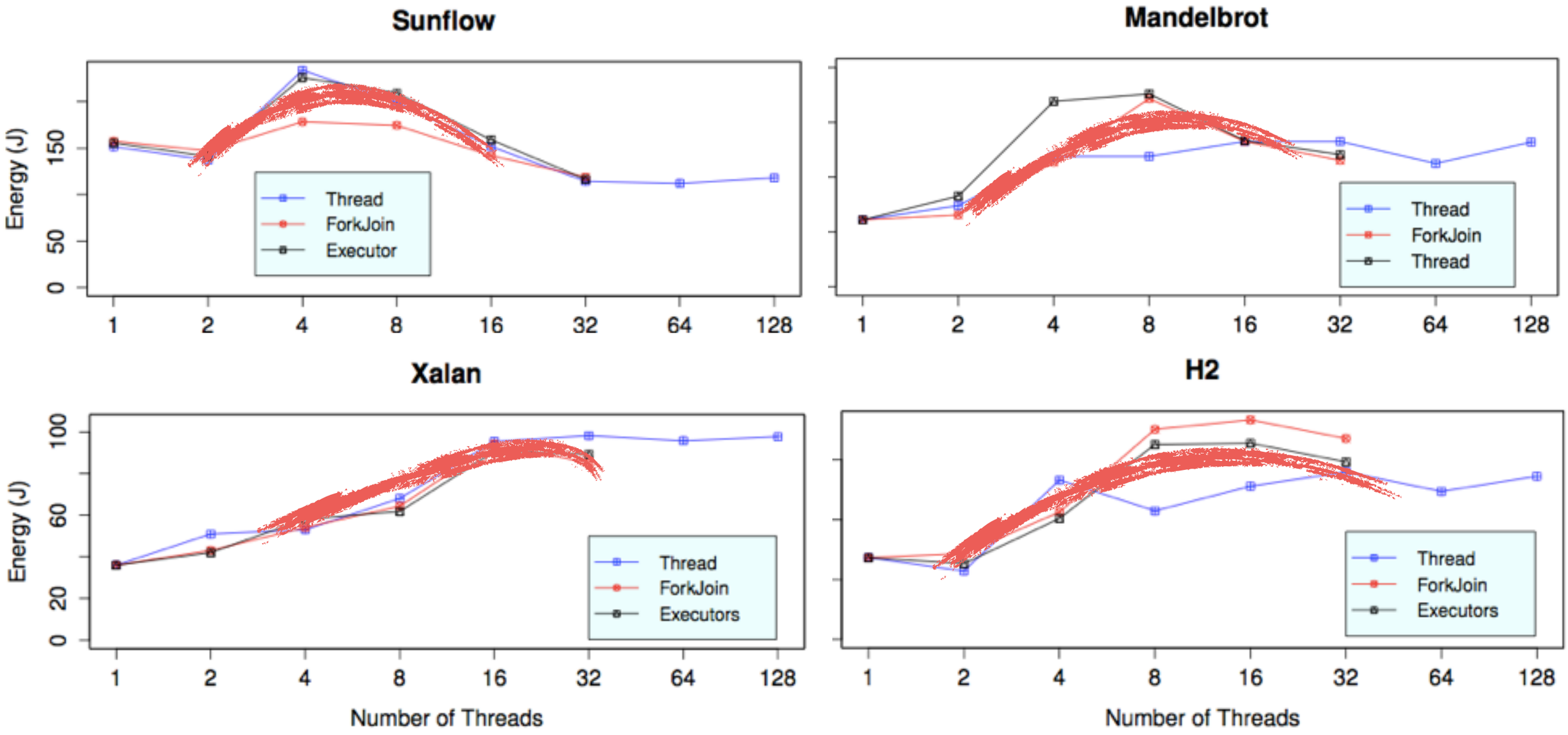


A 2×16-core **AMD CPUs**, running Debian, 2.4 GHz, 64GB of memory, JDK version 1.7.0 11, build 21.

Energy Consumption When Varying the Number of Threads



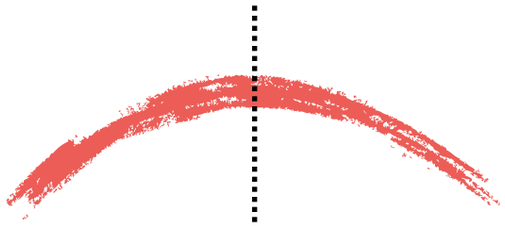
The Λ Curve


Sunflow
Energy (J)
0
50
150
Thread
ForkJoin
Executor
1
2
4
8
16
32
64
128
Mandelbrot
Thread
ForkJoin
Thread
Xalan
Energy (J)
0
20
60
100
Thread
ForkJoin
Executors
Number of Threads
H2
Thread
ForkJoin
Executors
Number of Threads

The Λ Curve

The Λ Curve

The Λ Curve



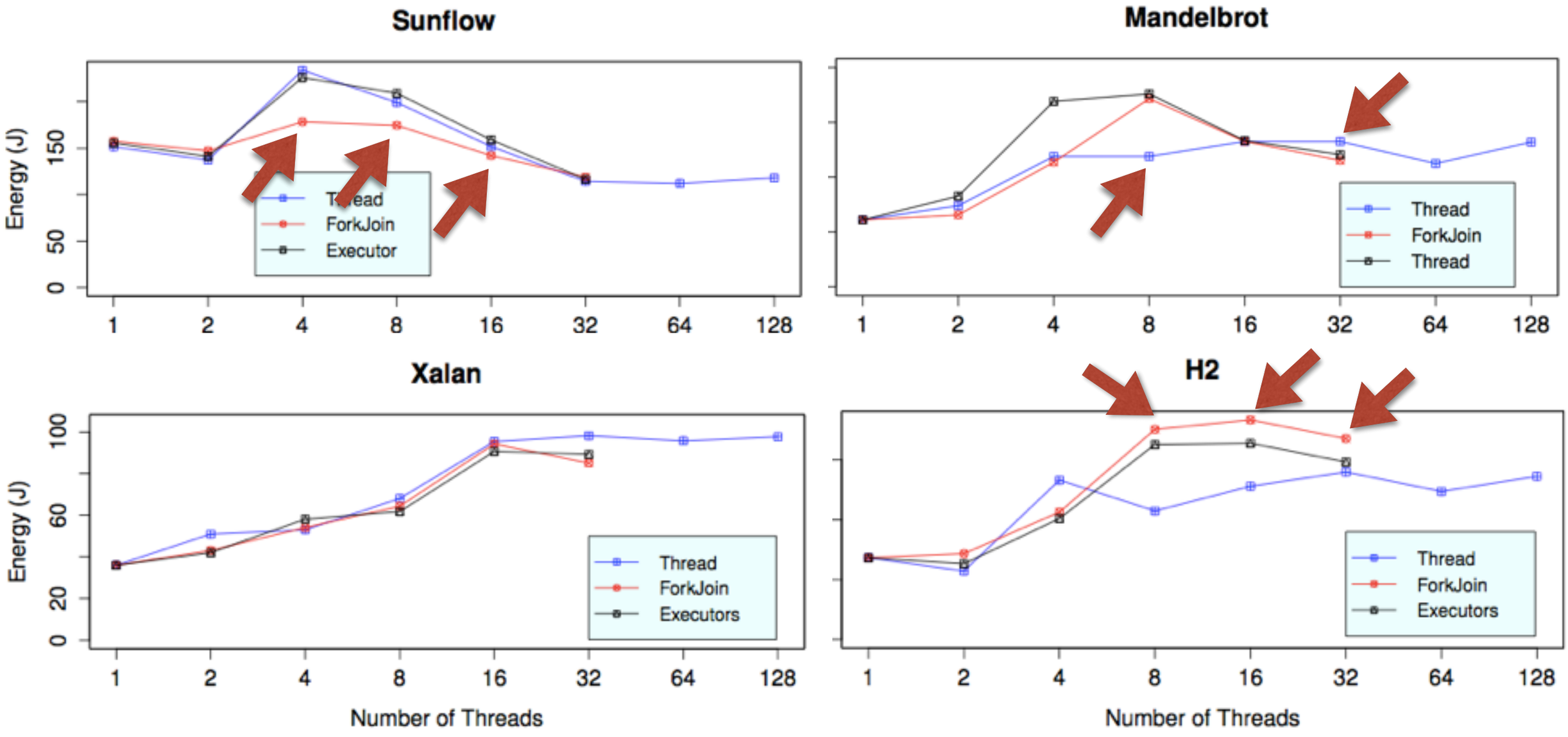
- More cores idle
- Frequency at a lower level

The Λ Curve

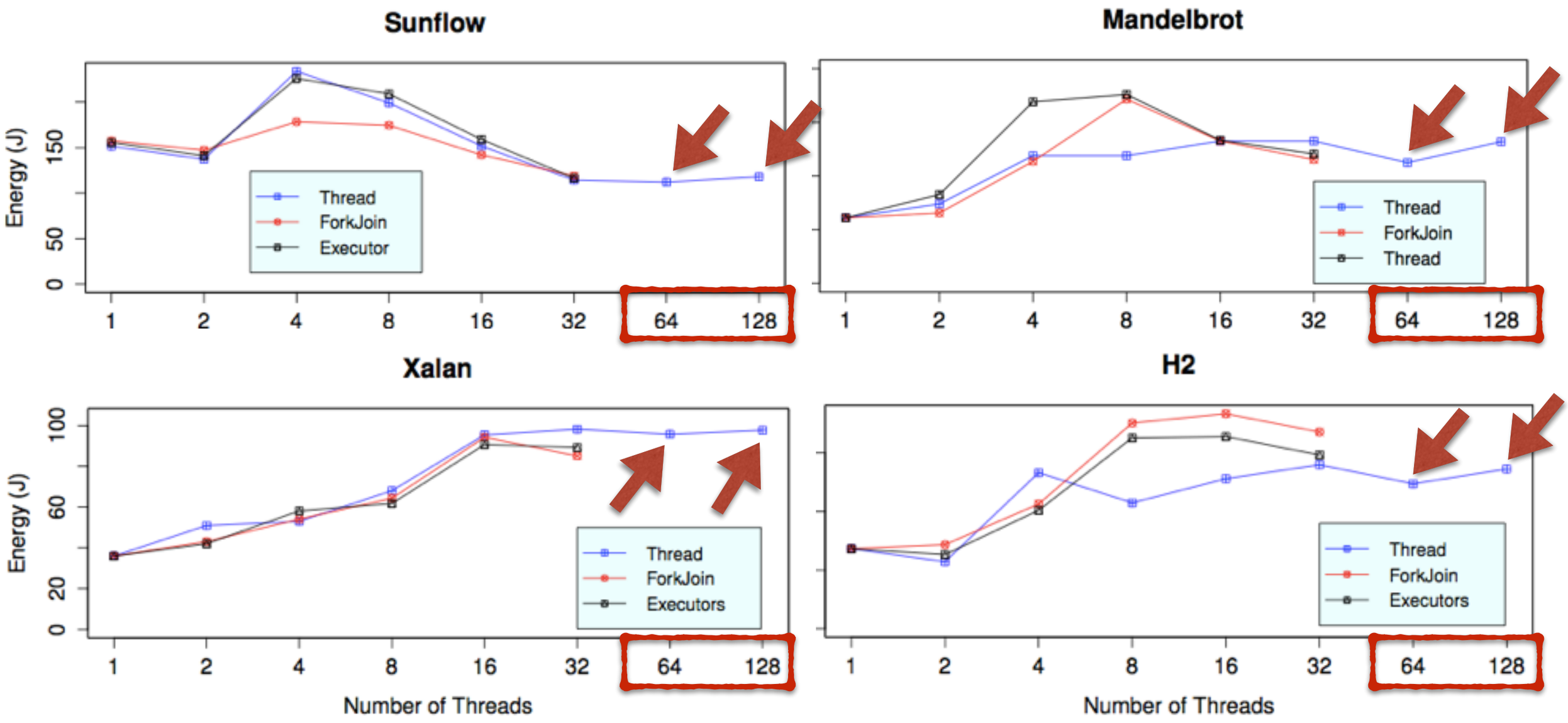
- More cores idle
- Frequency at a lower level

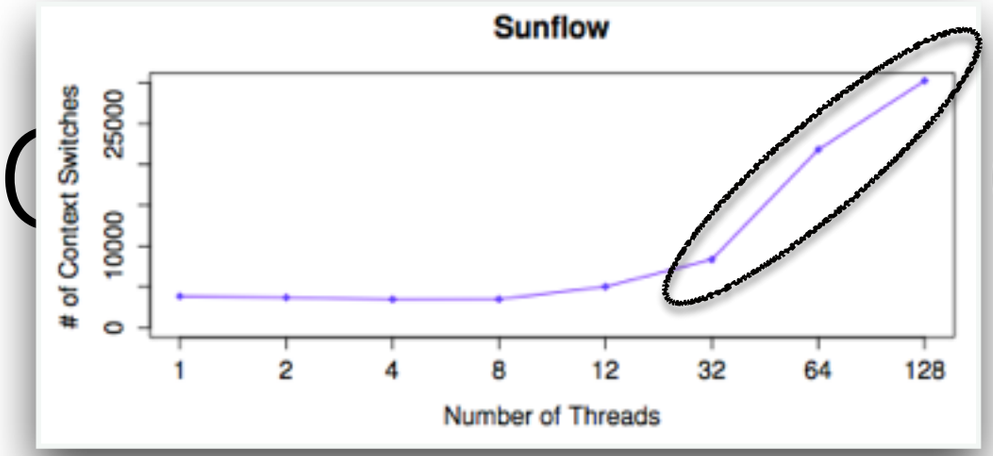
- More threads used, performance increase
- The greater the ratio between speedup and power, the steeper the \

Which programming style should I use?

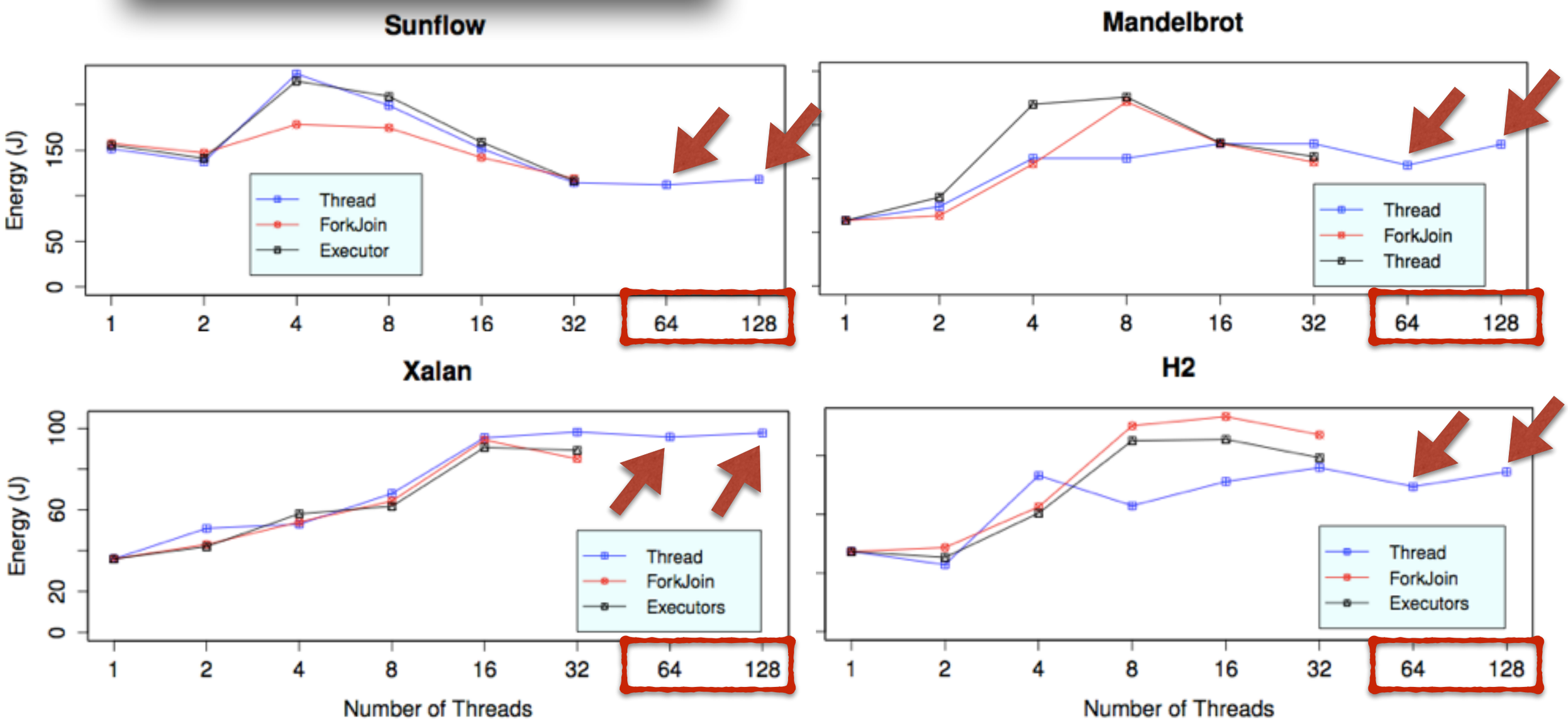


Overpopulating Cores with Threads

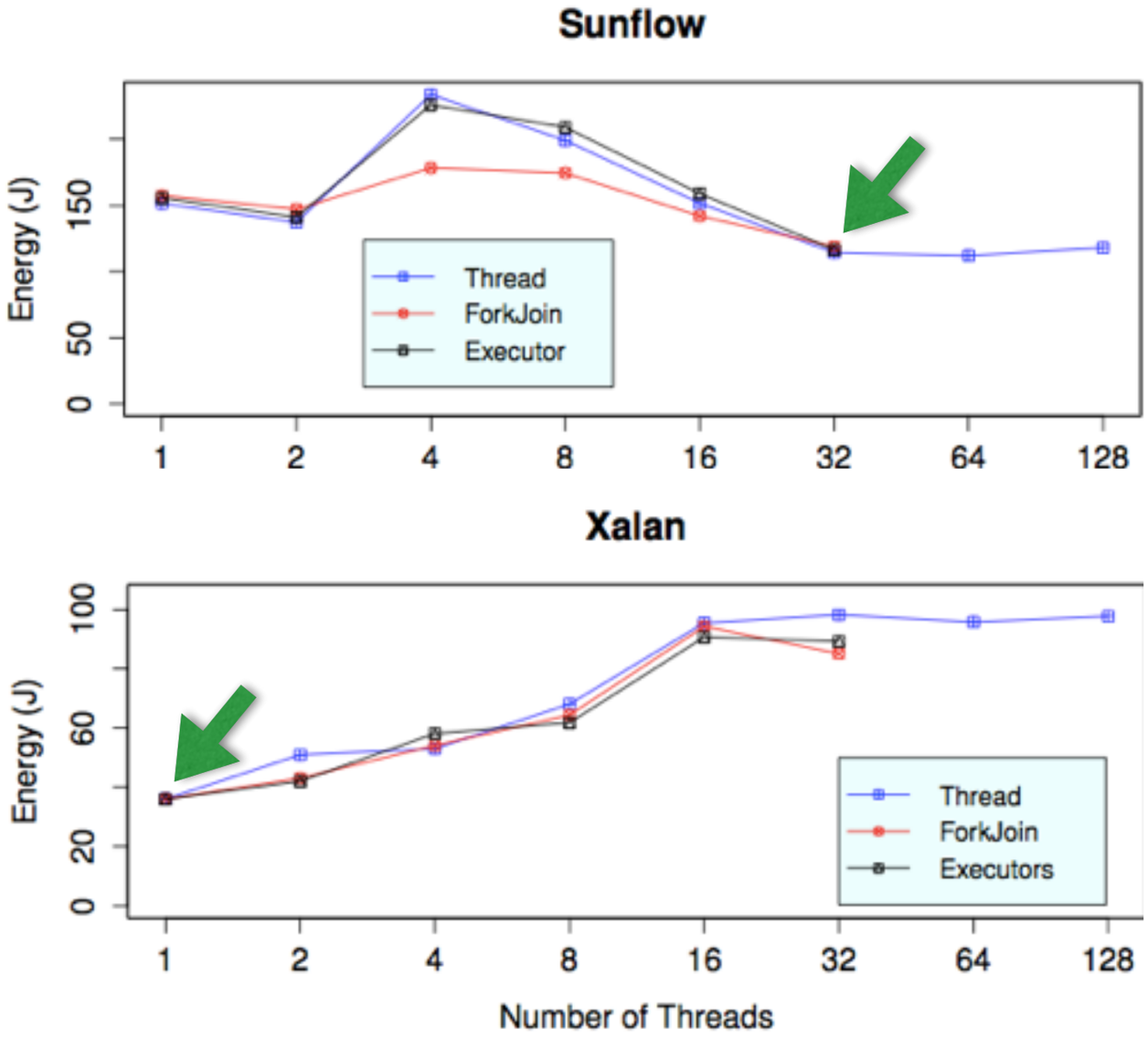


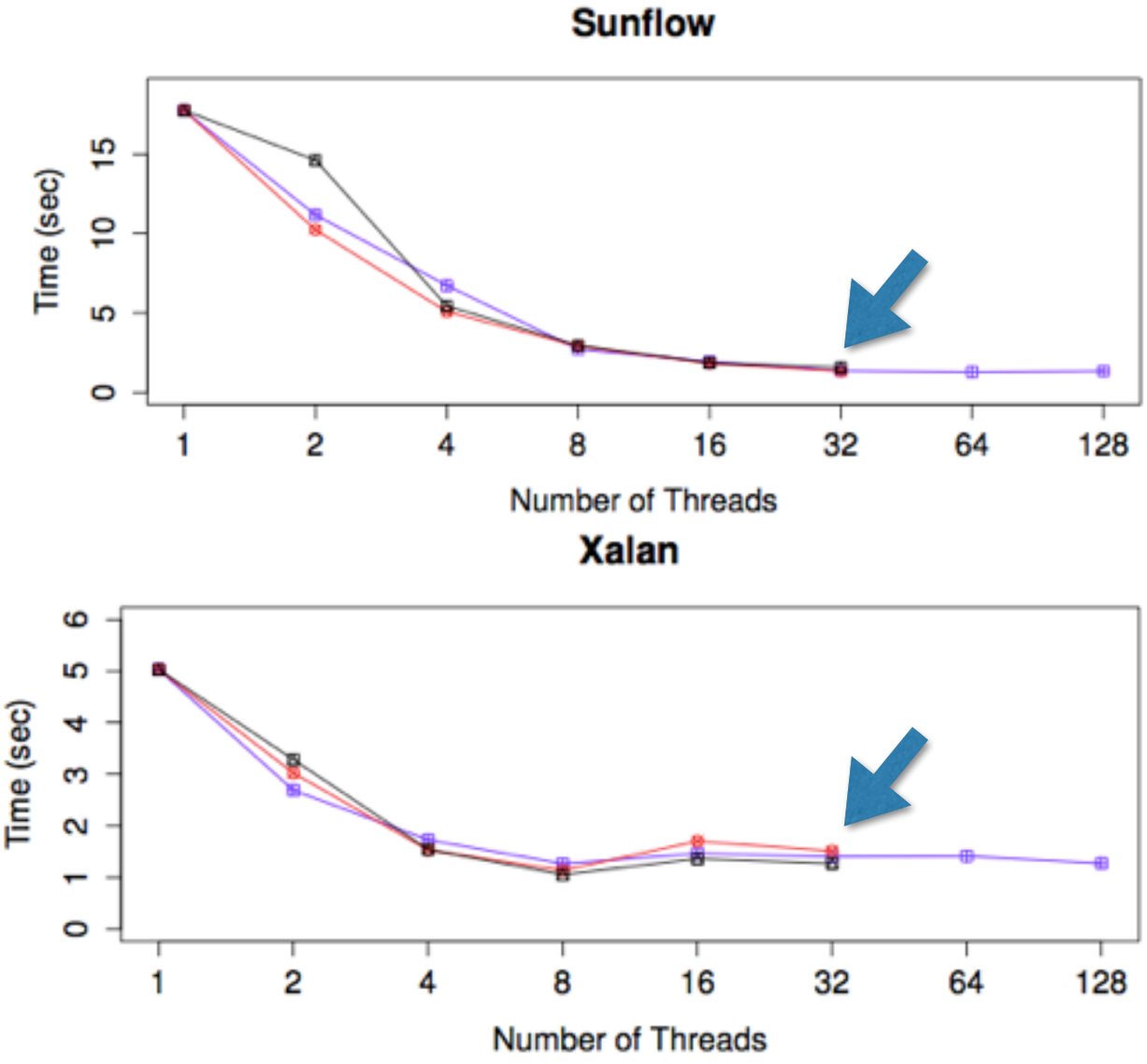


Cores with Threads



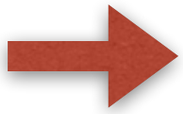
Faster ≠ Greener





Data Locality

```
public void compute() {
   ...
   NQueensSolver[] tasks = new NQueensSolver[size
       ];
   for (int i = 0; i < tasks.length; i++) {
      int[] newElements = new int[depth + 1];
      System.arraycopy(currentElements, 0,
                       newElements, 0, depth);
      tasks[i] = new NQueensSolver(newElements);
      tasks[i].fork();
   }
   ...
   for (int i = 0; i < tasks.length; i++) {
      if(tasks[i] != null) tasks[i].join();
   }
}
```



```
public void compute() {
   ...
   List<NQueensSolver> tasks = new ArrayList<>(
        size);
   for (int i = 0; i < tasks.size(); i++) {
      int[] newElements = new int[depth + 1];
      System.arraycopy(currentElements, 0,
                       newElements, 0, depth);
      tasks.add(new NQueensSolver(newElements));
   }
   ...
   invokeAll(tasks);
}
```

Copy

Fork/Join

Data Locality

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   NQueensSolver[] tasks = new NQueensSolver[size
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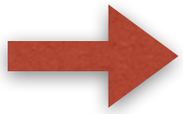

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      tasks.add(new NQueensSolver(newElements));
   }
   ...
   invokeAll(tasks);
}
```

Copy

Fork/Join

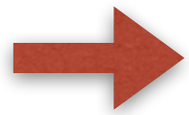
±10% of energy savings!

Copying vs Sharing

```
import static Arrays.*;
class Task extends RecursiveAction{
  public Task (User[] u) {}
  protected void compute() {
    if (u.length < N) { local(u); }
    else {
      int split = u.length / 2;

      User[] u1 = copyOfRange(u, 0,
          split);
      User[] u2 = copyOfRange(u,
          split, u.length);

      invokeAll(new Task(u1),
                new Task(u2));
    }
  }
}
```



```
class Task extends RecursiveAction{
  public Task (User[] u, int from,
      int to) {}
  protected void compute() {
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Copying

Sharing

Copying vs Sharing

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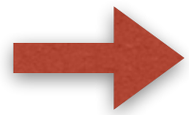

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±15% of energy savings!

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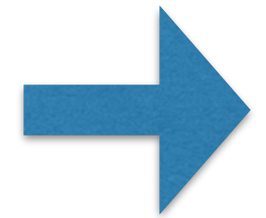

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    }
  }
}
```

Copying

Sharing

Solution

1. Add field variable

```
import static Arrays.*;
class Task extends RecursiveAction {
  private int from, to;
  public Task (User[] u) { ... }
  protected void compute() {
    if (u.length < N) { local(u); }
    else {
      int split = u.length / 2;

      User[] u1 = copyOfRange(u, 0, split);
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Solution

1. Add field variable
2. Add new constructor and update its usage

```
import static Arrays.*;
class Task extends RecursiveAction {
  private int from, to;
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Solution

1. Add field variable
2. Add new constructor and update its usage
3. Modify threshold management policy

```
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class Task extends RecursiveAction {
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}
```

Solution

1. Add field variable
2. Add new constructor and update its usage
3. Modify threshold management policy
4. Remove copy statements

```
class Task extends RecursiveAction {
  private int from, to;
  public Task (User[] u) { ... }
  private Task (User[] u, int from, int to) { ... }
  protected void compute() {
    if (to - from < N) { local(u, from, to); }
    else {
      int split = (from + to) / 2;

      invokeAll(
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4Mi+ Users

19Mi+ Repositories

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https://github.com/features

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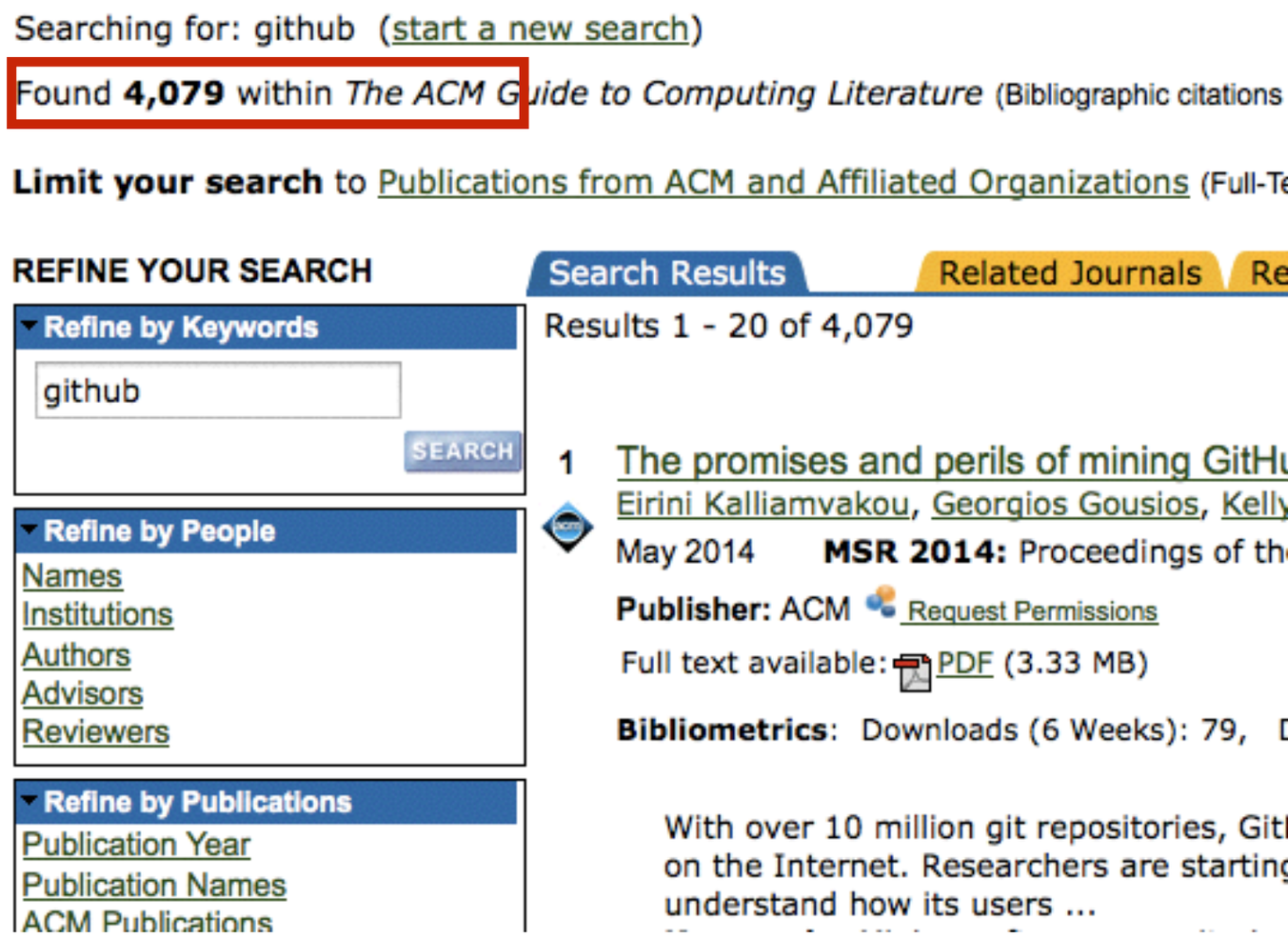

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Subjects	# LoC	# Dev	Last Commit
itemupdown	4,925	1	08-10-2013
jAcer	4,476	2	12-06-2014
educational	1,323	1	05-05-2014
scalatuts	253	2	11-17-2013
knn	3,099	1	11-25-2014
netflixoss	231,361	1	09-14-2013
doms-transformers	3,714	4	06-19-2014
ForkAndJoinUtility	127	1	03-31-2013
exhibitor	15,314	14	11-08-2014
Solitaire	1,527	1	11-18-2011
javaOneBR-2012	518	1	12-02-2012
mywiki	1,920	2	10-04-2012
ejisto	12,330	1	08-06-2014
cq4j	5,815	1	10-15-2013
MagicSquares	664	1	10-25-2013

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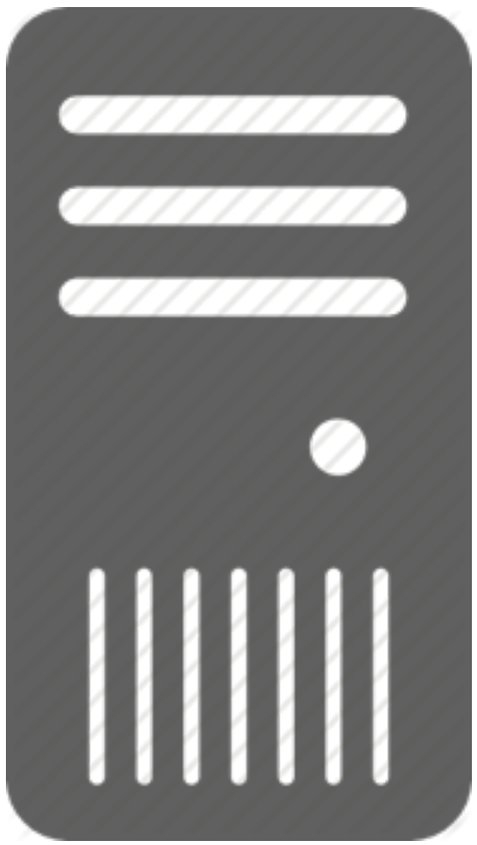
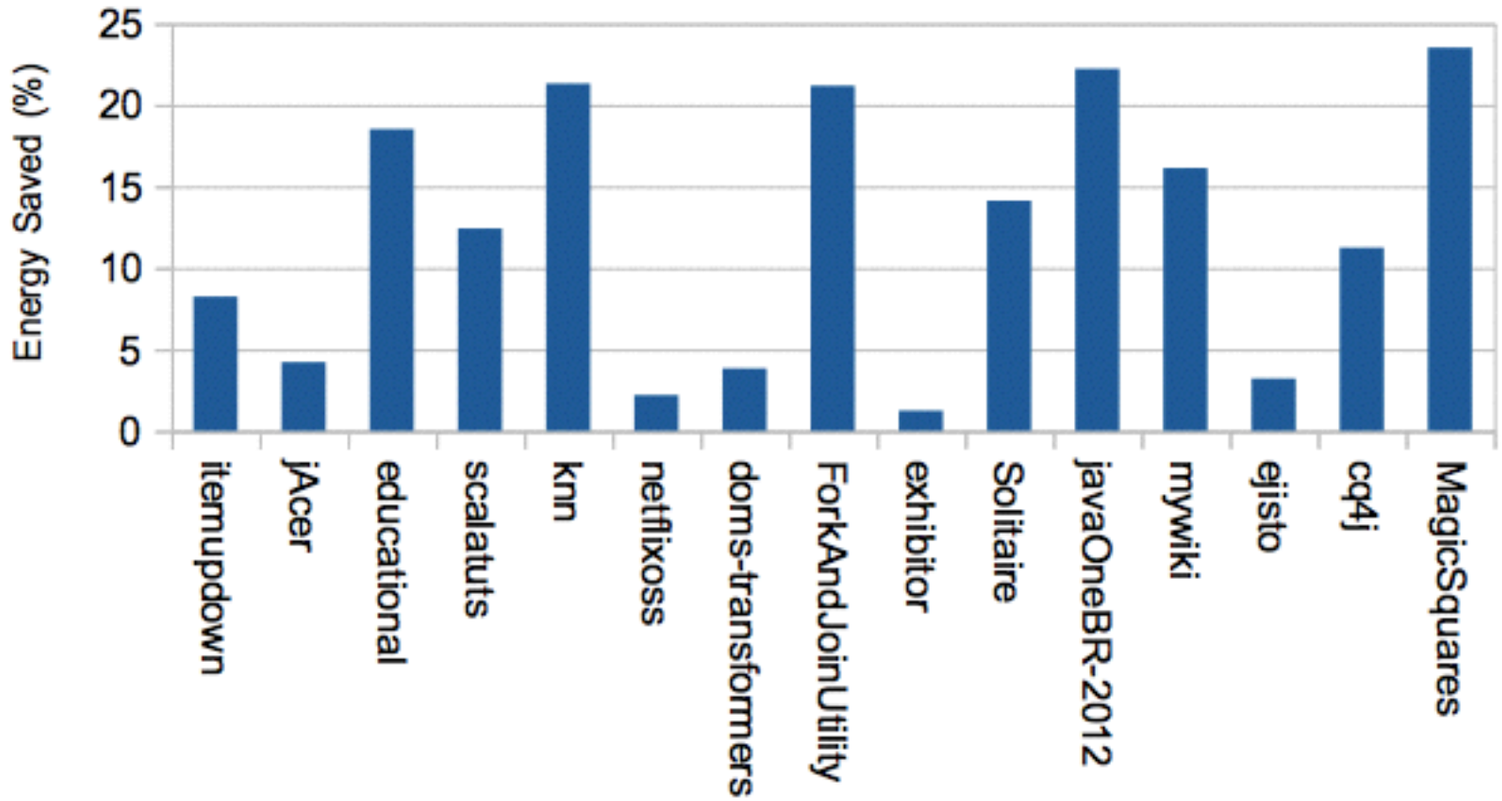
Experimental Environment



A 2×8-core (32-cores w/ hyper-threading) **Intel CPU**,running Debian, 2.60GHz, with 64GB of memory, JDK version 1.7.0 71, build 14.

Results


Energy Saved (%)
25
20
15
10
5
0
itemupdown
jAcer
educational
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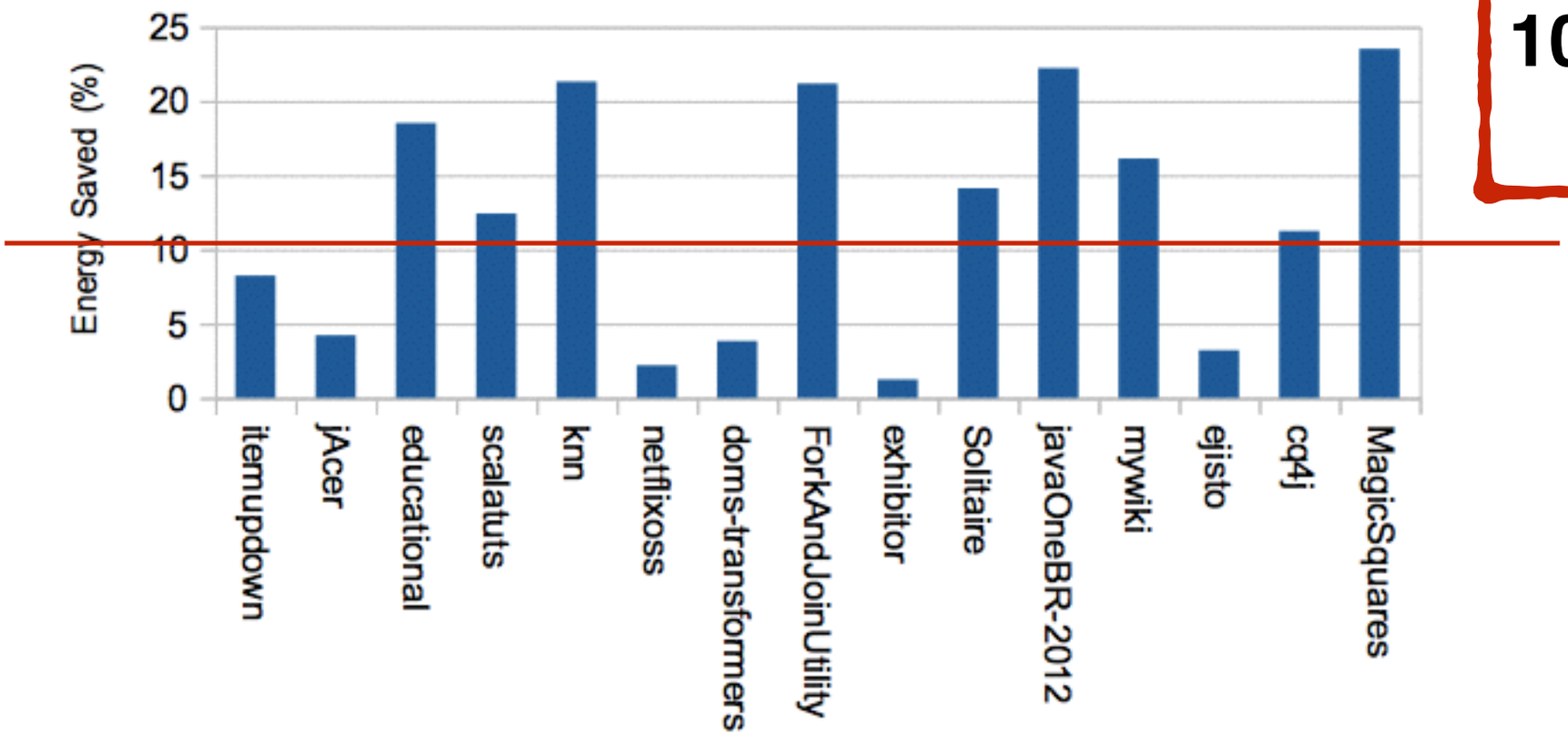

9/15 crossed the **10%** energy saving!

Patches

15 Pull Requests

- Proposed — #1 **Improving ForkJoin usage for better performance** — czbabl/itemupdown
- Proposed — #206 **Improving ForkJoin usage for better performance** on Dec 5, — Netflix/exhibitor
- Merged — #1 **Improving ForkJoin usage for better performance** — toby1984/jAcer
- Proposed — #1 **Improving ForkJoin usage for better performance** on Dec 5, 20 — robitobi/Solitaire
- Proposed — #1 **Improving ForkJoin usage for better performance** — nikkrichko/Educational
- Merged — #1 **Improving ForkJoin usage for better performance** on Dec 5, 20 — mariofts/javaOneBR-2012
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7/9 of projects that **replied** have **accepted**

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Propos and energy e

mariofts commented on Dec 8, 2014 — Owner

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Conclusions

There is a “brave new world” for Refactoring for Energy Efficiency.

Review 3

This paper has the main goal of identifying opportunities, and challenges in the context of (application level) refactoring for energy efficiency. In this line, the authors review a number of conferences in order to find researc articles related to energy and power. They select 16 papers. Six categories are created from those papers, and f each, problems, opportunities, and challenges are presented.

Overall, I found the paper interesting, with a varied list of opportunities, and a competent analysis of expected challenges. I am personally sure refactoring for energy efficiency will be the next hot topic in Green computing.

Conclusions

However, the questions is: When to refactor?

Conclusions

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Threads

ForkJoin

Conclusions

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Non Thread-Safe
Data Structures

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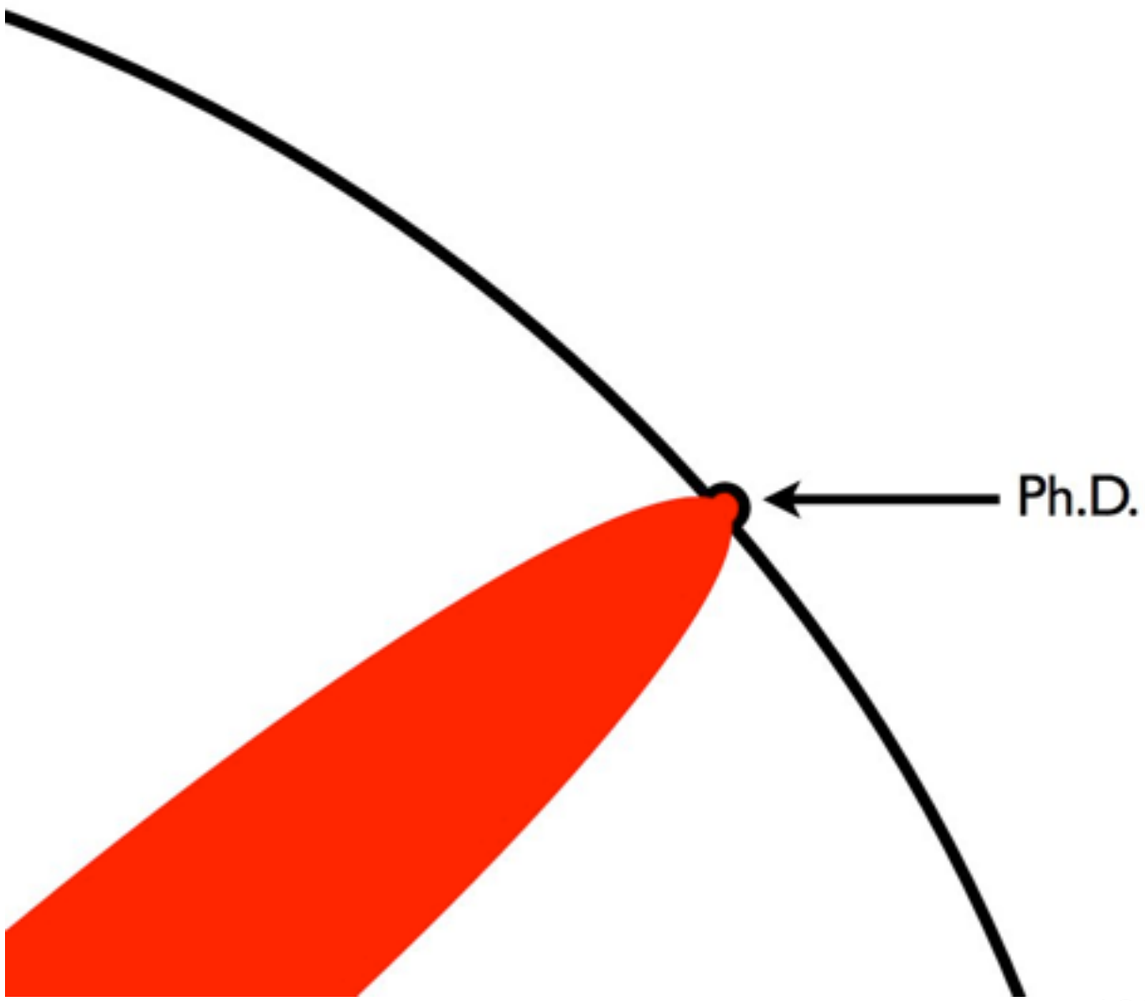

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Gustavo Pinto

Ph.D. Defense
Informatics Center
Federal University of Pernambuco

Recife, February/2015