UNIVERSITÄT
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Green Configuration

Energy Consumption of Configurable Software Systems


Max Weber


Alina Mailach


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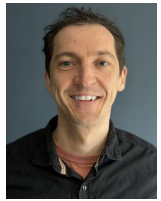
Christian Kalten.


Florian Sattler


Sven Apel


Norbert Siegmund

Energy Consumption at ecoCompute

CarbonDB - Real Time carbon emissions mapping to heterogenous IT infrastructure 🇬🇧

Arne Tarara

Green Coding Solutions

Embodied Carbon

Workloads, Use Cases

Software Systems

OS, Languages

Hardware

Rerouting the Cloud: Cutting 90% CO_2 and Cloud Costs with Smarter Workload Shifting 🇬🇧

Dryden Williams

CarbonRunner

Coding Smarter for a Greener Future | A comparison between Go & Java 🇬🇧

Moritz Bölter

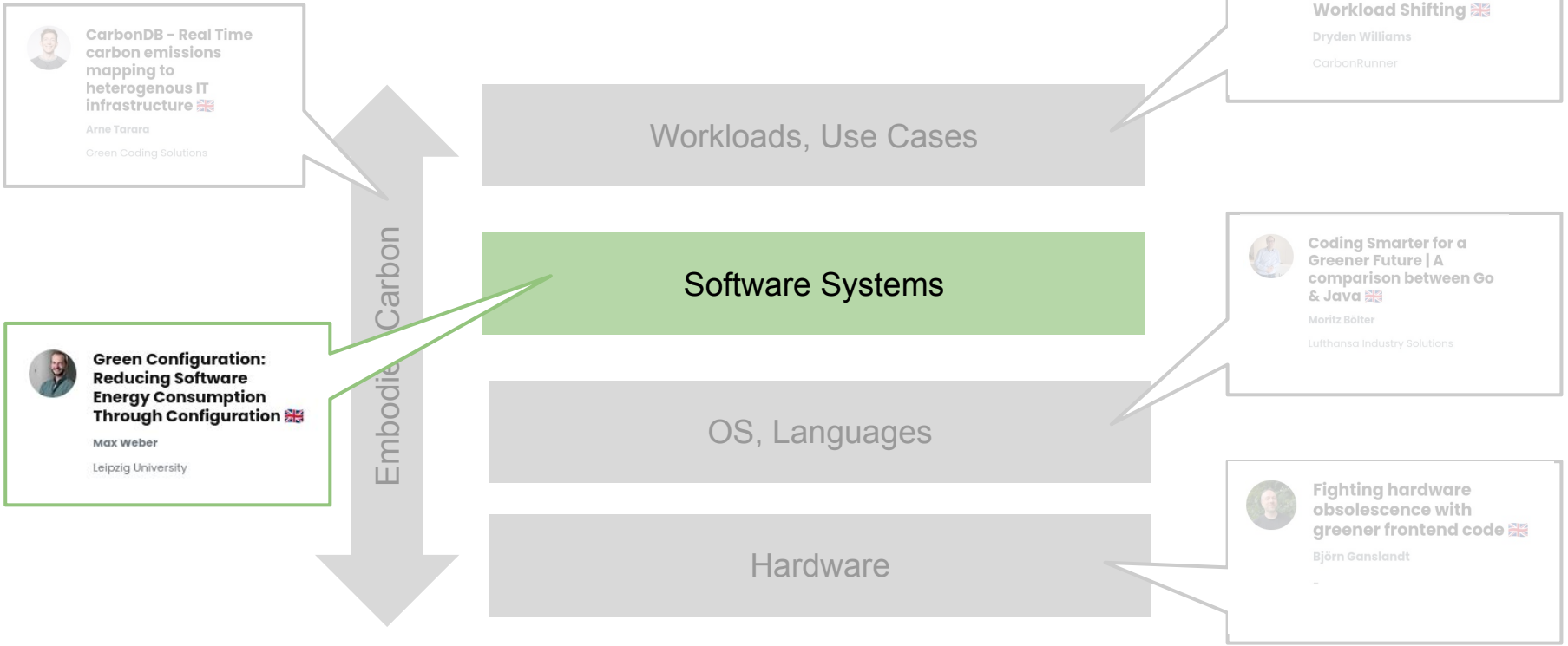
Lufthansa Industry Solutions

Fighting hardware obsolescence with greener frontend code 🇬🇧

Björn Ganslandt

-

Energy Consumption at ecoCompute

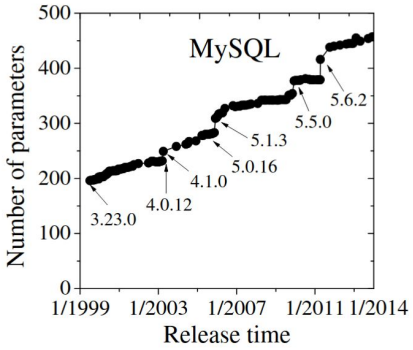


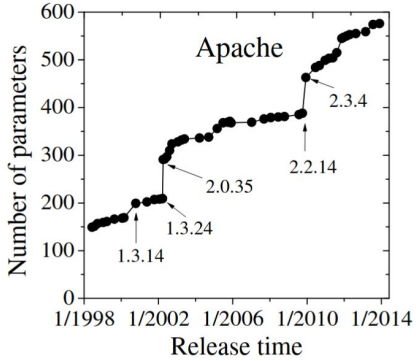
Energy Consumption at ecoCompute

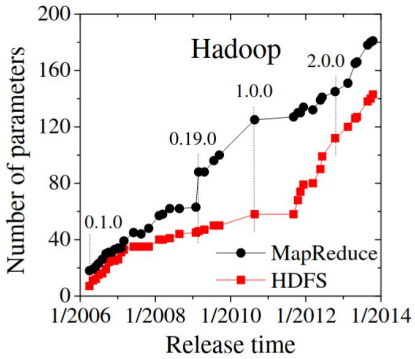
How can we reduce the energy consumption of software systems?

By tailoring software to its workload and usage scenario.

Configuration is everywhere!







Number of parameters today:

MySQL – 700+

Apache – 900+

Hadoop – 400+

Users stick to default configurations, leaving much potential unused.

1

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How can we **measure** software energy consumption?

Energy Consumption of Configurable Software Systems

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Debugging Energy consumption

3

Practitioners' perspective

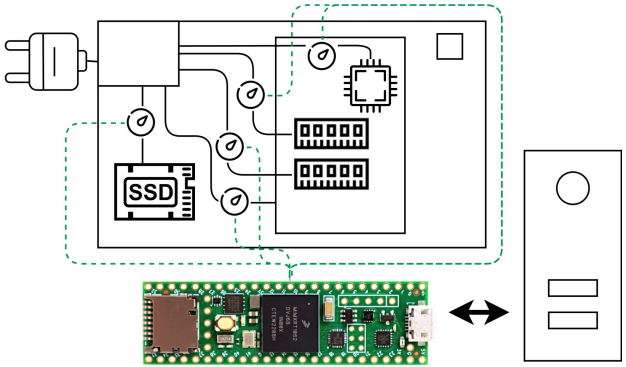
Measuring Energy Consumption up to Code Level

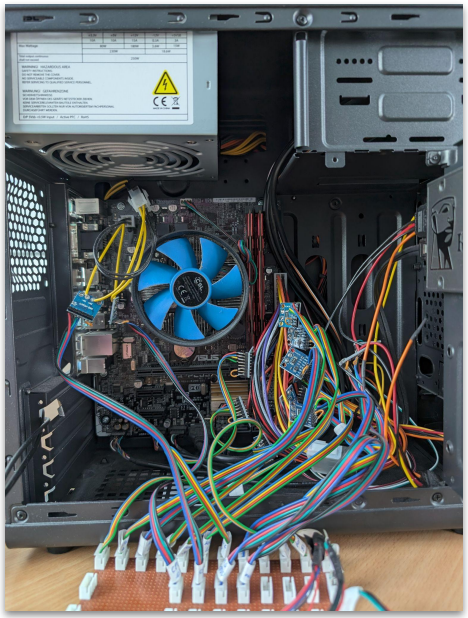
component-wise measurements
(adding up to the whole system)

High sampling rate:
3.5 kHz

no energy measurement bias

Accuracy: < 1.2%
measurement error





Hardware Components

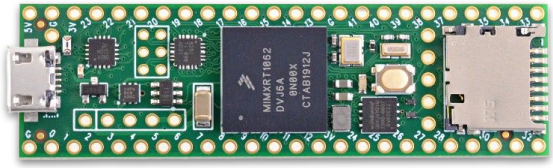
INA 226
Sample Time 280 us
Sample Rate 3.5 kHz

Raspberry Pi 4B

60€

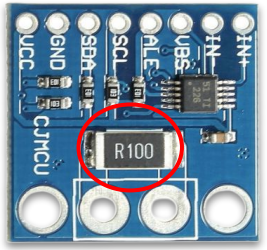
USB

Teensy 4.1



30€

I²C



5€

3,500 measurements per second
≙ 1 sample every 0.3 ms (for all components)

175€

Hardware Components

INA 226
Sample Time 280 us
Sample Rate 3.5 kHz

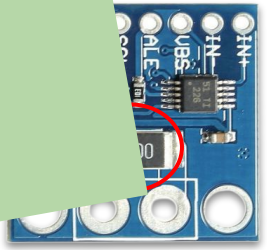
Raspberry Pi 4B

60€

USB

Teensy 4.1

Time spent until it worked reliably:
Priceless.

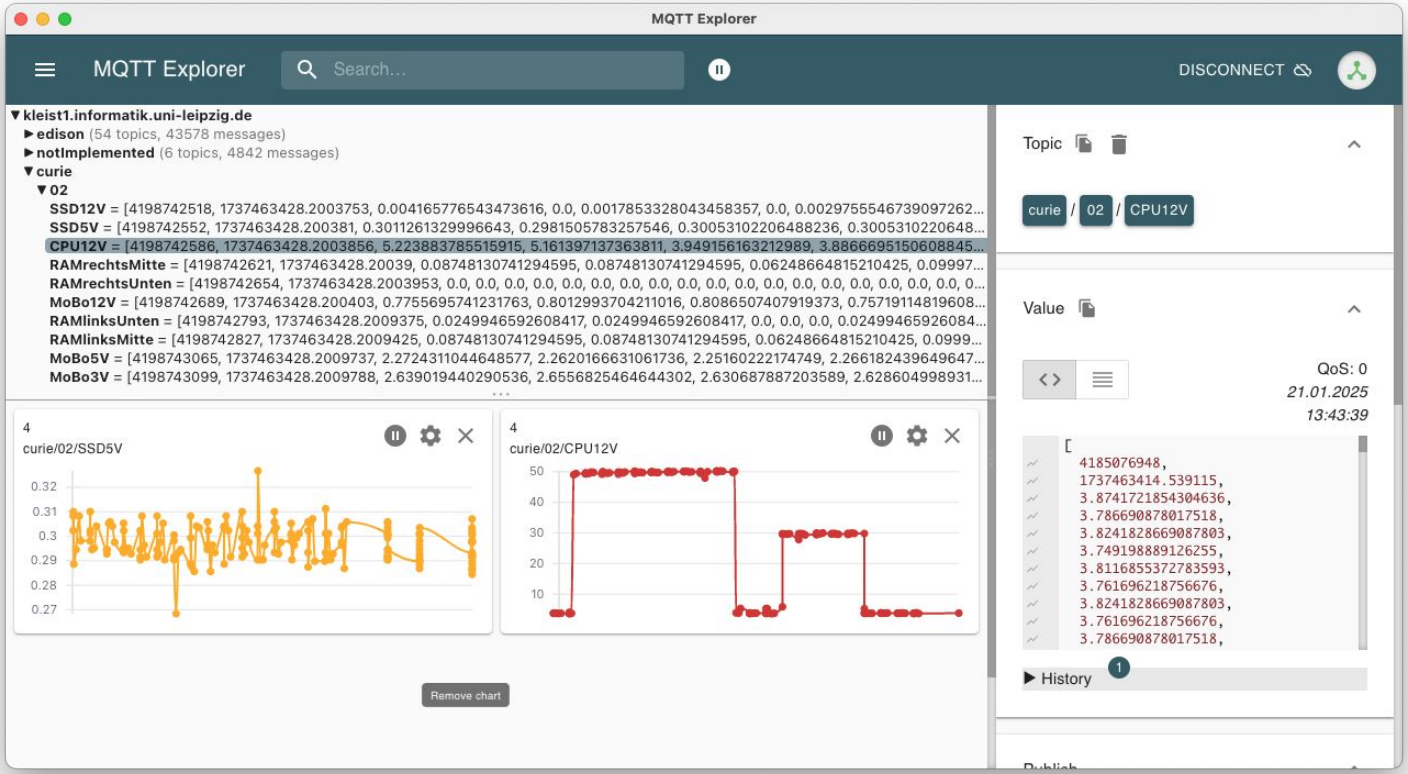


5€

3,500 measurements per second
≙ 1 sample every 0.3 ms (for all components)

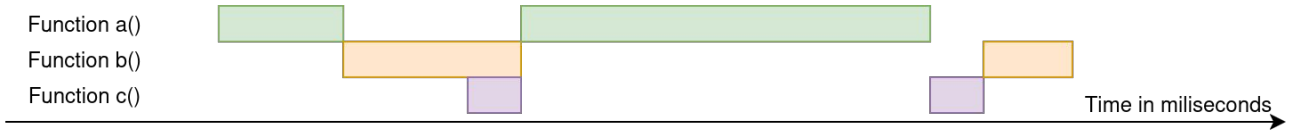
175€

Power Measurement

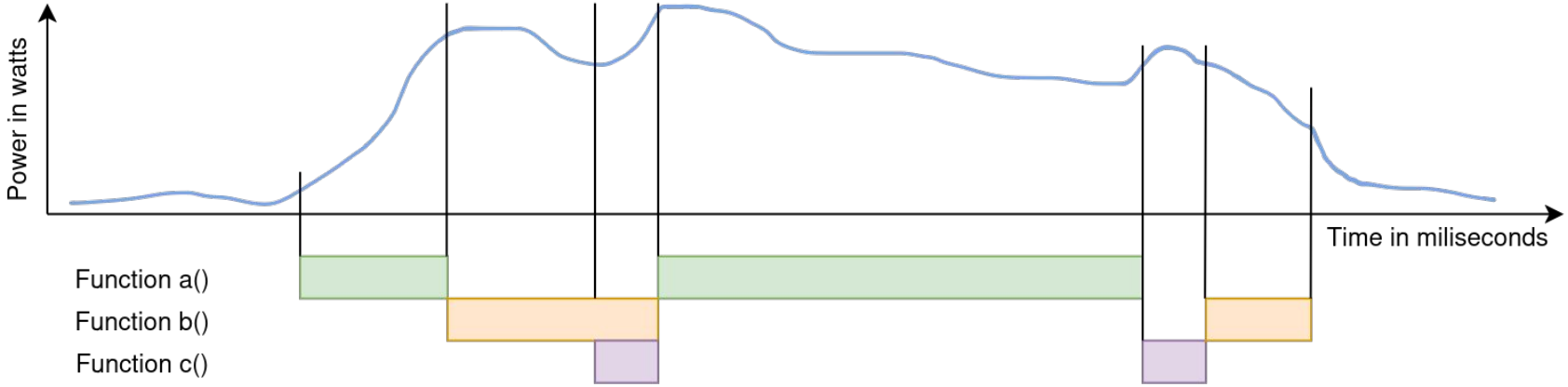


Performance Profiling

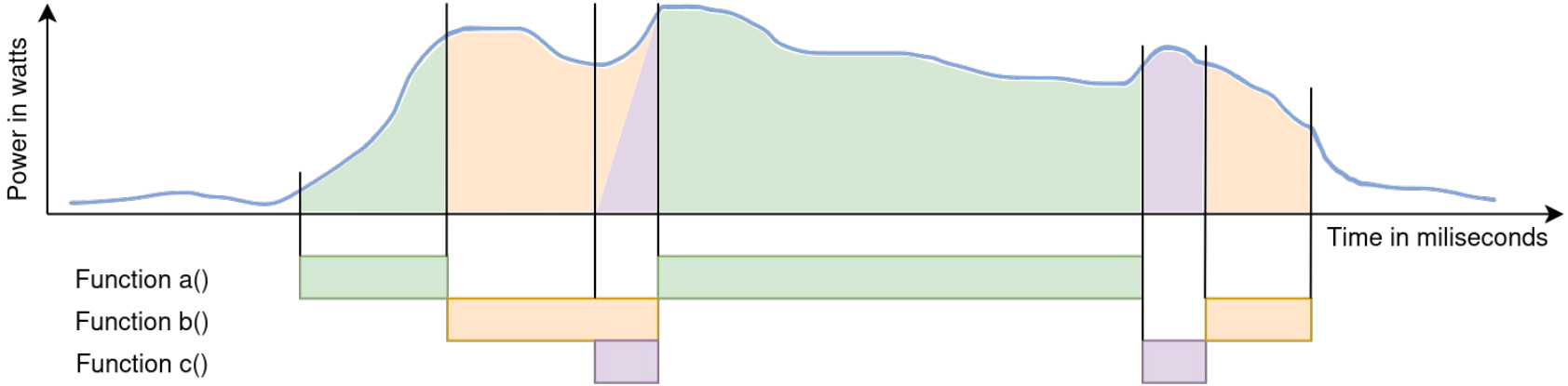
Linux *perf*



Synchronizing Energy and Performance Measurements



Synchronizing Energy and Performance Measurements



1

Assessing Energy Consumption

How can we **measure** software energy consumption?

Can we find a **reliable proxy**?

Energy Consumption of Configurable Software Systems

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Practitioners' perspective

Energy Metering is expensive, difficult and tool intensive.

Infeasible in many project settings.

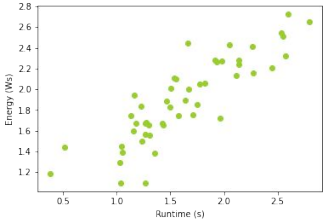
Solution: Using performance as a proxy for energy consumption

System-Level Correlation

Option-Level Correlation

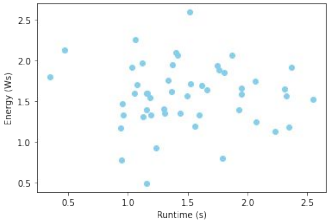
Literature Study Statements

positive correlation



"**perform significantly better** and **consume less energy** with only a small loss in QoS" [1]

no / absent correlation

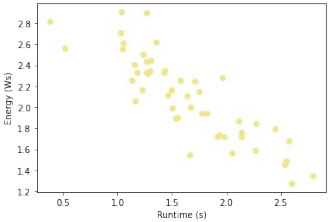


"the involved physical components **may not consume energy proportional to time**" [2]

"**caching** has an effect **on performance but not on energy consumption**" [2]

"no correlation if some **communication** comes into play" [4]

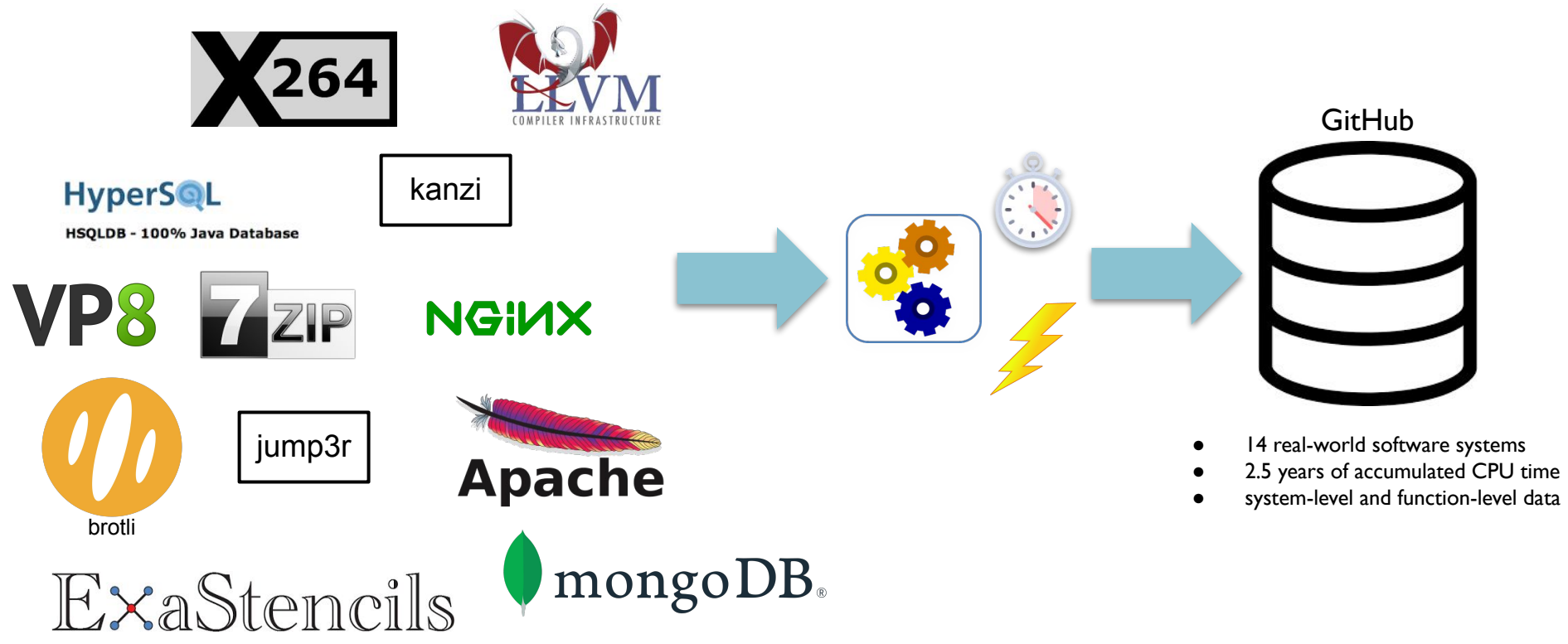
negative correlation



"computational offloading brings **better performance but not always better energy efficiency**" [3]

[1] Green: a framework for supporting energy-conscious programming using controlled approximation, 2020
[2] Evaluating the Impact of Caching on the Energy Consumption and Performance of Progressive Web Apps, 2020
[3] Analysis of Performance and Energy Consumption of Wearable Devices and Mobile Gateways in IoT Applications, 2019
[4] Quantifying energy use in dense shared memory HPC node, 2016

Empirical Study to Investigate Performance–Energy Correlation

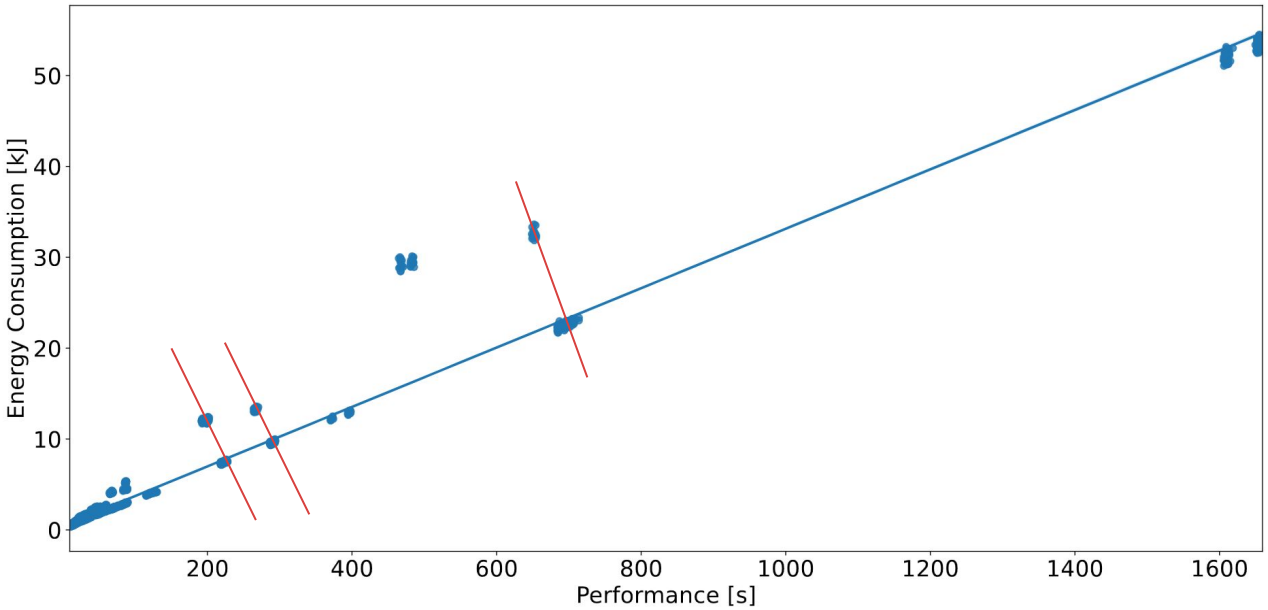


- 14 real-world software systems
- 2.5 years of accumulated CPU time
- system-level and function-level data

System-Level Correlation

lrzip

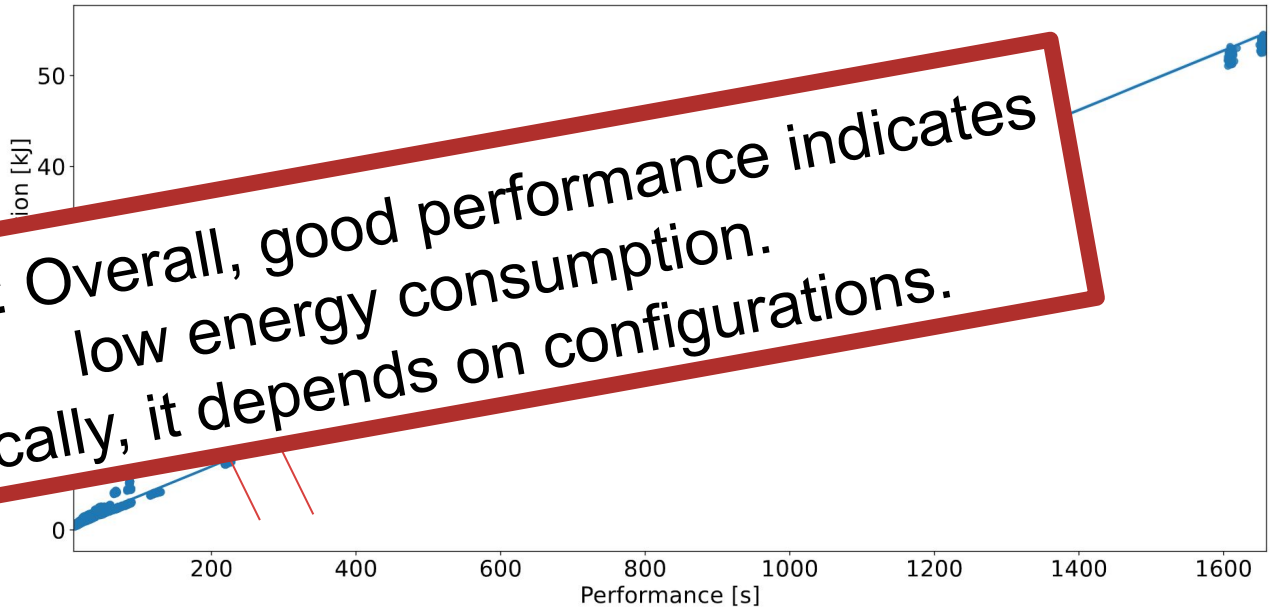
Correlation: 0.99



System-Level Correlation

lrzip

Correl

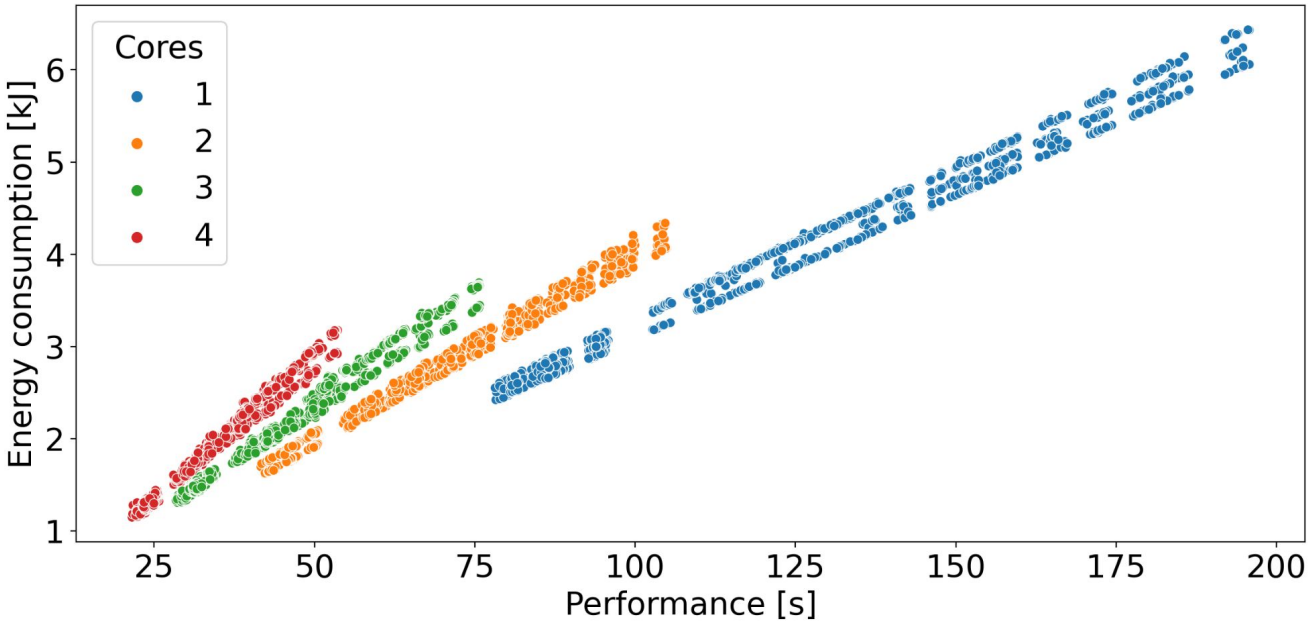


Finding: Overall, good performance indicates low energy consumption.
Locally, it depends on configurations.

Option-Level Correlation

Correlation: 0.99
MAPE: 10.3%

Correlation: 0.99
MAPE: 2.5%



Option-Level Correlation

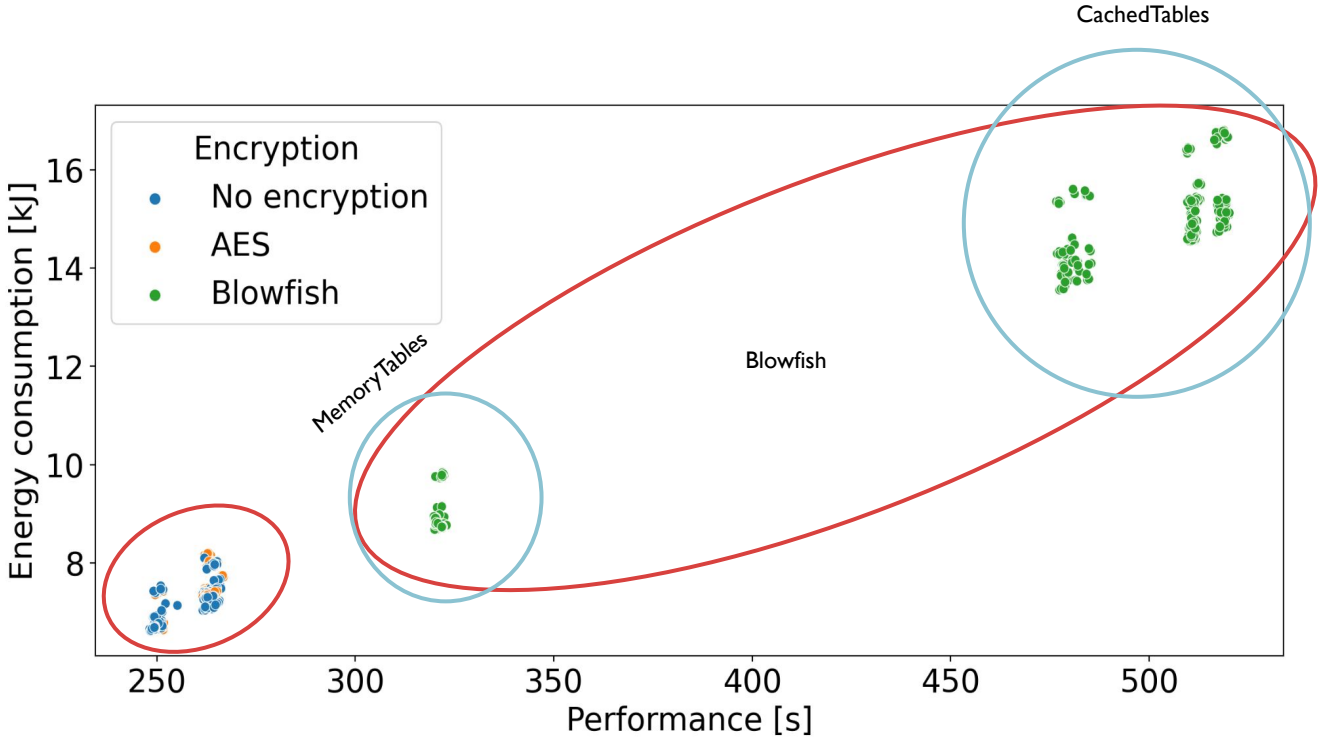
HyperSQL
HSQLDB - 100% Java Database

Correlation: 0.99
MAPE: 3.0%

Blowfish & MemoryTables

Correlation: 0.13
MAPE: 213.5%

!



Option-Level Correlation

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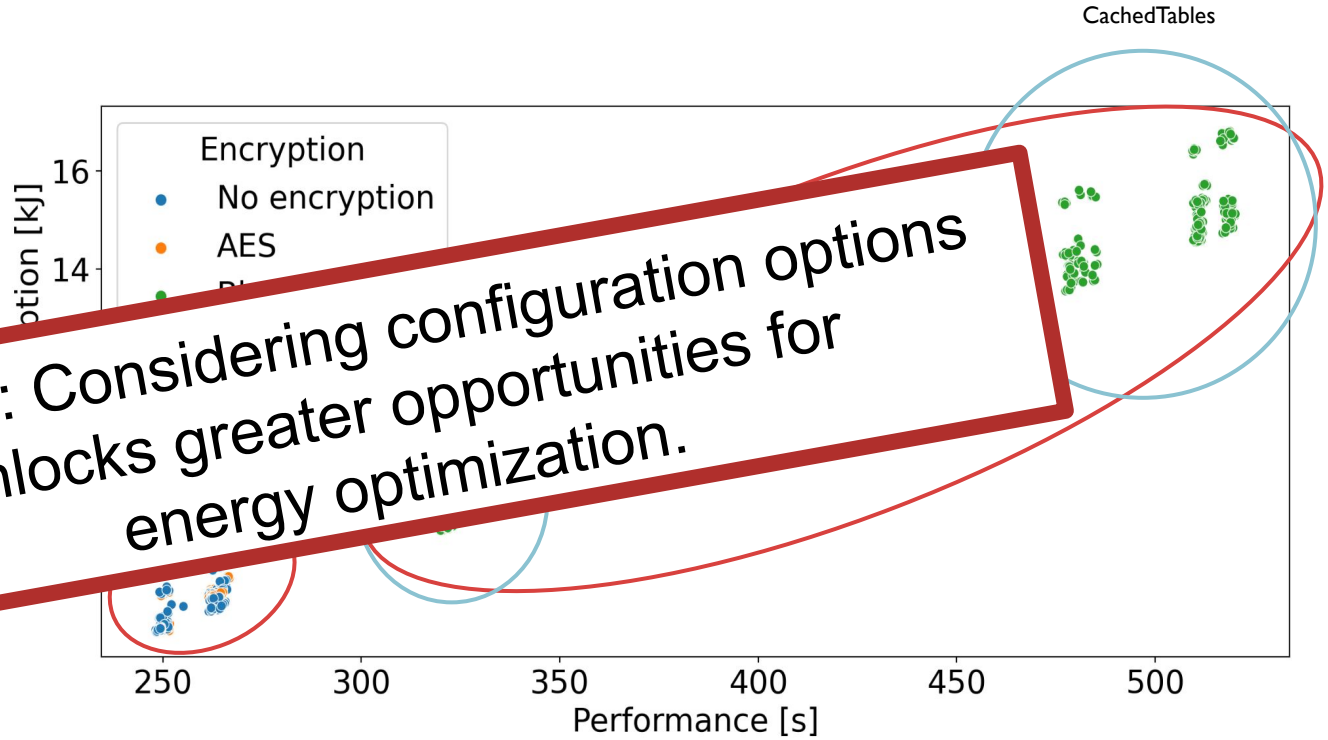

Finding: Considering configuration options unlocks greater opportunities for energy optimization.

Correl
MAPE:

Blowfish & Memory Tables

Correlation: 0.13
MAPE: 213.5%

1

Assessing Energy Consumption

How can we **measure** software energy consumption?

Can we find a **reliable proxy**?

How can we get **code-level insights**?

Energy Consumption of Configurable Software Systems

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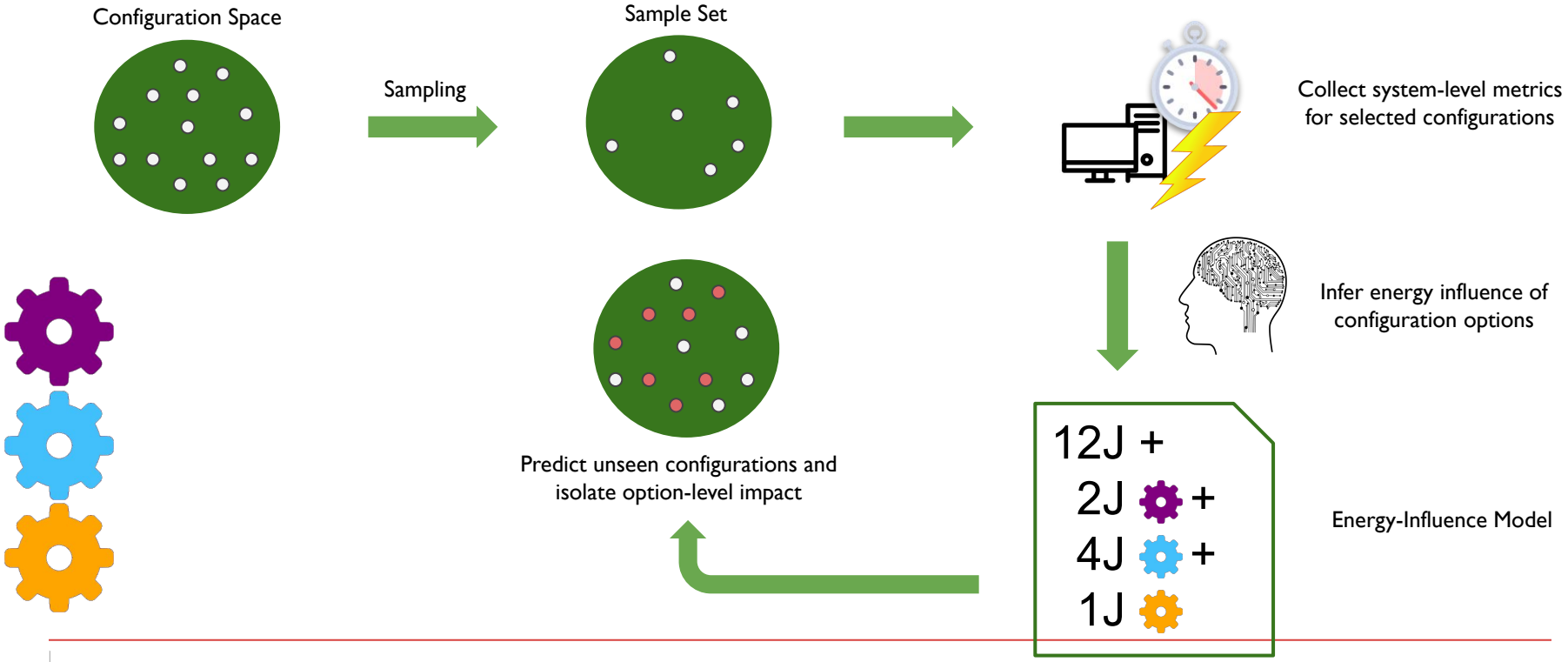
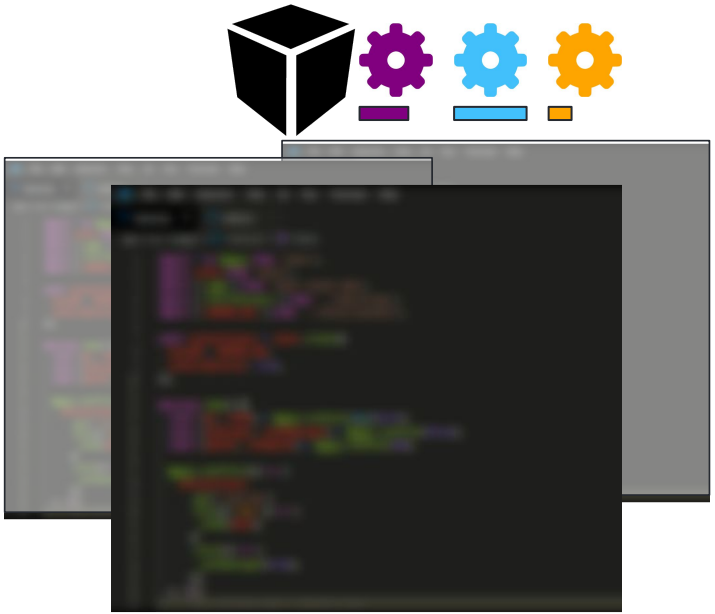
Practitioners' perspective

Building Energy-Influence Models for Configurable Systems



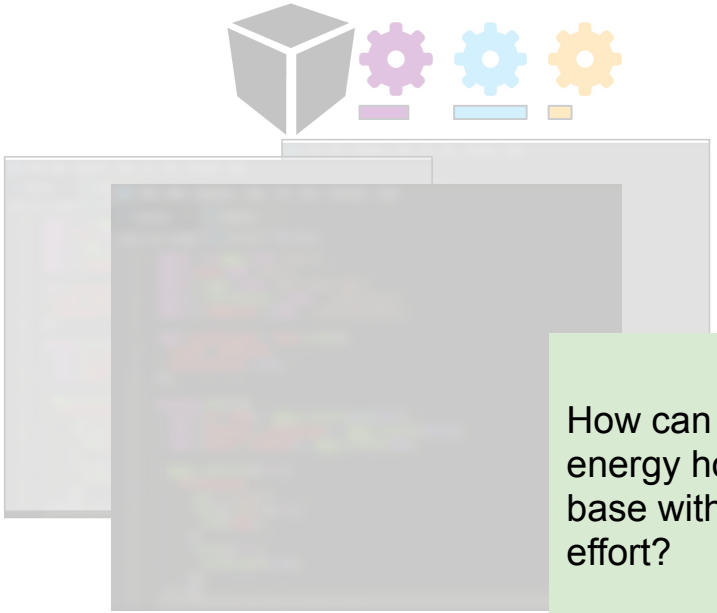


Black-Box Models

As a **user**, I can optimize configurations to reduce energy consumption 💪

… but I can't see **where** in the code the energy goes.

As a **developer**, how do I know which part of my code I need to change?

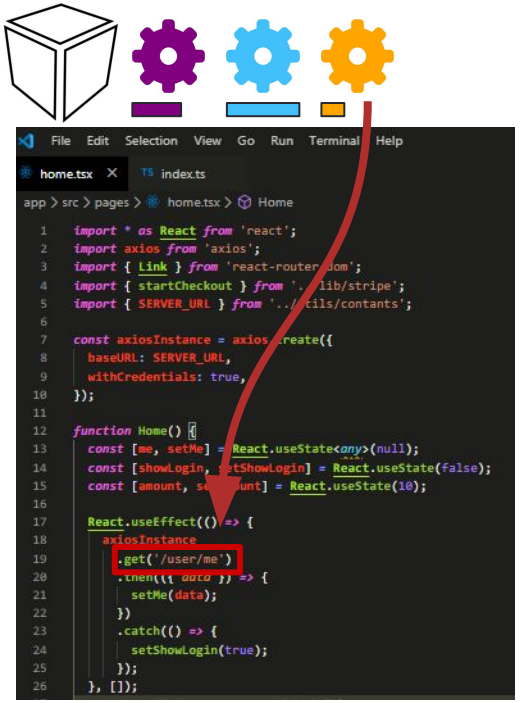


How can we **efficiently** pin point energy hotspots in the code base with minimal measurement effort?

Black-Box Models

As a **user**, I can optimize configurations to reduce energy consumption 💪

… but I can't see **where** in the code the energy goes.



Established White-Box Models

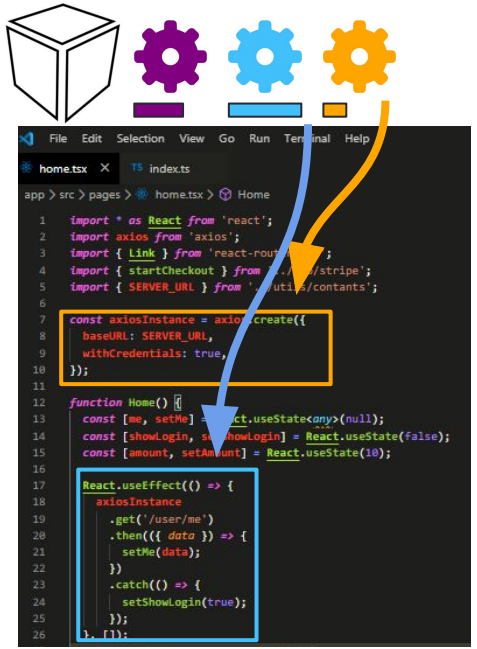
We know exactly **which** code statements consume energy.

…but measuring this across a full system is often **infeasible** 😔

Black-Box Models

As a **user**, I can optimize configurations to reduce energy consumption 💪

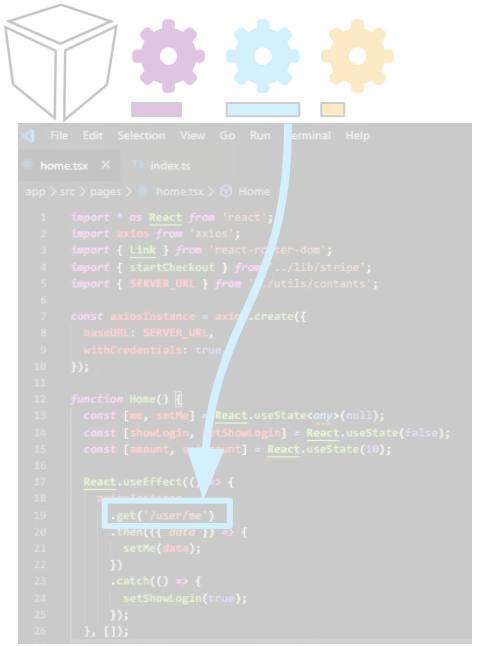
… but I can't see **where** in the code the energy goes. 😔



Method-Level White-Box Models

As a user, I still benefit from efficient configurations that save energy ⚡.

As a developer, I can identify which methods consume energy without measuring every single line of code.

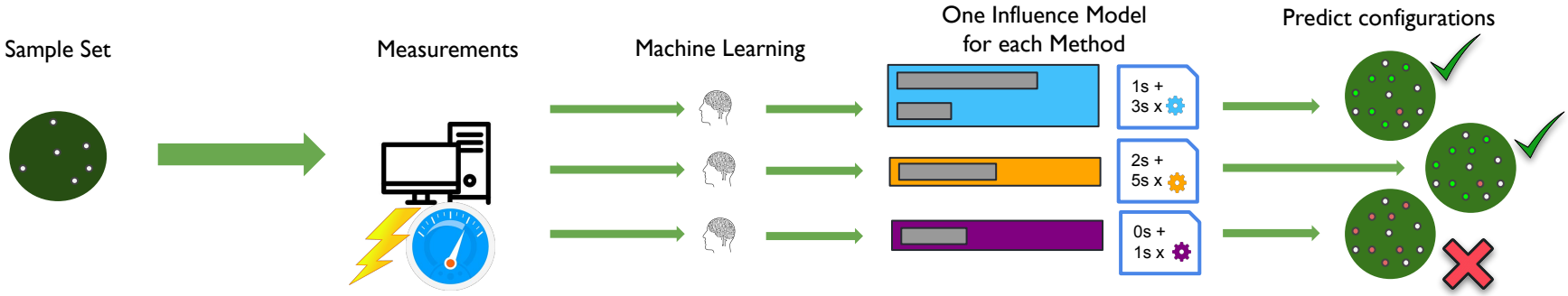


Established White-Box Models

We know exactly **which** code statements consume energy. 💪

…but measuring this across a full system is often **infeasible.** 😔

White-Box Energy Influence Models via Profiling

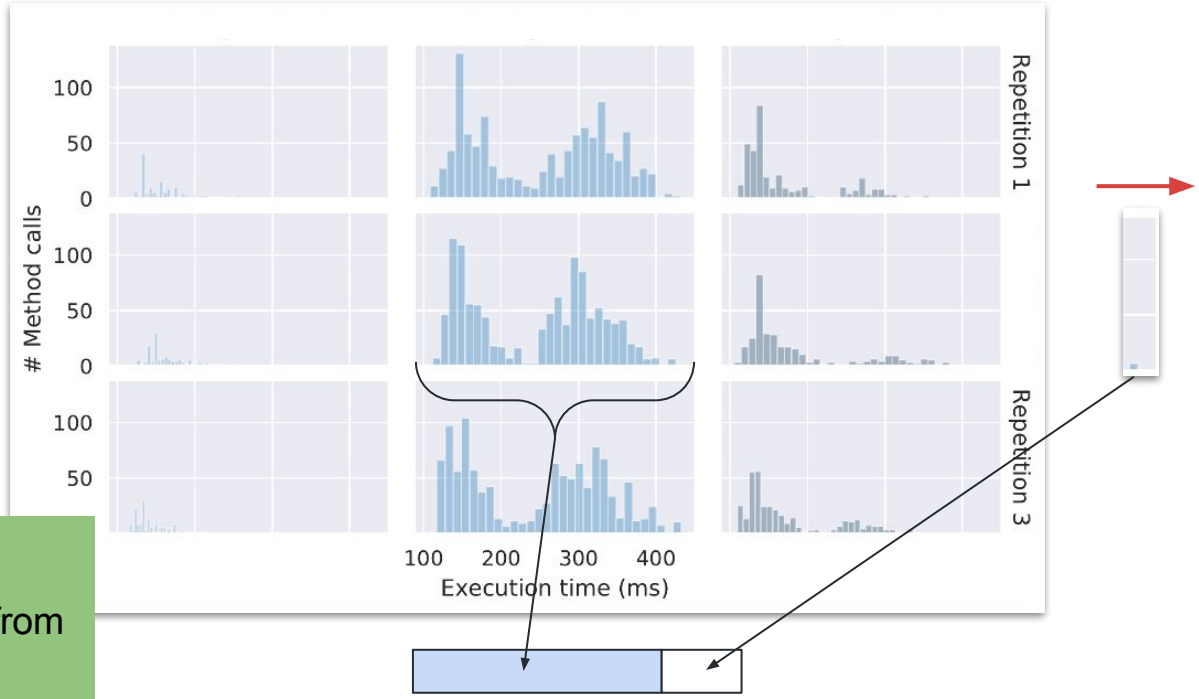


Challenge: Handling Variance in Measurement Data

Context variance

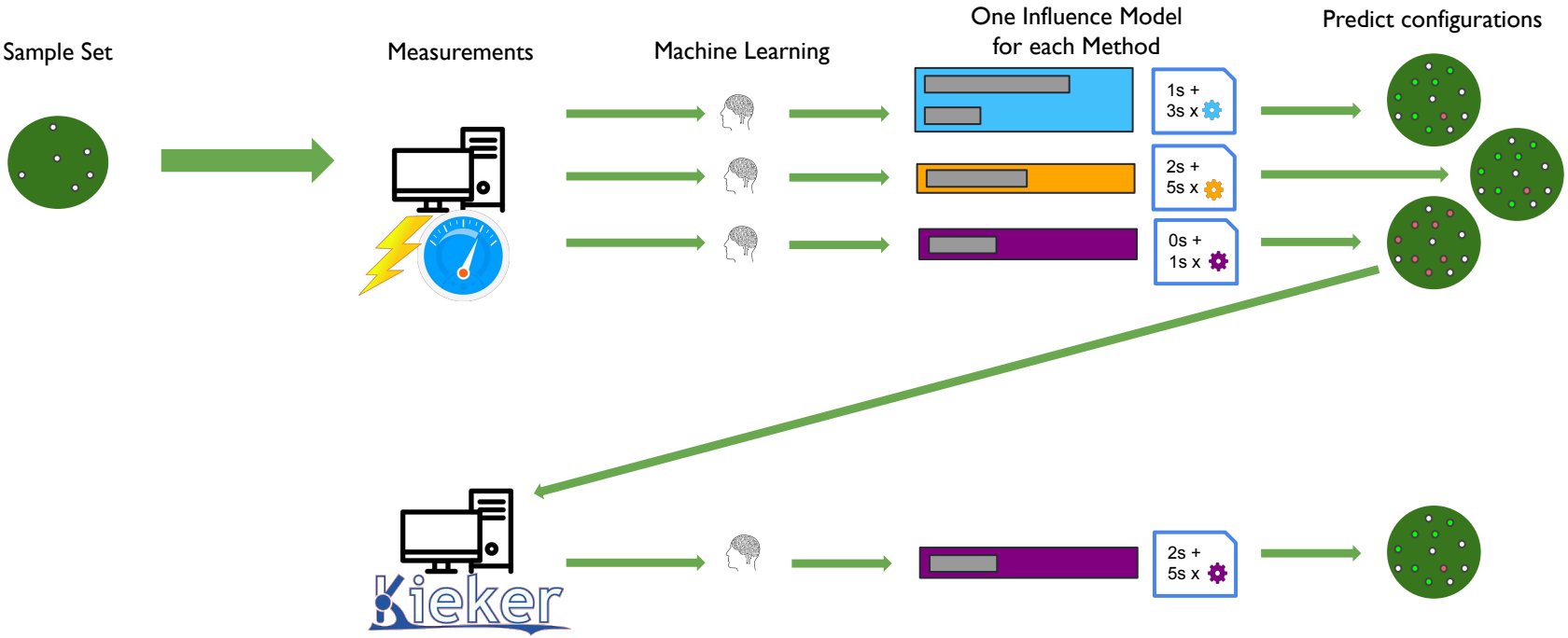
Configuration variance

Measurement variance

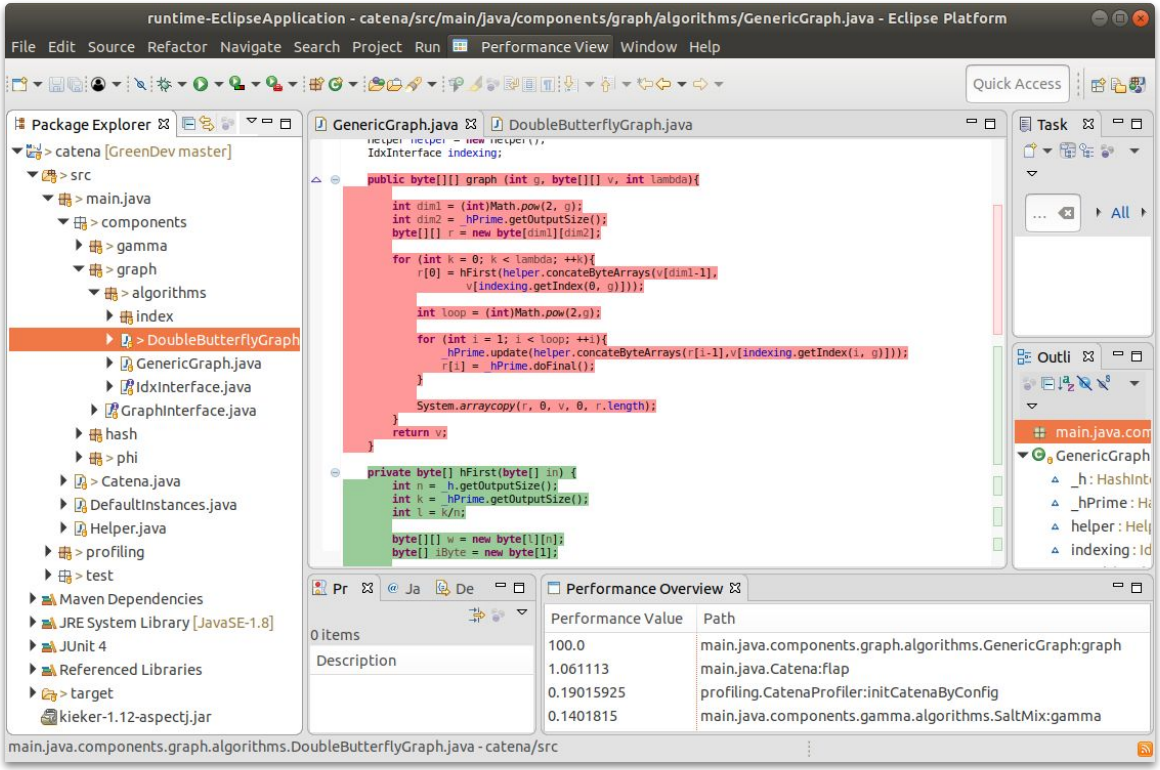


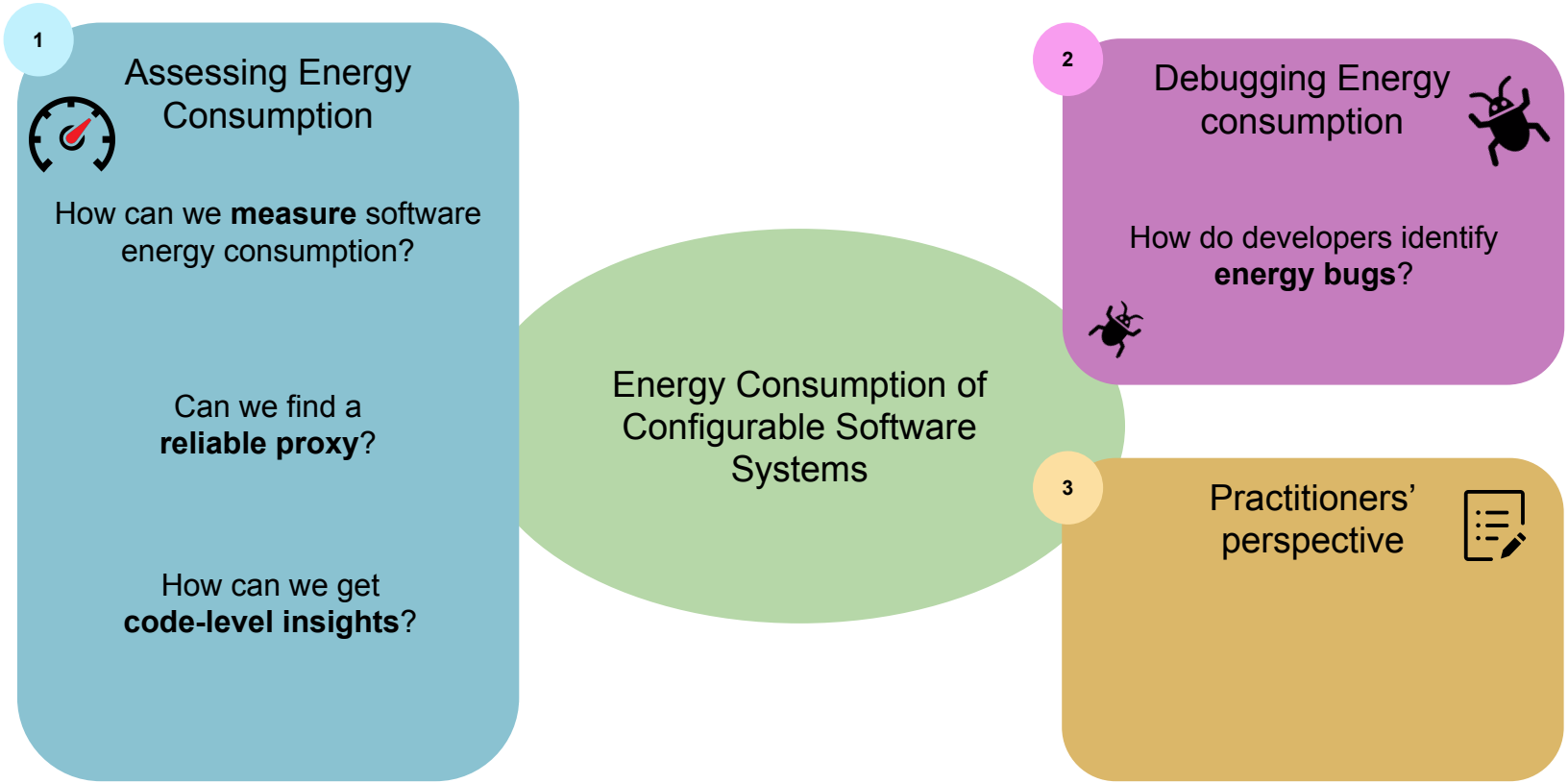
Solution: Filter large, non-deterministic outliers from context variance.

White-Box Energy Influence Models via Profiling



IDE Integration




1
Assessing Energy Consumption
How can we **measure** software energy consumption?
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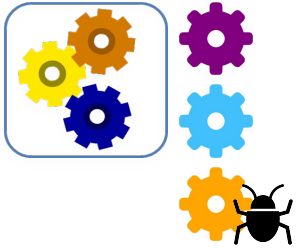
Debugging Energy consumption
How do developers identify **energy bugs**?
3
Practitioners' perspective

Energy Bugs in Configurable Systems

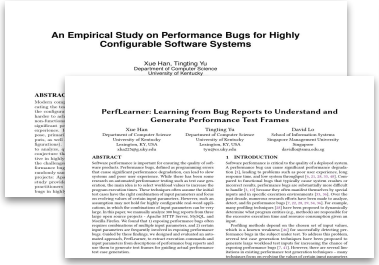
Functional bug

Energy bugs

Configuration-dependent bugs



Requires fixing code



An Empirical Study on Performance Bugs for Highly Configurable Software Systems

Xue Han, Tingting Yu
Department of Computer Science
University of Kentucky

PerfLearner: Learning from Bug Reports to Understand and Generate Performance Test Frames

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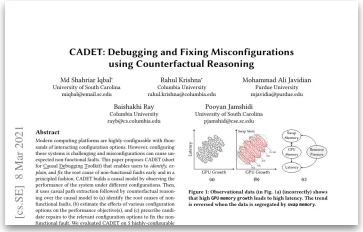
Lexington, KY, USA

David Lo
School of Information Systems
Singapore Management University
Singapore

Fixes are time consuming



CADET: Debugging and Fixing Misconfigurations using Counterfactual Reasoning

Md Shahriar Iqbal
University of South Carolina

Rahul Krishna*
Columbia University

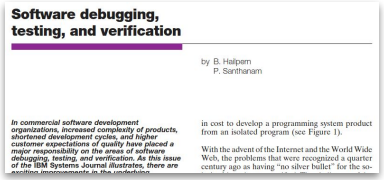
Mohammad Ali Javidian
Purdue University

Basuhakbi Ray
Columbia University

Pooyan Jamshidi
University of South Carolina

Abstract

What Does Debugging Literature Tell Us?

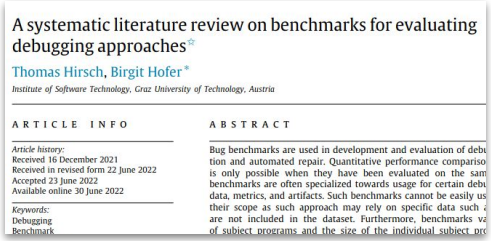

Software debugging, testing, and verification

by B. Hailpern
P. Santhanam

In commercial software development organizations, increased complexity of products, shortened development cycles, and higher customer expectations of quality have placed a major responsibility on the areas of software debugging, testing, and verification. As this issue of the IBM Systems Journal illustrates, there are exciting improvements in the underlying

in cost to develop a programming system product from an isolated program (see Figure 1).

With the advent of the Internet and the World Wide Web, the problems that were recognized a quarter century ago as having "no silver bullet" for the so-


A systematic literature review on benchmarks for evaluating debugging approaches☆

Thomas Hirsch, Birgit Hofer*

Institute of Software Technology, Graz University of Technology, Austria

ARTICLE INFO

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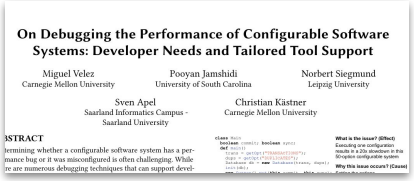
Available online 30 June 2022

Keywords:
Debugging
Benchmark

ABSTRACT

Bug benchmarks are used in development and evaluation of debu
tion and automated repair. Quantitative performance comparis
is only possible when they have been evaluated on the sam
benchmarks are often specialized towards usage for certain debu
data, metrics, and artifacts. Such benchmarks cannot be easily us
their scope as such approach may rely on specific data such
are not included in the dataset. Furthermore, benchmarks va
of subject programs and the size of the individual subject pr


On Debugging the Performance of Configurable Software Systems: Developer Needs and Tailored Tool Support

Miguel Velez
Carnegie Mellon University

Pooyan Jamshidi
University of South Carolina

Norbert Siegmund
Leipzig University

Sven Apel
Saarland Informatics Campus - Saarland University

Christian Kästner
Carnegie Mellon University

BSTRACT

ermining whether a configurable software system has a per-
mance bug or it was misconfigured is often challenging. While
re are numerous debugging techniques that can support devel-


Marc Eisenstadt

My Hairi est Bug Wa r Stories

Despite the availability of industrial-strength debuggers and integrated program development environments, professional programmers still engage in far more detective work than they should have to. This is their story—along with those of the ways they might eradicate their bugs.


Software Vi sualization for Debugging

Ron Baecker, Chris DiGiano, and Aaron Marcus

Representing programs through algorithm animation, typographic source-code presentation, and interactive visualization transforms the hunt for bugs into a cognitively accessible multimedia experience.

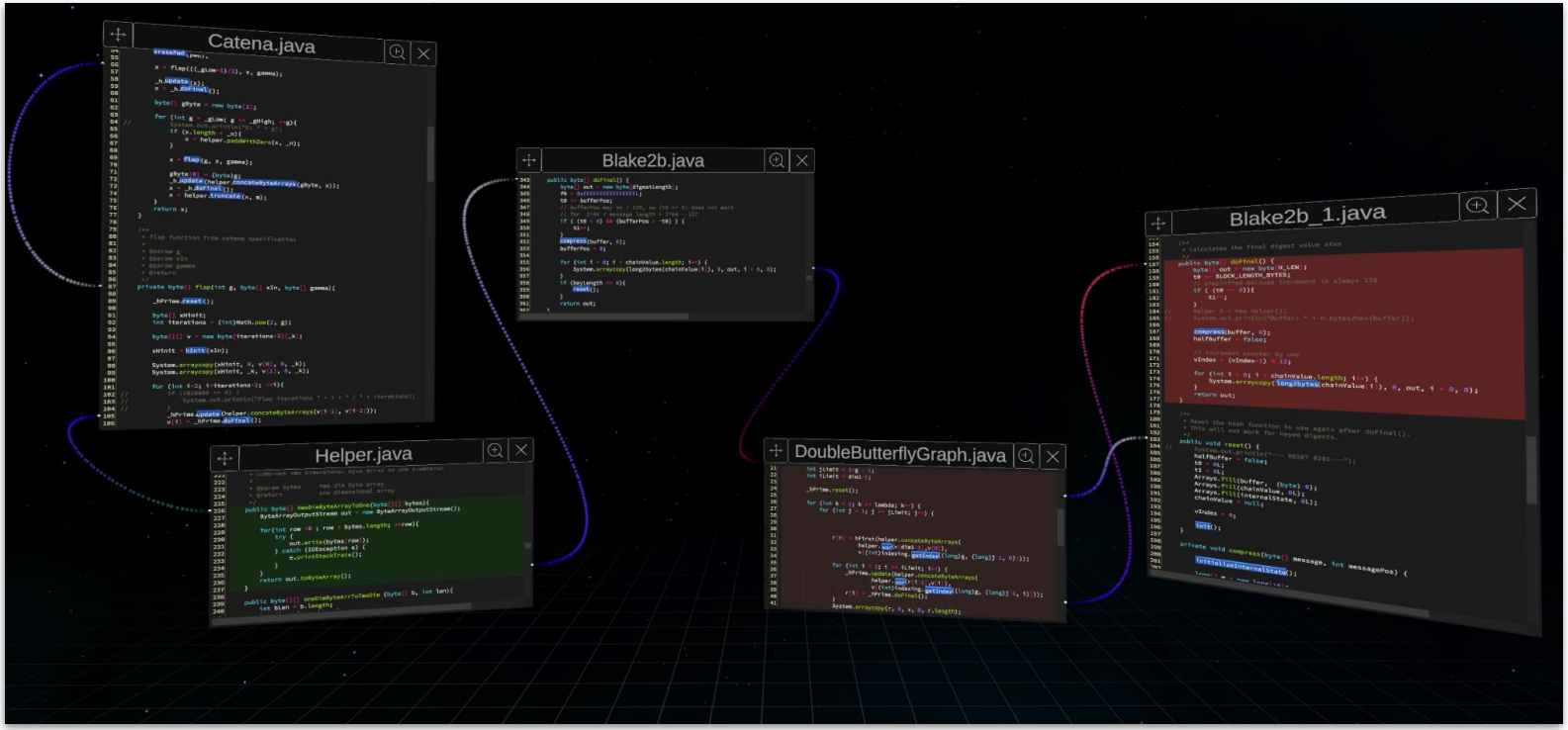
Algorithm Animation: How Does the Program Work?

- ❖ reviewing 74 publications
- ❖ revealed 12 debugging strategies

No clear consensus - literature shows fragmented perspectives on debugging.

[Miguel Velez, Pooyan Jamshidi, Norbert Siegmund, Sven Apel, and Christian Kästner. On debugging the performance of configurable software systems: Developer needs and tailored tool support]

Let’s observe developers debugging energy bugs in VR!

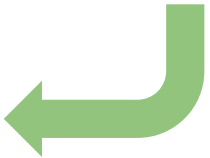


Case Study: Density Converter

(multi platform image density conversion)

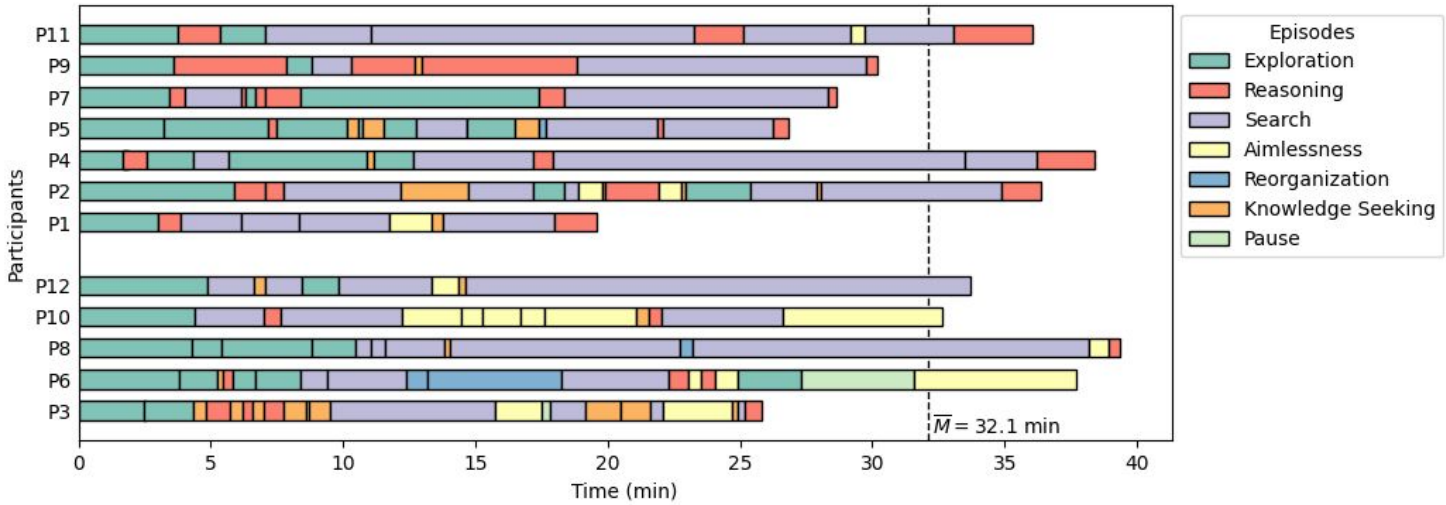
```
public final class Convert {
      public static void main(String[] rawArgs) {
        float fraction = 0.5f;
```

```
private static <T extends DensityDescriptor> Map<T, Dimension> getDensityBucketsWithFractionScale
          java.util.List<T> densities, Dimension srcDimension, Arguments args, float fraction) {
        double baseWidth = (double) srcDimension.width / fraction;
        double baseHeight = (double) srcDimension.height / fraction;
```



```
private void verticalFromWorkToDst(byte[][] workPixels, byte[] outPixels, int start, int delta) {
    // ...
    for (int x = start; x < dstWidth; x += delta) {
      final int xLocation = x * nrChannels;
      for (int y = dstHeight - 1; y >= 0; y--) {
        final int max = verticalSubsamplingData.arrN[y];
        for (int j = max - 1; j >= 0; j--) {
          int valueLocation = verticalSubsamplingData.arrPixel[index];
          float arrWeight = verticalSubsamplingData.arrWeight[index];
          // ...
```

Debugging as Episodes



Reasoning appears substantially more often in successful debugging.

Aimlessness seem to be a possible predictor for failure.

P11, reasoning:

"I need to understand what is going on in order to be able to formulate hypotheses".

P4, (problem-specific) exploration:

"Usually I try to get a fairly complete picture of something first."

P9, aimlessness:

"[...] there is no point in staying in such a frustrating moment."

Debugging as Episodes

Reasoning appears substantially more often in successful debugging.

...essness seem ...a possible ...tor for failure.

Finding: Developers do not follow a single strategy when debugging; they engage in goal-oriented episodes.

P11, reasoning

"I need to understand what is going on in order to be able to formulate hypotheses".

P4, (problem-specific) exploration:

"Usually I try to get a fairly complete picture of something first."

P9, aimlessness:

"[...] there is no point in staying in such a frustrating moment."

Energy Consumption of Configurable Software Systems

1

Assessing Energy Consumption

How can we **measure** software energy consumption?

Can we find a **reliable proxy**?

How can we get **code-level insights**?

2

Debugging Energy consumption

How can we identify **energy bugs**?

3

Practitioners' perspective

What is the **current state** of green software engineering?

Optimizing Software Energy Consumption in Practice

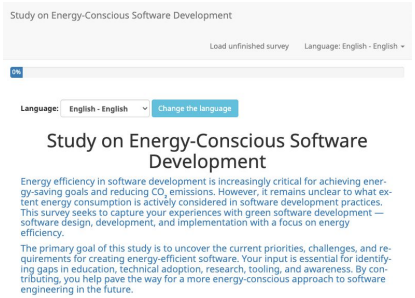
What is the **current state** of software energy consumption in practice?

How do practitioners **relate software energy consumption to other metrics** such as runtime performance?

134 developer

Bundesverband green.software

reddit

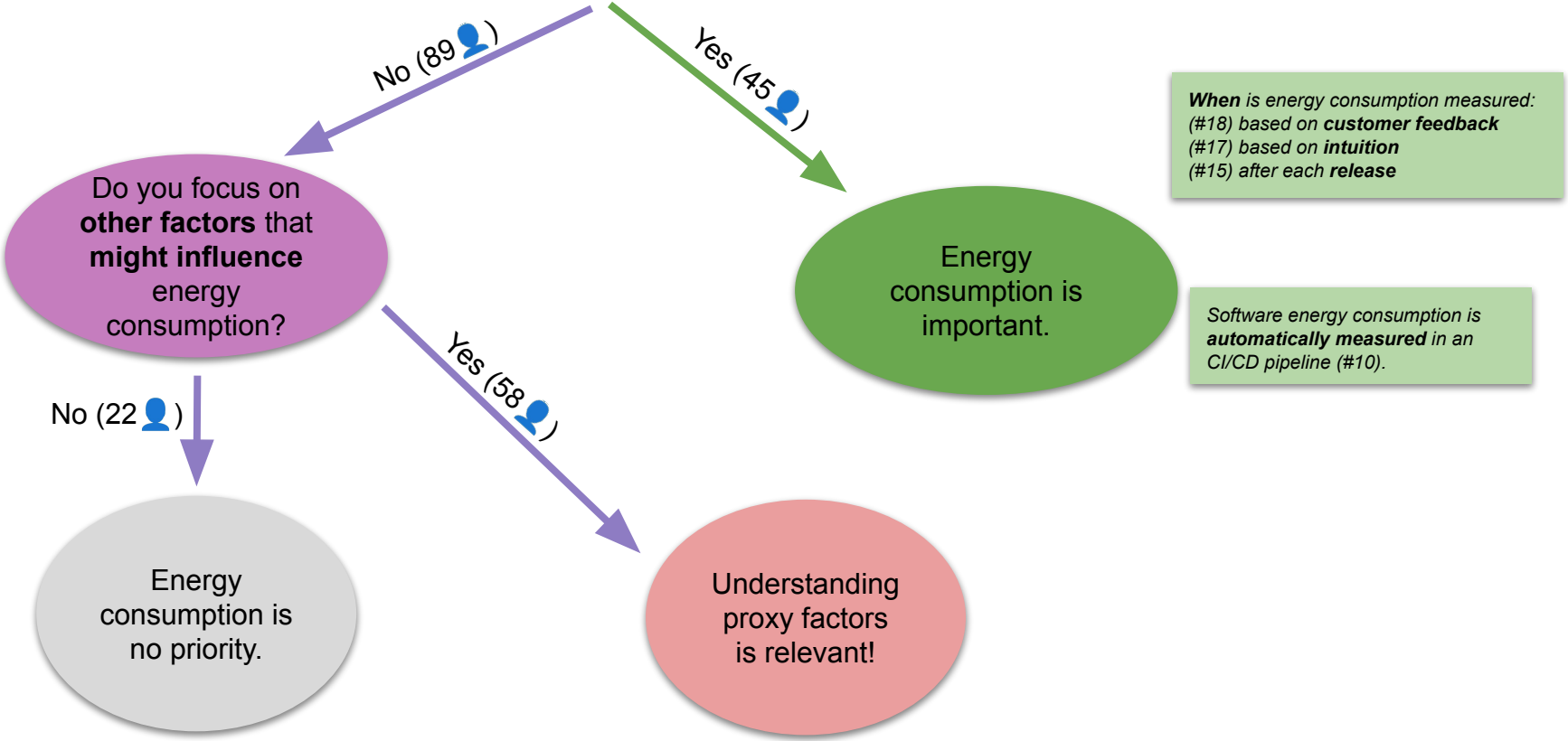


online survey

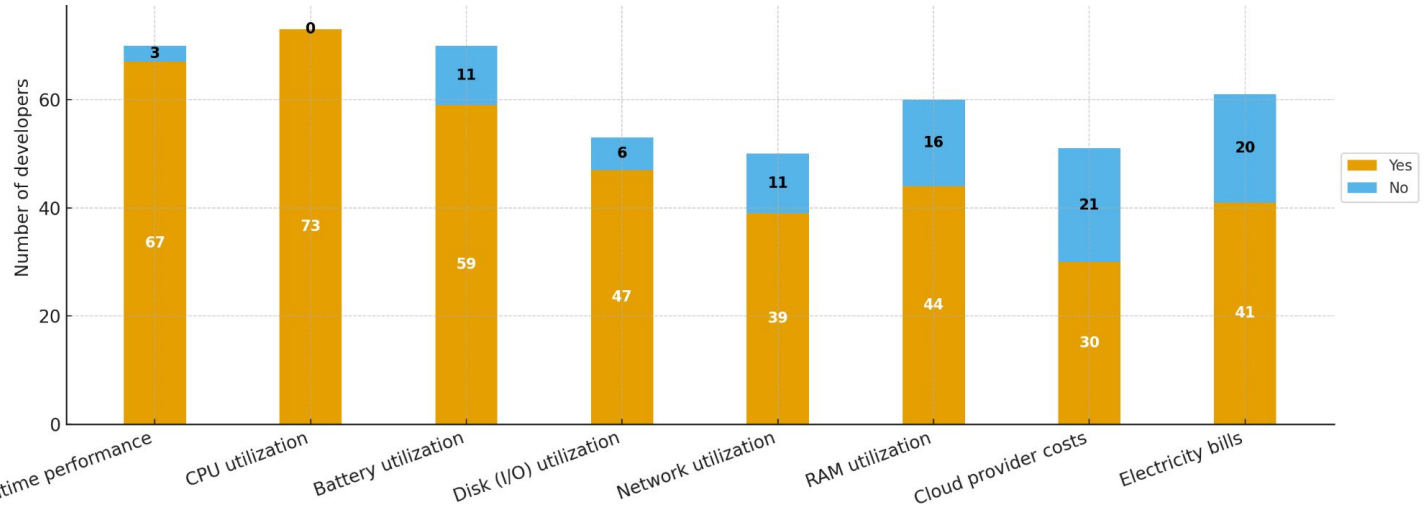
> 480 open text answers

> 20 hours manual analysis

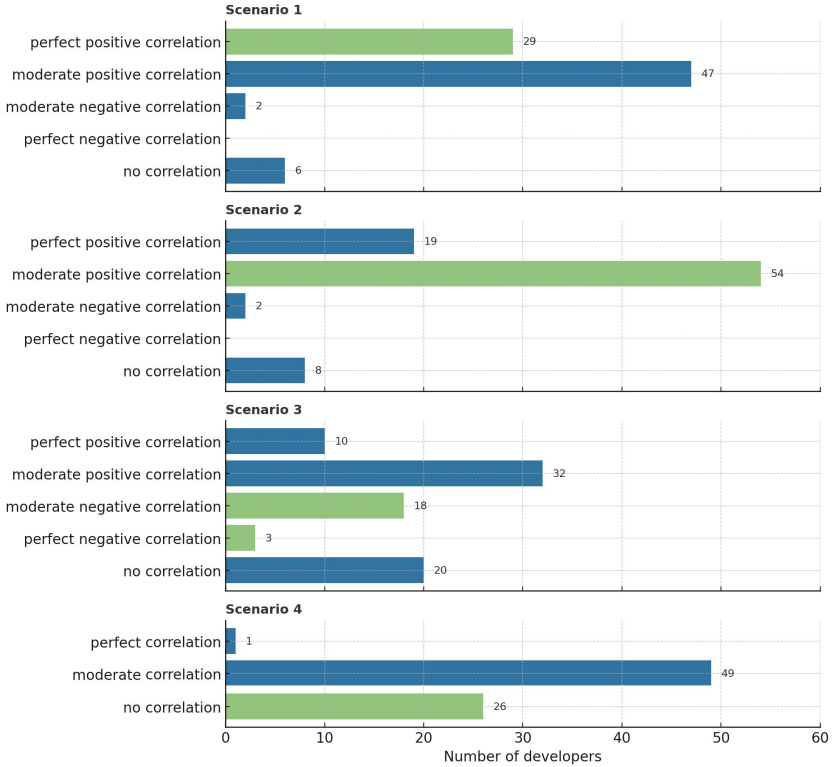
Is energy consumption relevant in participants' projects?

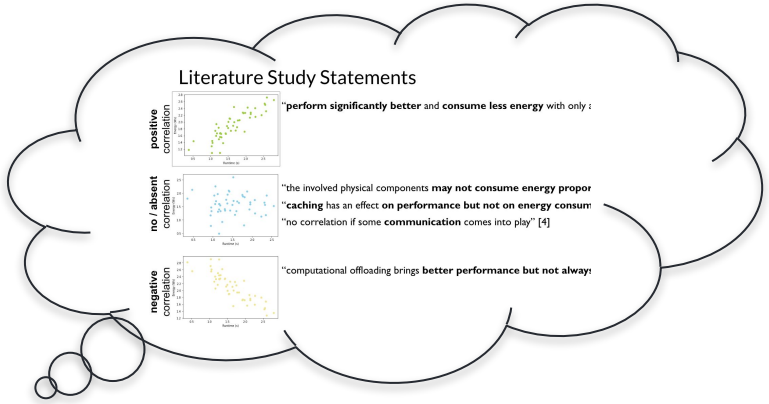


What metrics are considered good proxies for energy?



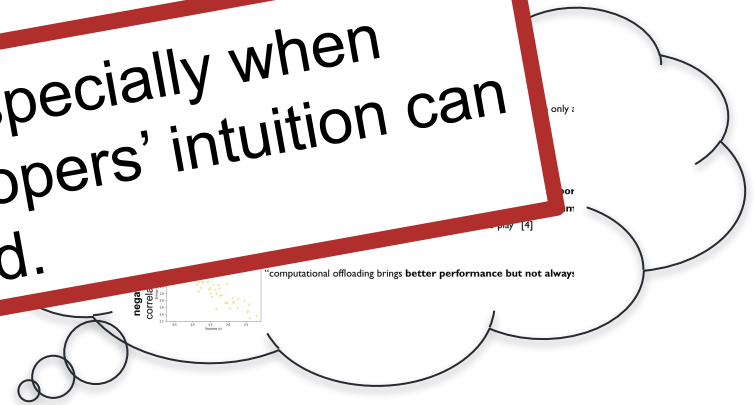
Do Developers Intuitively Know when Performance is a good Proxy for Energy?





Do Developers Intuitively Know when Performance is a good Proxy for Energy?

Finding: It depends! Especially when positively correlated developers' intuition can be trusted.



How to Support Practitioners

Barriers to Overcome

Barriers preventing energy measurement:
(55👤) Management is not interested
(46👤) Customers are not interested
(36👤) Not applicable in our use case

Persistent obstacles:
(14👤) Lack of energy measurement tooling
(10👤) Energy efficiency is perceived as complex
(06👤) Lack of education and training

Contra there are problems:
(11👤) Energy consumption is not important
(06👤) No perceived challenges
(05👤) Energy is not considered a cost driver

Actions

(13👤) Increasing awareness

(17👤) Provide better energy measurement tools

(08👤) Educate developers and stakeholders

(06👤) 'just' use efficient languages (C, C++, Rust)

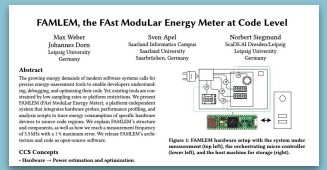
(06👤) Introduce public regulations

(04👤) Enforce transparency, especially for cloud providers

(05👤) Adopt efficient algorithms and implementations

1

Assessing Energy Consumption


FAMLEM, the FAst ModuLar Energy Meter at Code Level

Max Weber, Johannes Dorn, Leipzig University, Germany
Sven Apel, Saarland Informatics Campus, Saarland University, Saarbrücken, Germany
Norbert Siegmund, ScaDS.AI Dresden/Leipzig, Leipzig University, Germany

Abstract

The growing energy demands of modern software systems calls for precise energy-assessment tools to enable developers understanding, debugging, and optimizing their code. Yet, existing tools are constrained by low sampling rates or platform restrictions. We present FAMLEM (FAst ModuLar Energy Meter), a platform-independent system that integrates hardware probes, performance profiling, and analysis scripts to trace energy consumption of specific hardware devices to source code regions. We explain FAMLEM's structure and components, as well as how we reach a measurement frequency of 3.5 kHz with a 1 % maximum error. We release FAMLEM's architecture and code as open-source software.

CCS Concepts

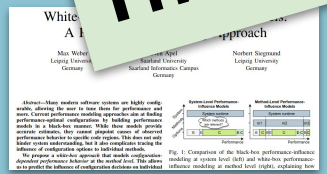
• Hardware → Power estimation and optimization.

Figure 1: FAMLEM hardware setup with the system under measurement (top left), the orchestrating micro controller (lower left), and the host machine for storage (right).


Twins or False Friends? A Study on Energy Consumption and Performance of Configurable Software

Max Weber*, Christian Kaltenecker†, Florian Sattler†, Sven Apel†, Norbert Siegmund*

* Leipzig University, Germany
† Saarland University, Saarland Informatics Campus, Germany

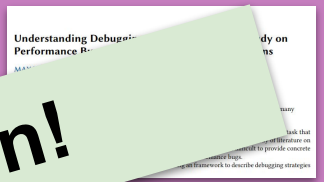

Approach

Max Weber, Leipzig University, Germany
Sven Apel, Saarland University, Saarland Informatics Campus, Germany
Norbert Siegmund, Leipzig University, Germany

Fig. 1: Comparison of the black-box performance-influence modeling at system level (left) and white-box performance-influence modeling at method level (right), explaining how

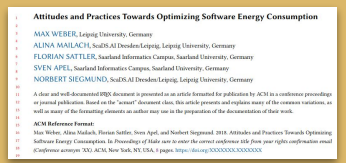
2

Debugging Energy consumption


Understanding Debuggi… Performance …dy on …ns

3

Practitioners' perspective


Attitudes and Practices Towards Optimizing Software Energy Consumption

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UNIVERSITÄT
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on the job market
from march ‘26
😏

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